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MODERN DIAGNOSTIC METHODS AND INDICATORS FOR EVALUATING THE EFFECTIVENESS OF VIRTUAL LABORATORIES

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Abstract
This article explores contemporary diagnostic approaches and assessment indicators used to evaluate the effectiveness of virtual laboratories in educational environments. The paper examines technological, pedagogical, and psychological criteria for diagnostics, along with performance metrics that reflect student engagement, learning outcomes, and system usability. The study emphasizes the growing role of virtual laboratories in STEM education and highlights methods that ensure their quality, reliability, and long-term educational value.

Keywords: Virtual laboratories, digital diagnostics, educational technology, learning analytics, assessment indicators, STEM education

Introduction

The rapid digitalization of education has significantly transformed the learning environment, leading to the widespread adoption of virtual laboratories across disciplines such as physics, chemistry, biology, computer science and engineering. Virtual laboratories offer safe, flexible, and cost-effective opportunities for conducting experiments and simulations that are difficult or expensive to implement in traditional settings. As their usage grows, the need for reliable diagnostic methods and evaluation indicators becomes increasingly critical. This article outlines modern approaches used for assessing the

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effectiveness of virtual laboratories, focusing on technological performance, pedagogical relevance, cognitive engagement, and learning outcomes.

Modern Diagnostic Methods for Virtual Laboratories:

1. Learning Analytics. Learning analytics is one of the most advanced diagnostic tools used to evaluate virtual laboratory environments. It includes:

- Data tracking: time spent on tasks, number of attempts, interaction patterns, heatmaps.
- Behavioral analysis: clickstream data, navigation paths, error tracking.
- Predictive analytics: identifying students at risk and measuring learning progress.

These diagnostics provide real-time insights into student performance and interaction quality.

2. Performance-Based Assessment. Virtual labs allow automated assessment of procedural and conceptual competencies. This includes:

- correctness of experiment steps,
- accuracy of recorded measurements,
- ability to interpret results,
- completion time and optimization choices.

Such diagnostics help determine how well students apply theoretical knowledge in simulated conditions.

3. Cognitive Diagnostic Models (CDM). CDM methods evaluate specific knowledge and skills acquired during virtual laboratory work. They allow educators to identify:

- gaps in conceptual understanding,
- misconceptions in scientific reasoning,
- mastery of complex procedural steps.
- This approach supports personalized learning pathways.

4. Usability Testing. The usability of virtual labs is diagnosed using: interface evaluation; task difficulty analysis; user satisfaction surveys; completion rates and error frequency. Popular tools include SUS (System Usability Scale) and heuristic evaluation frameworks.

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5. Embedded Assessment Tools. Some platforms include built-in diagnostic features such as: pre-tests and post-tests; interactive quizzes; automated feedback modules; progress dashboards. These tools ensure continuous evaluation during learning.

These indicators measure academic achievement and conceptual understanding. They include: improvement between pre-test and post-test scores; mastery of laboratory procedures; ability to solve complex problems; retention of knowledge over time.

Student engagement is critical for virtual learning. Indicators include: frequency and duration of virtual lab usage; number of completed experiments; participation in optional tasks; self-reported motivation and satisfaction.

These indicators assess system quality: loading speed; stability and absence of errors; compatibility with devices; responsiveness of simulations. High technical quality ensures a smooth learning experience.

These metrics measure how well virtual labs support educational objectives: alignment with curriculum standards; clarity of instructions; level of scaffolding and feedback; adaptability for different learner levels. Virtual laboratories are often evaluated based on economic factors: reduced need for physical equipment; scalability for large groups; long-term maintenance costs; return on investment (ROI) in learning outcomes. Evaluation includes checking whether virtual labs: support learners with disabilities, offer multilingual options, provide flexible access (mobile, offline, etc.). Inclusivity is essential for modern education.

Table 1. Diagnostic Indicators of Virtual Laboratory Performance – Core Diagnostic Indicators

Indicator Category	Specific Indicators	Purpose
Technical Performance	System load time, error rate, simulation speed, device compatibility	Measures stability and reliability of the virtual lab platform
User Interaction	Number of clicks, navigation path, time-on-task, completion rates	Diagnoses how effectively learners interact with the system
Learning Analytics	Pre-test/post-test results, conceptual mastery scores, error frequency	Identifies learning progress and conceptual understanding
Engagement Metrics	Session frequency, duration, optional task participation	Measures motivational and engagement levels
Usability Indicators	SUS score, ease-of-navigation rating, clarity of instructions	Evaluates user experience and interface quality

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Table -2. Sample Diagnostic Questions for Evaluating Virtual Labs

How effectively does the virtual lab support students in understanding complex scientific concepts?
Are learners able to complete laboratory procedures without instructor assistance?
Does the platform provide real-time feedback that enhances learning?
What usability issues do students frequently encounter (navigation difficulties, unclear instructions, technical glitches)?
How often do students voluntarily revisit the virtual lab for additional practice?
Does the virtual lab reduce the need for physical resources and costs?

Table -3. Sample Student Feedback Survey Items

Students rate each item from 1 (Strongly Disagree) to 5 (Strongly Agree).				
The virtual laboratory was easy to use and navigate	Instructions for each experiment were clear and understandable	Feedback provided by the system was helpful in correcting my mistakes	The simulations felt realistic and helped me understand the material better	I feel more confident performing real laboratory tasks after using the virtual lab.

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The combination of technological, pedagogical, and analytical tools creates a comprehensive system for diagnosing the effectiveness of virtual laboratories. Modern diagnostic methods such as learning analytics and CDM allow precise measurement of student skills, while usability testing ensures the system is user-friendly. At the same time, indicators such as learning achievement, engagement, and cost-efficiency help institutions assess the long-term value of implementing virtual labs.

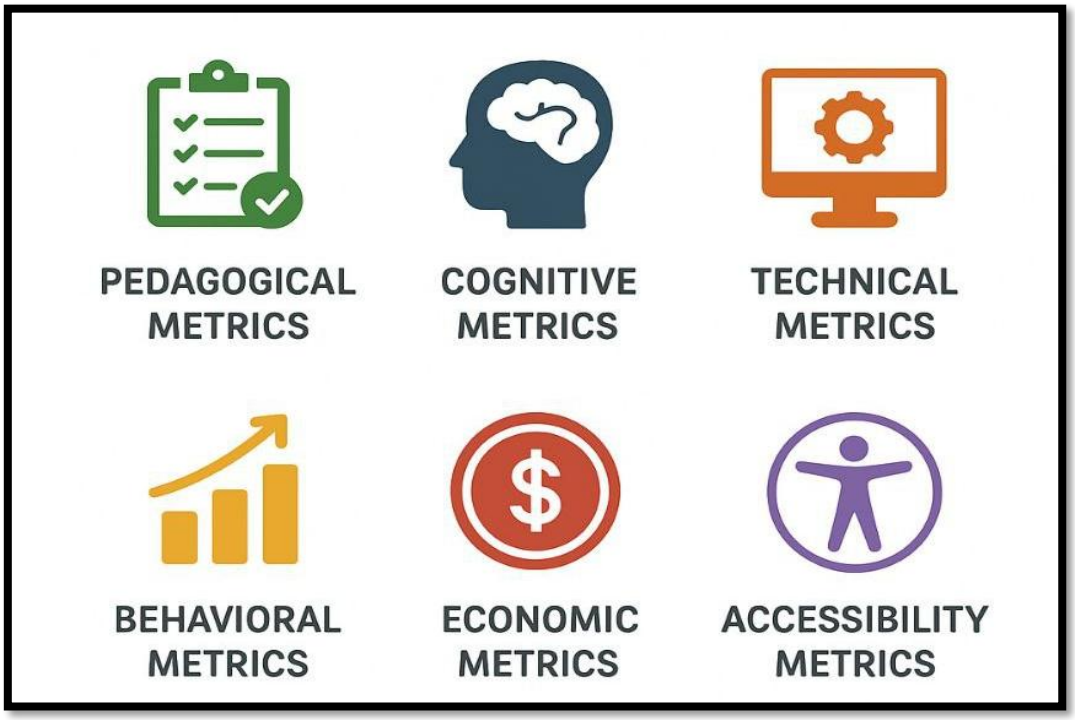

Figure -1. Summary of Evaluation Metric Categories

Description:

- Pedagogical Metrics: Alignment with curriculum, development of critical thinking, mastery of procedures.
- Cognitive Metrics: Knowledge retention, conceptual depth, ability to apply theory.
- Technical Metrics: Server performance, system responsiveness, stability.
- Behavioral Metrics: Engagement frequency, interaction patterns, motivation indicators.
- Economic Metrics: Cost reduction, scalability, resource optimization.

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➢ Accessibility Metrics: Inclusiveness for learners with disabilities, platform flexibility.

Thus, the infographic demonstrates that the evaluation of virtual laboratories is multidimensional and covers not only educational outcomes, but also technical, economic and social aspects.

Virtual laboratories have become indispensable tools for contemporary education, offering interactive and innovative learning opportunities. Effective diagnostics and evaluation indicators play a central role in ensuring their quality and relevance. By applying modern diagnostic methods, educators can obtain detailed insights into student learning processes, improve instructional strategies, and optimize digital laboratory environments. The integration of learning analytics, usability evaluation, and outcome-based measurement ensures that virtual laboratories meet the growing demands of the educational landscape.

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