VIRTUAL LABORATORIES IN SCIENCE EDUCATION AT ISLAMIC ELEMENTARY SCHOOLS: A LITERATURE REVIEW

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ABSTRACT

Science education emphasizes the development of conceptual understanding, science process skills, and scientific attitudes through practical activities. However, the implementation of laboratory-based science learning in Madrasah Ibtidaiyah is often constrained by limited laboratory facilities, equipment, and instructional resources. Virtual Laboratories have emerged as an alternative learning environment that can address these limitations. This study aimed to examine the use of Virtual Laboratories in science education at Madrasah Ibtidaiyah through a literature review. The study reviewed national and international scholarly publications published between 2015 and 2025. Relevant literature was retrieved from Scopus, ERIC, and Google Scholar and analyzed using thematic content analysis. The findings indicate that Virtual Laboratories provide a flexible and interactive learning environment that supports practical science instruction. The synthesis identified three major educational benefits: improving students' conceptual understanding, strengthening science process skills, and increasing learning motivation. The review also suggests that Virtual Laboratories are compatible with the cognitive characteristics of elementary school students, although their implementation is influenced by the availability of digital infrastructure and teachers' technological and pedagogical competencies. Therefore, Virtual Laboratories should be regarded as complementary learning environments that enrich rather than replace conventional laboratory activities in science education.

Keywords: Literature Review; Madrasah Ibtidaiyah; Science Education; Virtual Laboratory.

ABSTRAK

Pembelajaran Ilmu Pengetahuan Alam (IPA) menekankan penguasaan konsep, keterampilan proses sains, dan sikap ilmiah melalui kegiatan praktikum. Namun, pelaksanaan praktikum di Madrasah Ibtidaiyah masih menghadapi berbagai kendala, seperti keterbatasan laboratorium, peralatan, dan bahan praktikum. Virtual Laboratory menjadi salah satu alternatif pembelajaran yang berpotensi mengatasi keterbatasan tersebut. Penelitian ini bertujuan untuk mengkaji pemanfaatan Virtual Laboratory dalam pembelajaran IPA di Madrasah Ibtidaiyah melalui telaah literatur. Penelitian menggunakan metode literature review dengan menelaah berbagai

artikel ilmiah nasional dan internasional yang dipublikasikan pada periode 2015–2025. Literatur diperoleh dari basis data Scopus, ERIC, dan Google Scholar, kemudian dianalisis menggunakan thematic content analysis. Hasil kajian menunjukkan bahwa Virtual Laboratory berperan sebagai lingkungan belajar alternatif yang mendukung pelaksanaan praktikum IPA secara lebih fleksibel dan interaktif. Sintesis literatur mengidentifikasi tiga manfaat utama, yaitu meningkatkan pemahaman konsep, mengembangkan keterampilan proses sains, serta meningkatkan motivasi belajar peserta didik. Implementasi Virtual Laboratory di Madrasah Ibtidaiyah dinilai relevan dengan karakteristik perkembangan kognitif siswa sekolah dasar, meskipun masih menghadapi tantangan berupa keterbatasan infrastruktur digital dan kompetensi guru. Oleh karena itu, Virtual Laboratory tidak dimaksudkan untuk menggantikan laboratorium konvensional, tetapi sebagai pelengkap pembelajaran praktikum yang dapat memperluas kesempatan belajar sains secara lebih efektif.

Kata Kunci: Pembelajaran IPA; literature review; Madrasah Ibtidaiyah; Virtual Laboratory.

A. Introduction

Science education plays a fundamental role in developing students' understanding of the natural world while fostering scientific reasoning, inquiry skills, and positive scientific attitudes (Gizaw & Sota, 2023; Vieira & Tenreiro-Vieira, 2016). Beyond acquiring scientific concepts, students are expected to observe phenomena, conduct investigations, interpret evidence, and draw logical conclusions. Therefore, science learning should provide meaningful learning experiences that integrate conceptual knowledge with scientific processes (Al-Barakat et al., 2025; Pinar et al., 2025).

Practical activities are an essential component of science instruction because they enable students to experience scientific inquiry directly (Gericke et al., 2023; Park et al., 2023). Through experimentation, students develop conceptual understanding alongside observation, investigation, problem-solving, and evidence-based reasoning. Such experiences contribute to the development of scientific literacy and help students construct knowledge through active engagement rather than passive reception of information (Cooper, 2023; Mohzana et al., 2023)

Despite its importance, practical science instruction remains difficult to implement in many Madrasah Ibtidaiyah (Islamic elementary schools) (Borger et al., 2023; Matos et al., 2023). Limited laboratory facilities, insufficient equipment and materials, restricted instructional time, and teachers' limited experience in organizing laboratory activities often reduce opportunities for students to participate in hands-on experiments (Wen et al., 2023; Zhang et al., 2022). Consequently, science instruction is frequently dominated by theoretical explanations, limiting students' opportunities to develop scientific process skills through authentic learning experiences (Abuhassna & Alnawajha, 2023).

Recent advances in educational technology have introduced Virtual Laboratories (Virtual Labs) as an alternative approach to practical science learning (Liu et al., 2015; Potkonjak et al., 2016). Virtual Labs simulate laboratory activities through interactive computer-based environments, allowing students to conduct experiments without relying entirely on physical laboratories or laboratory equipment (Alhashem & Alfailakawi, 2023; Atchia & Rumjaun, 2023).These digital environments provide safe, flexible, and repeatable learning experiences while reducing the financial and logistical constraints associated with conventional laboratory instruction.

Previous studies have consistently reported positive outcomes associated with the use of Virtual Labs in science education (Serrano-Perez et al., 2023). Research indicates that Virtual Labs improve students' conceptual understanding, learning motivation, scientific process skills, and critical thinking abilities (Kolil & Achuthan, 2024). Interactive simulations also facilitate the visualization of scientific phenomena that are difficult to observe in conventional classroom settings, making abstract concepts more accessible to learners (Alnagrat et al., 2022).

Although the educational benefits of Virtual Labs have been widely documented, most existing studies have focused on secondary schools and higher education. Evidence regarding their implementation in Madrasah Ibtidaiyah remains limited. This gap is

important because elementary school students are generally at the concrete operational stage of cognitive development, where learning is more effective when supported by visual representations and concrete experiences. Understanding how Virtual Labs can support science learning in this educational context is therefore essential.

This study aims to review the existing literature on the use of Virtual Laboratories in science learning at Madrasah Ibtidaiyah. Specifically, the review synthesizes current evidence regarding the educational benefits of Virtual Labs, identifies challenges associated with their implementation, and discusses their relevance to the cognitive characteristics of elementary school students. The findings are expected to provide a conceptual foundation for teachers, schools, and researchers seeking to integrate Virtual Laboratories into science instruction in Islamic elementary schools.

B. Research Methods

2.1 Research Design

This study employed a literature review design to synthesize previous research on the implementation of Virtual Laboratories in science education, with particular emphasis on their relevance to learning in Madrasah Ibtidaiyah (Islamic elementary schools). A literature review was selected because it enables researchers to integrate findings from previous studies, identify recurring themes, and develop a comprehensive understanding of the current state of knowledge regarding a particular topic (Escudero-Mancebo et al., 2023). Rather than testing hypotheses, this study aimed to examine patterns of evidence concerning the educational benefits, implementation challenges, and pedagogical relevance of Virtual Laboratories in science learning.

2.2 Literature Search Strategy

The literature search was conducted between March and April 2026 using three academic databases: Scopus and Google Scholar. Scopus were selected as the primary sources of international publications, while Google Scholar was used to identify relevant national publications that complemented the international evidence.

The search process employed combinations of the following keywords*: "Virtual Laboratory", "Virtual Lab", "science education", "science learning", "elementary school", "primary education", and "Madrasah Ibtidaiyah".* Searches were performed in both English and Indonesian to ensure comprehensive coverage of studies relevant to the Indonesian educational context. To maintain the relevance of the review to recent developments in educational technology, only publications published between 2015 and 2025 were considered for analysis.

2.3 Literature Selection

The literature selection process was guided by predetermined inclusion and exclusion criteria to ensure the quality and relevance of the reviewed studies. The inclusion criteria were as follows: peer-reviewed journal articles published between 2015 and 2025; studies focusing on Virtual Laboratories or virtual laboratory-based learning in science education; studies conducted at elementary, secondary, or higher education levels that reported findings relevant to science learning; publications written in English or Indonesian. Publications were excluded if they: were duplicate records; did not specifically address Virtual Laboratories in science education; consisted only of editorials, opinion papers, or non-peer-reviewed publications; lacked sufficient methodological or empirical information. Following the screening process, the selected publications were reviewed in detail to identify evidence relevant to the objectives of this study.

2.4 Data Analysis

The selected literature was analyzed using thematic content analysis. Each publication was read thoroughly to identify its research objectives, methods, principal findings, and educational implications. Similar findings were then grouped into broader themes through an iterative comparison process. The synthesis focused on five major themes that consistently emerged across the reviewed literature: (1) the characteristics of Virtual Laboratories as digital learning environments, (2) their educational benefits for science learning, (3) their relevance to elementary students' cognitive development, (4) their implementation

in Madrasah Ibtidaiyah, and (5) the challenges and future directions of Virtual Laboratory integration in science education.

The findings of the selected studies were subsequently synthesized to provide an integrated interpretation of current evidence rather than merely summarizing individual publications. This thematic synthesis served as the basis for developing the Results and Discussion section of this study.

C. Results and Discussion

3.1 Virtual Laboratories as an Alternative Learning Environment

Virtual Laboratories (Virtual Labs) have emerged as an alternative learning environment that supports practical science instruction through digital simulation. Unlike conventional laboratories, Virtual Labs allow students to conduct experiments in a computer-based environment that replicates essential laboratory activities, including observation, experimentation, data interpretation, and conclusion drawing. This approach enables students to engage in scientific inquiry without being constrained by the availability of laboratory facilities, equipment, or consumable materials. Consequently, Virtual Laboratories are increasingly recognized as an effective solution for schools with limited laboratory resources while maintaining the experiential nature of science learning.

The reviewed literature indicates that Virtual Laboratories differ from conventional laboratories not only in terms of learning media but also in learning flexibility. Conventional laboratories require physical infrastructure, laboratory equipment, and scheduled practical sessions, whereas Virtual Laboratories provide opportunities for repeated experimentation, independent exploration, and immediate feedback within a safe digital environment. These characteristics enable students to investigate scientific phenomena more efficiently while minimizing safety risks and operational costs. Therefore, Virtual Laboratories should be viewed as complementary learning environments that enrich practical science instruction rather than replacing conventional laboratory activities.

Table 1. Comparison between Conventional Laboratories and Virtual Laboratories

Aspect	Conventional Laboratory	Virtual Laboratory
Learning environment	Physical laboratory	Computer-based simulation
Equipment	Requires laboratory tools and materials	Digital simulation without physical equipment
Accessibility	Limited by place and schedule	Accessible anytime and anywhere
Safety	Potential laboratory hazards	Safe learning environment
Cost	High operational and maintenance costs	Lower operational costs
Learning flexibility	Limited opportunities for repetition	Experiments can be repeated multiple times

The synthesis of previous studies suggests that the primary contribution of Virtual Laboratories lies in their ability to provide flexible and interactive learning experiences while preserving the essential characteristics of scientific experimentation. Rather than functioning solely as digital substitutes for conventional laboratories, Virtual Laboratories facilitate inquiry-based learning by allowing students to observe phenomena, manipulate variables, and evaluate experimental outcomes in a structured learning environment. These characteristics make Virtual Laboratories particularly relevant for science education, especially in schools where access to laboratory facilities remains limited.

3.2 Educational Benefits of Virtual Laboratories in Science Learning

The reviewed literature consistently indicates that Virtual Laboratories contribute positively to science learning across different educational contexts. Although the reported outcomes vary among studies, three major educational benefits emerge consistently: improving conceptual understanding, strengthening science process skills, and increasing students' learning motivation. These findings suggest that Virtual Laboratories function not only as digital learning media but also as instructional environments that support meaningful science learning.

One of the most widely reported benefits of Virtual Laboratories is the improvement of students' conceptual understanding. Interactive simulations allow learners to visualize scientific phenomena that are difficult to observe through conventional classroom instruction. By repeatedly observing experiments and

manipulating variables, students are better able to connect theoretical concepts with observable scientific processes. Several studies have reported that students who learned through Virtual Laboratories demonstrated better conceptual understanding than those who participated only in conventional instruction.

Virtual Laboratories also facilitate the development of science process skills. Digital experiments provide opportunities for students to observe, investigate, formulate hypotheses, analyze experimental results, and draw evidence-based conclusions. These activities encourage active participation throughout the learning process while allowing experiments to be repeated without limitations related to laboratory facilities or materials. Consequently, Virtual Laboratories support inquiry-based science learning by creating opportunities for exploration and scientific reasoning.

Another important benefit identified in the reviewed literature is increased learning motivation. Interactive visualizations, immediate feedback, and opportunities for independent experimentation encourage greater student engagement during science learning. The flexibility of Virtual Laboratories also enables students to learn at their own pace, revisit experiments whenever necessary, and explore scientific concepts beyond classroom instruction. These characteristics contribute to a more student-centered learning environment and encourage greater participation in science activities.

Table 2. Synthesis of the Educational Benefits of Virtual Laboratories in Science Learning

Educational Benefit	Evidence from Previous Studies	Implications for Science Learning
Conceptual understanding	Interactive simulations improve students' understanding of abstract scientific concepts.	Students connect theoretical knowledge with observable scientific phenomena.
Science process skills	Virtual experiments support observation, investigation, data interpretation, and scientific reasoning.	Students develop inquiry skills and evidence-based thinking.
Learning motivation	Interactive learning environments increase participation, curiosity, and engagement.	Students become more active and independent during science learning.

Overall, the literature suggests that the effectiveness of Virtual Laboratories extends beyond technological innovation. Their educational value lies in supporting conceptual learning, scientific inquiry, and active student participation simultaneously. Therefore, Virtual Laboratories can serve as an effective complement to conventional laboratory activities, particularly in schools where access to laboratory facilities remains limited.

3.3 Implementation of Virtual Laboratories in Madrasah Ibtidaiyah

The implementation of Virtual Laboratories in *Madrasah Ibtidaiyah* should consider the cognitive characteristics of elementary school students. According to Piaget's theory, children aged 7–12 years are generally in the concrete operational stage, during which learning is more effective when abstract concepts are presented through concrete experiences and visual representations. Science learning at this level therefore requires instructional media that enable students to observe, explore, and interact with scientific phenomena in meaningful ways rather than relying solely on verbal explanations.

Virtual Laboratories provide learning experiences that are consistent with these developmental characteristics. Interactive simulations allow students to observe scientific processes, manipulate experimental variables, and immediately visualize the consequences of their actions. Such activities encourage active participation while helping students relate theoretical concepts to observable phenomena. For schools with limited laboratory facilities, Virtual Laboratories also offer practical opportunities to maintain experimental learning without requiring complete laboratory infrastructure.

Several digital platforms are available to support the implementation of Virtual Laboratories in science learning. International platforms such as PhET Interactive Simulations, OLabs, and Labster provide interactive simulations covering various science topics. In Indonesia, teachers may also utilize the Rumah Belajar platform developed by the Ministry of Education, which includes virtual laboratory resources that can be integrated into classroom

instruction. These platforms may be incorporated into lesson plans as introductory activities, guided investigations, or independent learning tasks, depending on students' learning objectives and available technological resources.

Table 3. Examples of Virtual Laboratory Platforms for Science Learning

Platform	Access	Main Features	Potential Use in Madrasah Ibtidaiyah
PhET Interactive Simulations	Free	Interactive science simulations	Concept introduction and guided experiments
OLabs	Free	Virtual laboratory activities	Practical science learning
Labster	Free/ Paid	3D laboratory simulations	Advanced science visualization
Rumah Belajar	Free	Virtual laboratory and digital learning resources	Science learning aligned with the Indonesian curriculum

Overall, the reviewed literature suggests that the successful implementation of Virtual Laboratories depends not only on technology availability but also on teachers' ability to integrate digital experiments into inquiry-based science learning. When appropriately implemented, Virtual Laboratories can complement classroom instruction by providing meaningful experimental experiences that are consistent with the cognitive characteristics and learning needs of students in *Madrasah Ibtidaiyah*.

3.4 Challenges and Recommendations for Virtual Laboratory Implementation

Despite their educational potential, the implementation of Virtual Laboratories in science learning is not without challenges. The reviewed literature indicates that technological infrastructure remains one of the primary barriers, particularly in schools with limited access to computers, mobile devices, and stable internet connections. These limitations may reduce students' opportunities to participate in virtual experiments and affect the effectiveness of technology-based science instruction.

Another important challenge concerns teachers' digital competence. The successful integration of Virtual Laboratories requires teachers to possess not only technological skills but also pedagogical competence in designing inquiry-based learning activities.

Virtual simulations should not be used merely as demonstration tools; instead, they need to be integrated into lesson plans that encourage observation, questioning, experimentation, data interpretation, and reflection. Therefore, continuous professional development is essential to support teachers in utilizing digital learning technologies effectively.

The reviewed studies also emphasize that Virtual Laboratories should complement rather than replace conventional laboratory activities. Although virtual simulations provide flexible, safe, and cost-effective learning experiences, direct interaction with laboratory equipment remains important for developing practical manipulation skills. Consequently, a blended approach that combines virtual and conventional laboratory activities is considered the most appropriate strategy for science education, particularly in schools where laboratory resources are limited.

Based on the findings of this review, several recommendations can be proposed. Schools should improve access to digital learning infrastructure and encourage the integration of Virtual Laboratories into science instruction. Teachers should receive regular training on the pedagogical use of digital laboratory simulations, while educational policymakers should continue expanding freely accessible virtual laboratory platforms that are aligned with the national curriculum. Future studies are also encouraged to investigate the effectiveness of Virtual Laboratories specifically in *Madrasah Ibtidaiyah*, as empirical evidence within this educational context remains limited.

Overall, Virtual Laboratories offer considerable opportunities to enrich science learning by expanding access to practical activities, supporting inquiry-based instruction, and increasing student engagement. Nevertheless, their successful implementation depends on the availability of technological resources, teachers' instructional competence, and appropriate integration into classroom practice. When these factors are addressed, Virtual Laboratories can become an effective complement to conventional science laboratories in supporting meaningful learning experiences for elementary school students.

D. Conclussion

This literature review demonstrates that Virtual Laboratories represent a promising learning environment for supporting science education, particularly in contexts where access to conventional laboratory facilities is limited. The reviewed studies consistently indicate that Virtual Laboratories provide opportunities for interactive experimentation, enabling students to observe scientific phenomena, manipulate variables, and construct conceptual understanding through inquiry-based learning.

The synthesis of previous studies identified three major educational benefits of Virtual Laboratories. First, Virtual Laboratories enhance students' conceptual understanding by facilitating the visualization of abstract scientific concepts through interactive simulations. Second, they support the development of science process skills by encouraging observation, investigation, data interpretation, and evidence-based reasoning. Third, they increase students' learning motivation by providing flexible, engaging, and student-centered learning experiences.

For *Madrasah Ibtidaiyah*, Virtual Laboratories offer a practical alternative for implementing science practical activities despite limitations in laboratory facilities and learning resources. Nevertheless, their successful implementation depends on adequate technological infrastructure, teachers' digital and pedagogical competencies, and thoughtful integration into inquiry-based science instruction. Virtual Laboratories should therefore be viewed as complementary learning environments that enrich, rather than replace, conventional laboratory activities.

This review also highlights the need for further empirical studies focusing specifically on the implementation of Virtual Laboratories in *Madrasah Ibtidaiyah*. Future research should examine their effectiveness across different science topics, learning models, and technological platforms to provide stronger evidence for improving science education at the elementary level.

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