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Analysis of the Effectiveness of Virtual Laboratory Use on Elementary School Students' Science Learning Outcomes

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ABSTRACT

Science learning outcomes in elementary schools remain relatively low due to limited laboratory facilities, teacher-centered instruction, and low student engagement in science learning activities. Virtual laboratories have emerged as innovative educational technologies that provide interactive and inquiry-based learning experiences to support science learning effectiveness. This study aimed to analyze the effectiveness of virtual laboratory utilization on elementary school students' science learning outcomes through a Systematic Literature Review (SLR) approach. The study reviewed scientific articles published between 2020 and 2025 obtained from reputable databases such as Scopus, Google Scholar, ERIC, and ScienceDirect. The selected studies were analyzed descriptively and thematically based on learning outcomes, science literacy, science process skills, motivation, and inquiry abilities. The findings revealed that virtual laboratories significantly improved students' science learning achievement, conceptual understanding, scientific literacy, and higher-order thinking skills. Technologies such as PhET simulations, augmented reality, and immersive virtual reality created meaningful, engaging, and student-centered learning experiences that enhanced students' motivation and inquiry participation. Furthermore, virtual laboratories provided effective solutions to limitations in laboratory facilities, safety concerns, and instructional resources in elementary schools. Therefore, virtual laboratory utilization can be considered an effective and innovative strategy for improving science learning quality and promoting active scientific exploration among elementary school students.

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1. INTRODUCTION

Science education at the elementary school level plays an important role in developing students' understanding of natural phenomena, scientific inquiry skills, problem-solving abilities, and critical thinking competencies. Through science learning, students are expected to actively explore their environment, conduct experiments, and construct knowledge based on observation and investigation. However, in many elementary schools, science learning outcomes remain relatively low and have become a continuing challenge in educational practice. Several factors contribute to this condition, including limited laboratory facilities, teacher-centered instructional approaches, low student learning motivation, and the lack of interactive learning media that can support meaningful scientific experiences. As a result, students often experience difficulties in understanding abstract scientific concepts and applying scientific knowledge in real-life contexts. In Indonesia, low science learning outcomes have been associated with students' low interest in learning, monotonous online learning practices, and the dominance of lecture-based teaching methods that reduce students' active participation in the learning process (Wiradarma et al., 2021). These conditions indicate that elementary science education still requires innovative instructional strategies capable of creating more engaging, contextual, and inquiry-based learning experiences.

The challenges in science learning become more significant when schools lack adequate laboratory facilities and experimental equipment. Science education ideally involves practical activities and direct experimentation to help students understand scientific concepts concretely. However, many elementary schools, particularly in developing educational contexts, still face limitations in providing complete laboratory facilities due to financial constraints, infrastructure problems, and limited educational resources. Esguerra et al. (2025) explained that inadequate science laboratory facilities hinder the development of students' science process skills and contribute to low science proficiency levels. Without sufficient opportunities to conduct experiments, students tend to rely solely on theoretical explanations from textbooks and teachers, resulting in superficial conceptual understanding. Furthermore, science learning that lacks practical experiences often reduces students' curiosity, exploration, and inquiry skills, which are essential components of scientific literacy. Consequently, students may struggle to relate scientific concepts to real-world phenomena and demonstrate low achievement in science learning outcomes.

In addition to limited laboratory access, differences in students' academic abilities, literacy competencies, and attitudes toward science also influence science learning outcomes at the elementary level. Slim et al. (2022) reported that students' reading literacy, mathematical abilities, and attitudes toward science significantly affect variations in science and technology learning outcomes among elementary school students. Students with low academic readiness often experience difficulties understanding scientific explanations, interpreting data, and conducting analytical reasoning during science learning activities. Moreover, negative attitudes toward science may reduce students' motivation to engage actively in learning processes. These findings indicate that science education requires instructional approaches that not only provide conceptual explanations but also foster student engagement, motivation, and active participation through meaningful learning experiences. Therefore, integrating innovative educational technologies into science instruction has become increasingly important to address these educational challenges.

One of the most promising technological innovations in science education is the use of virtual laboratories (VL). Virtual laboratories are digital learning environments that simulate scientific experiments and practical activities through interactive multimedia, animations, simulations, and virtual experimentation platforms. Virtual laboratories enable students to conduct experiments safely, flexibly, and repeatedly without depending entirely on physical laboratory facilities. In addition, VL provides visual representations of scientific concepts that may be difficult to observe directly in traditional classroom settings. The integration of virtual laboratories into science learning is considered highly relevant in modern education because it supports inquiry-based learning, enhances student engagement, and facilitates conceptual understanding through interactive experiences. Virtual laboratories also provide cost-effective alternatives for schools with limited laboratory resources while maintaining opportunities for students to develop scientific inquiry and experimentation skills.

Several studies have demonstrated the positive impact of virtual laboratory integration on students' science learning outcomes. Tsai et al. (2021) found that augmented reality (AR)-based virtual chemistry laboratories significantly improved elementary school students' learning effectiveness and motivation in chemistry learning. The study revealed that students became more enthusiastic and actively involved in scientific exploration activities when using interactive virtual laboratory environments. Similarly, Roosyanti (2022) reported that the PhET virtual laboratory effectively helped elementary school students visualize difficult science concepts and created more meaningful learning experiences. Through virtual simulations, students could observe abstract scientific processes that are difficult to demonstrate through conventional teaching methods. These findings indicate that virtual laboratories can increase students' conceptual understanding by providing visual and interactive representations of scientific phenomena.

Research focusing on elementary science education also revealed that virtual laboratories contribute positively to students' interest and engagement in learning activities. Kumala et al. (2021) developed a virtual laboratory for teaching symbiosis concepts to fourth-grade elementary students and found that the media was valid, feasible, and effective in visualizing abstract concepts while improving students' learning interest. The use of virtual simulations allowed students to observe scientific interactions dynamically, making the learning process more attractive and understandable. Furthermore, Liu et al. (2022) reported that immersive virtual reality (IVR)-based science learning significantly improved fourth-grade students' science achievement, increased learning motivation, and reduced cognitive load during learning activities. These findings suggest that virtual laboratories can create engaging and cognitively supportive learning environments that help students process scientific information more effectively.

At the junior high school level, previous studies also confirmed the effectiveness of virtual laboratories in improving science literacy and inquiry skills. Putri (2021) found that inquiry-based virtual laboratory learning in optics education produced moderate N-Gain improvements in students' science literacy. Similarly, Polihito et al. (2025) reported that the use of PhET virtual laboratories in learning about matter and its changes significantly improved students' science literacy and academic achievement. Cao et al. (2024) further explained that virtual reality technology improved elementary and junior high school students' science achievement, problem-solving skills, and self-efficacy. In addition, Esguerra et al. (2025) revealed that combining virtual laboratories with guided inquiry significantly improved junior high school students' science process skills. These studies collectively demonstrate that virtual laboratories provide opportunities for students to engage actively in scientific exploration, experimentation, and inquiry-based learning activities that support conceptual understanding and science learning achievement.

The effectiveness of virtual laboratories can be explained through constructivist learning theory, which emphasizes that knowledge is actively constructed through meaningful experiences and interactions with learning environments. Virtual laboratories provide interactive simulations that allow students to explore scientific concepts independently, manipulate variables, observe outcomes, and reflect on experimental results. Through these inquiry-oriented learning experiences, students develop deeper conceptual understanding and critical reasoning skills. Reyes et al. (2024) and Kapıcı et al. (2022) argued that virtual laboratories offer safe, flexible, cost-efficient, and visually rich experimental experiences that can equal or even surpass traditional laboratories in supporting conceptual understanding and inquiry skills development. Alhashem and Alfailakawi (2023) similarly emphasized that virtual laboratories enhance accessibility to science experimentation while reducing logistical limitations associated with physical laboratory implementation. Therefore, the integration of virtual laboratories in elementary science education is considered highly beneficial for improving learning effectiveness and supporting technology-enhanced learning environments.

Despite the growing evidence supporting virtual laboratory implementation, several research gaps remain unresolved. First, many previous studies primarily focused on measuring the effectiveness of virtual laboratories in terms of cognitive achievement and learning motivation, while other important dimensions such as science process skills, collaboration, inquiry competence, and cognitive load remain underexplored (Reyes et al., 2024; Kapıcı et al., 2022). Second, many existing studies concentrate on specific virtual laboratory platforms such as Labster or PhET,

limiting broader understanding regarding the comparative effectiveness of different types of virtual laboratory technologies in elementary science learning contexts. Third, research involving elementary school students remains relatively limited compared to studies conducted at secondary and higher education levels. Although several studies investigated virtual laboratory applications for specific science topics such as symbiosis, optics, matter, and chemistry, there is still a lack of long-term experimental studies involving broader elementary science themes and larger sample sizes (Tsai et al., 2021; Kumala et al., 2021; Putri, 2021; Polihito et al., 2025; Roosyanti, 2022).

Another important research gap concerns instructional design and theoretical foundations in virtual laboratory implementation. Kapıcı et al. (2022), Reyes et al. (2024), and Chen et al. (2025) emphasized the need for further studies examining optimal guidance levels in virtual laboratory inquiry learning, including comparisons between guided support and direct presentation approaches. The effectiveness of virtual laboratories may depend significantly on how instructional scaffolding and inquiry processes are designed during learning activities. Moreover, issues related to digital equity, internet access, teacher readiness, and implementation sustainability remain insufficiently explored. Reyes et al. (2024) and Polihito et al. (2025) noted that disparities in technological access and digital literacy among schools may affect the effectiveness and sustainability of virtual laboratory implementation. These challenges are particularly relevant in elementary school contexts where technological infrastructure and teacher competencies vary considerably.

Based on these considerations, further research is needed to analyze the effectiveness of virtual laboratory utilization on elementary school students' science learning outcomes comprehensively. This study offers novelty by focusing specifically on the effectiveness of virtual laboratory implementation in elementary science learning through a quasi-experimental approach that examines not only students' cognitive achievement but also the role of interactive digital experimentation in improving learning engagement and conceptual understanding. Unlike previous studies that primarily focused on media development or limited instructional contexts, this research emphasizes the practical effectiveness of virtual laboratories in supporting elementary science education in broader classroom settings. In addition, this study contributes to the growing discussion regarding technology-enhanced science learning by providing empirical evidence related to virtual laboratory implementation at the elementary school level, which remains relatively underexplored in previous literature.

Therefore, the purpose of this study is to analyze the effectiveness of virtual laboratory utilization on elementary school students' science learning outcomes.

2. LITERATURE REVIEW

Science Learning Outcomes in Elementary Education

Science learning outcomes in elementary education represent students' achievement in understanding scientific concepts, applying scientific knowledge, and developing inquiry-based thinking skills through learning experiences. Science education at the elementary level is designed not only to transfer knowledge but also to cultivate curiosity, critical thinking, experimentation skills, and problem-solving abilities. Effective science learning enables students to observe natural phenomena, formulate hypotheses, conduct investigations, and draw conclusions based on evidence. However, many elementary school students still demonstrate low science learning outcomes due to limited learning resources, lack of practical activities, and teacher-centered instructional approaches. Conventional science instruction often focuses on memorization and theoretical explanation rather than active experimentation and inquiry processes, causing students to experience difficulties in understanding abstract scientific concepts and applying them in real-life situations (Wiradarma et al., 2021; Slim et al., 2022).

Several studies also revealed that students' science learning achievement is influenced by multiple internal and external factors, including learning motivation, literacy skills, prior academic abilities, and attitudes toward science learning. Students with low reading literacy and weak mathematical reasoning tend to experience difficulties in understanding scientific explanations and

interpreting experimental results. Moreover, limited opportunities to engage in hands-on experiments and scientific exploration reduce students' curiosity and active participation during science learning activities. The lack of adequate science laboratory facilities in many schools further contributes to low science proficiency and weak science process skills among students. Consequently, innovative instructional approaches and technology-enhanced learning media are needed to create more engaging and meaningful science learning experiences in elementary schools (Esguerra et al., 2025; Wiradarma et al., 2021).

Virtual Laboratory in Science Education

Virtual laboratory (VL) is a digital learning environment that simulates scientific experiments and practical activities using interactive multimedia, animations, simulations, and virtual experimentation tools. Virtual laboratories are designed to provide students with opportunities to conduct experiments safely, flexibly, and repeatedly without depending entirely on physical laboratory facilities. In science education, virtual laboratories help students visualize abstract scientific concepts and processes that are difficult to observe directly in conventional classroom settings. The use of virtual laboratories has become increasingly important in modern education because technological advancements enable more interactive and immersive learning experiences that support inquiry-based and student-centered learning approaches (Kapıcı et al., 2022; Reyes et al., 2024).

The integration of virtual laboratories in science learning offers several educational advantages. Virtual laboratories allow students to explore scientific phenomena independently, manipulate variables during experiments, and receive immediate feedback regarding experimental outcomes. In addition, virtual laboratories reduce limitations associated with laboratory costs, safety risks, and equipment availability, making science experimentation more accessible to schools with limited resources. Several studies indicated that virtual laboratories can equal or even surpass traditional laboratories in improving conceptual understanding, inquiry skills, and students' engagement in science learning activities. Furthermore, virtual laboratories support flexible learning because students can access simulations repeatedly both inside and outside the classroom environment (Alhashem & Alfailakawi, 2023; Kapıcı et al., 2022).

The Effectiveness of Virtual Laboratories on Science Learning Outcomes

Previous studies have demonstrated that virtual laboratories positively influence students' science learning outcomes across various educational levels. Virtual laboratories create interactive learning experiences that improve students' conceptual understanding, academic achievement, and motivation in science learning. Tsai et al. (2021) found that augmented reality (AR)-based virtual chemistry laboratories significantly improved elementary school students' learning effectiveness and motivation. The visual and interactive features provided by AR-based virtual laboratories enabled students to understand scientific concepts more concretely and participate actively in learning activities. Similarly, Roosyanti (2022) reported that PhET virtual laboratory simulations effectively visualized difficult science concepts for elementary school students and created more meaningful learning experiences.

Research findings also revealed that virtual laboratories improve students' science literacy and inquiry competencies. Putri (2021) found that inquiry-based virtual laboratory learning in optics education significantly improved junior high school students' science literacy with moderate N-Gain scores. In addition, Polihito et al. (2025) reported that the use of PhET virtual laboratories in learning about matter and its changes significantly increased students' science literacy and academic achievement. These findings indicate that virtual laboratories not only improve cognitive learning outcomes but also support students' inquiry processes and scientific reasoning abilities. Through interactive simulations, students become more engaged in observing phenomena, conducting investigations, and drawing conclusions based on experimental evidence (Putri, 2021; Polihito et al., 2025).

Virtual Laboratory and Students' Motivation in Science Learning

Learning motivation plays an essential role in determining students' participation and achievement in science education. Students who are motivated tend to engage more actively in

inquiry activities, explore learning materials independently, and demonstrate greater persistence during problem-solving processes. Virtual laboratories contribute positively to students' motivation because they provide visually attractive, interactive, and technology-supported learning environments. The use of multimedia simulations, animations, and immersive digital environments increases students' curiosity and enthusiasm toward science learning activities. Liu et al. (2022) found that immersive virtual reality (IVR)-based science learning significantly increased fourth-grade students' science achievement and motivation while reducing cognitive load during learning activities. The study indicated that students became more interested and actively involved in scientific exploration when learning through virtual environments.

Similarly, Cao et al. (2024) reported that virtual reality-based science learning improved elementary and junior high school students' academic achievement, problem-solving abilities, and self-efficacy. The immersive and interactive nature of virtual laboratories encourages students to explore scientific concepts more independently and confidently. Kumala et al. (2021) also explained that virtual laboratory media developed for elementary science learning effectively improved students' learning interest because abstract scientific concepts could be visualized dynamically through interactive simulations. Therefore, virtual laboratories can create enjoyable and motivating science learning environments that support students' active participation and learning achievement (Cao et al., 2024; Kumala et al., 2021).

Inquiry-Based Learning and Virtual Laboratory Integration

The integration of inquiry-based learning approaches within virtual laboratory environments has been widely recognized as an effective strategy for improving students' science process skills and conceptual understanding. Inquiry-based learning emphasizes active exploration, questioning, experimentation, and evidence-based reasoning during learning activities. Virtual laboratories support inquiry-based learning by allowing students to conduct simulations, test hypotheses, manipulate variables, and analyze experimental results independently. Through these inquiry-oriented experiences, students develop scientific reasoning skills and deeper conceptual understanding because they actively participate in constructing knowledge rather than passively receiving information from teachers (Reyes et al., 2024; Kapıcı et al., 2022).

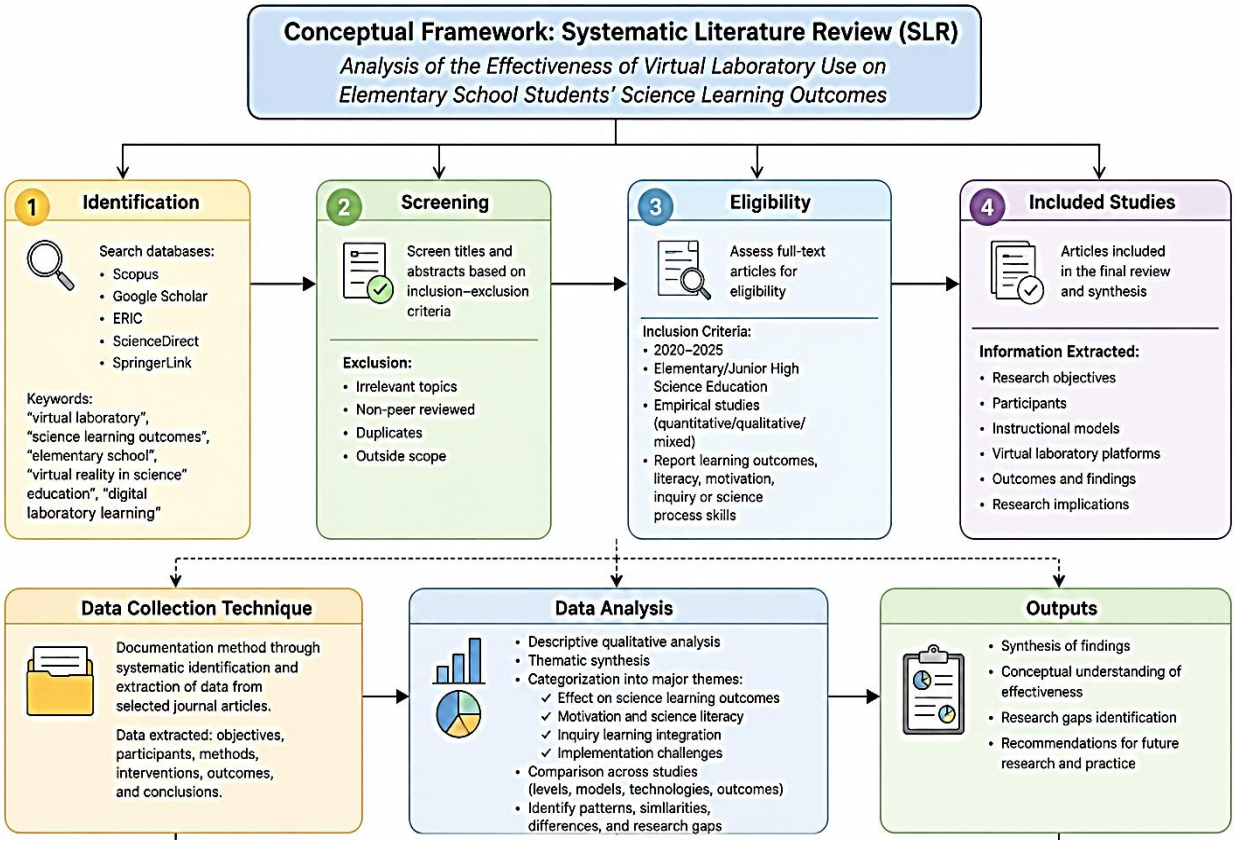
Several studies confirmed the effectiveness of combining virtual laboratories with inquiry learning models. Esguerra et al. (2025) found that virtual laboratory-assisted guided inquiry significantly improved junior high school students' basic science process skills. Similarly, Putri (2021) explained that inquiry-oriented virtual laboratory learning enhanced students' scientific literacy because students were actively involved in observing, analyzing, and interpreting scientific phenomena during experimentation activities. These findings indicate that virtual laboratories become more effective when integrated with instructional models that emphasize inquiry, exploration, and student-centered learning processes. Therefore, virtual laboratory implementation should be supported by appropriate instructional strategies and scaffolding to maximize students' learning outcomes and inquiry skill development (Esguerra et al., 2025; Putri, 2021).

3. METHOD

This study employed a Systematic Literature Review (SLR) method to analyze the effectiveness of virtual laboratory utilization on elementary school students' science learning outcomes. The SLR approach was selected because it enables researchers to identify, evaluate, and synthesize findings from previous empirical studies systematically and comprehensively. The review process followed several stages, including identification, screening, eligibility assessment, and inclusion of relevant articles. Scientific articles were collected from reputable international and national databases such as Scopus, Google Scholar, ERIC, ScienceDirect, and SpringerLink using keywords including "virtual laboratory," "science learning outcomes," "elementary school," "virtual reality in science education," and "digital laboratory learning." The inclusion criteria consisted of: (1) articles published between 2020 and 2025; (2) studies focusing on virtual laboratory implementation in elementary or junior high school science learning; (3) empirical studies employing quantitative, qualitative, or mixed-method approaches; and (4) articles

discussing learning outcomes, science literacy, motivation, inquiry skills, or science process skills. Meanwhile, articles unrelated to science learning, non-peer-reviewed publications, and duplicated studies were excluded from the review process. Data collection techniques in this study involved documentation methods through systematic identification and extraction of relevant information from selected journal articles, including research objectives, participants, instructional models, virtual laboratory platforms, findings, and research implications.

The collected data were analyzed using descriptive qualitative analysis combined with thematic synthesis techniques. The analysis process involved categorizing findings from selected studies into several major themes, including the effectiveness of virtual laboratories on science learning outcomes, the impact on students' motivation and science literacy, the integration of inquiry-based learning approaches, and challenges in virtual laboratory implementation. Furthermore, the reviewed studies were compared based on educational level, learning models, types of virtual laboratory technology, and reported learning outcomes to identify patterns, similarities, and differences among previous findings. The validity and reliability of the review were maintained by conducting article selection systematically based on predetermined inclusion criteria and reviewing relevant studies critically. The results of the analysis were then synthesized narratively to provide a comprehensive understanding of the effectiveness of virtual laboratory utilization in elementary science education, identify existing research gaps, and formulate recommendations for future studies related to technology-enhanced science learning.



4. RESULTS AND DISCUSSION

The results of the Systematic Literature Review (SLR) indicate that the utilization of virtual laboratories in science learning generally provides positive effects on elementary school students' science learning outcomes. Most reviewed studies reported improvements in conceptual understanding, science literacy, learning motivation, inquiry skills, and science process skills after the implementation of virtual laboratory-based learning. The findings also demonstrate that virtual laboratories integrated with inquiry-based or interactive learning models tend to produce more significant improvements compared to conventional science instruction.

Table 1. Summary of the Effectiveness of Virtual Laboratory Utilization on Elementary School Students' Science Learning Outcomes

No	Researcher(s)	Virtual Laboratory / Technology	Educational Level	Main Findings
1	Tsai et al. (2021)	AR Virtual Chemistry Lab	Elementary School	Significantly improved learning effectiveness and students' motivation in science learning
2	Roosyanti (2022)	PhET Virtual Laboratory	Elementary School	Effectively visualized difficult science concepts and created meaningful learning experiences
3	Kumala et al. (2021)	Virtual Laboratory for Symbiosis	Grade IV Elementary School	Valid and feasible media that improved conceptual understanding and students' interest
4	Liu et al. (2022)	Immersive Virtual Reality (IVR)	Grade IV Elementary School	Increased science achievement and motivation while reducing cognitive load
5	Putri (2021)	Inquiry-Based Virtual Laboratory	Junior High School	Improved science literacy with moderate N-Gain results
6	Polihito et al. (2025)	PhET Virtual Laboratory	Junior High School	Significantly increased science literacy and learning achievement
7	Esguerra et al. (2025)	Virtual Laboratory + Guided Inquiry	Grade VII	Improved students' science process skills significantly
8	Cao et al. (2024)	Virtual Reality-Based Science Learning	Elementary & Junior High School	Improved achievement, problem-solving skills, and self-efficacy

Based on Table 1, it can be interpreted that the implementation of virtual laboratories consistently contributes positively to students' science learning outcomes across different educational levels and science topics. The reviewed studies indicate that virtual laboratories not only improve students' cognitive achievement but also enhance motivation, inquiry abilities, science literacy, and science process skills. Interactive technologies such as augmented reality, virtual reality, and PhET simulations provide visual and experiential learning opportunities that help students understand abstract scientific concepts more effectively. Furthermore, the integration of inquiry-based approaches within virtual laboratory environments appears to strengthen students' active participation and scientific reasoning processes. These findings suggest that virtual laboratories can serve as effective technology-based learning media for supporting interactive, meaningful, and student-centered science learning in elementary education.

Discussion

The findings of this Systematic Literature Review (SLR) demonstrate that the utilization of virtual laboratories in elementary science education is generally effective in improving students' science learning outcomes, conceptual understanding, scientific literacy, and higher-order thinking skills. The reviewed studies consistently indicate that virtual laboratory integration creates more interactive, engaging, and meaningful science learning experiences compared to traditional teaching approaches. These findings support the main objective of this study, namely to analyze the effectiveness of virtual laboratory utilization on elementary school students' science learning

outcomes. The effectiveness of virtual laboratories can be observed through improvements in students' academic achievement, inquiry participation, science process skills, and motivation during science learning activities. In the context of elementary science education, virtual laboratories offer important solutions to educational challenges related to limited laboratory facilities, restricted experimental opportunities, and the dominance of teacher-centered instruction in classrooms.

One of the major findings of this review is that virtual laboratories significantly improve students' science learning achievement and conceptual understanding. Many reviewed studies reported that students who learned through virtual laboratory-assisted instruction achieved higher posttest scores and learning gains than students who experienced conventional learning methods. Roosyanti (2022) explained that the use of PhET virtual laboratories in elementary science learning effectively helped students visualize difficult scientific concepts and enabled them to discover concepts independently through interactive simulations. This finding indicates that virtual laboratories support meaningful learning because students become actively involved in scientific exploration processes rather than passively receiving explanations from teachers. Through interactive visualization, students can observe scientific phenomena dynamically, manipulate experimental variables, and understand abstract concepts more concretely. These learning experiences are particularly important in elementary science education because young learners often experience difficulties understanding abstract scientific processes through verbal explanations alone.

The positive impact of virtual laboratories on learning outcomes is also supported by studies involving augmented reality (AR) and immersive virtual technologies. Nadiyyah et al. (2025) found that AR-based virtual chemistry laboratories significantly improved elementary school students' science learning outcomes and motivation compared to control groups. Similarly, Liu et al. (2022) reported that immersive virtual reality (IVR)-based science learning increased elementary students' academic achievement and learning motivation while reducing cognitive load during science instruction. These findings suggest that immersive and visually rich virtual learning environments can improve students' understanding by providing experiential learning opportunities that resemble real scientific exploration. In virtual environments, students are able to interact directly with simulated scientific objects and processes, which facilitates deeper conceptual understanding and long-term memory retention. Consequently, virtual laboratories become effective tools for helping students understand scientific concepts that are difficult, abstract, or impossible to observe directly in traditional classroom settings.

The effectiveness of virtual laboratories is also reflected in studies measuring students' science literacy and inquiry abilities. Polihito et al. (2025) reported that the use of PhET virtual laboratories in junior high school science learning significantly improved students' science literacy and academic achievement, with posttest scores ranging from 88 to 92, which were substantially higher than pretest results. Although the study focused on junior high school students, the findings remain relevant for elementary science education because science literacy development begins during the primary education stage. Virtual laboratories support science literacy development by encouraging students to observe, analyze, interpret, and communicate scientific information through inquiry-oriented learning activities. Through simulations and experimental tasks, students become more actively involved in scientific reasoning processes and evidence-based learning experiences. These findings align with constructivist learning theory, which emphasizes that meaningful knowledge is constructed through active interaction with learning environments and experiential inquiry processes.

Furthermore, virtual laboratories contribute positively to the development of science process skills and higher-order thinking competencies among students. Science process skills such as observing, classifying, communicating, hypothesizing, and interpreting data are essential components of science education because they enable students to think scientifically and solve problems systematically. Several reviewed studies demonstrated that virtual laboratory-assisted learning improves these skills significantly. Nadiyyah et al. (2025), Tsai et al. (2021), and Syar et al. (2023) explained that virtual laboratories provide opportunities for students to conduct independent experimentation and inquiry activities that strengthen science process skills. Through

virtual simulations, students can repeatedly perform experiments, observe scientific changes carefully, and evaluate experimental results without facing the limitations often found in conventional laboratory environments. Consequently, students become more confident and competent in applying scientific methods during learning activities.

The positive contribution of virtual laboratories to higher-order thinking skills is also supported by several systematic reviews and meta-analyses. Meronda et al. (2025), Fitriah and Zawanis (2024), and Byukusenge et al. (2022) concluded that virtual laboratory implementation contributes positively to students' analytical thinking, critical thinking, and scientific reasoning abilities. These findings indicate that virtual laboratories not only improve factual knowledge but also enhance students' cognitive processing and inquiry capacities. Virtual laboratory environments encourage students to analyze data, evaluate experimental outcomes, and formulate conclusions independently. In contrast to traditional science instruction that often emphasizes memorization and procedural tasks, virtual laboratories provide opportunities for students to engage in active problem-solving and inquiry-based learning activities. Therefore, virtual laboratories are considered highly relevant for supporting twenty-first century educational goals that emphasize critical thinking, creativity, collaboration, and digital literacy skills.

Another important finding of this review concerns the role of virtual laboratories in addressing the limitations of physical laboratory facilities in elementary schools. Many schools experience challenges related to inadequate science equipment, limited laboratory access, financial constraints, and safety considerations during practical science activities. Virtual laboratories provide practical solutions to these problems because they allow students to conduct simulations and experiments digitally without requiring expensive or hazardous laboratory materials. Reyes et al. (2024), Kapıcı et al. (2022), and Alhashem and Alfailakawi (2023) emphasized that virtual laboratories are flexible, cost-effective, visually rich, and safe alternatives to conventional laboratories. In elementary school contexts, where students' safety and equipment limitations are major concerns, virtual laboratories become highly beneficial instructional tools. Students can safely conduct experiments involving chemicals, energy transformations, or scientific reactions that may be difficult or risky to implement directly in elementary classrooms.

The reviewed studies also indicate that virtual laboratories increase students' motivation and interest in science learning. Motivation is a crucial factor influencing students' academic achievement because motivated students are more likely to participate actively in learning activities, explore scientific concepts independently, and persist during problem-solving processes. Virtual laboratories create visually attractive and interactive learning environments that make science learning more enjoyable and engaging. Liu et al. (2022) found that IVR-based science learning reduced students' cognitive load while simultaneously increasing motivation and achievement. Similarly, Roosyanti (2022) reported that PhET-based virtual learning made science instruction more meaningful and attractive to elementary school students. The use of simulations, animations, and interactive digital tools stimulates students' curiosity and encourages them to explore scientific concepts enthusiastically. As a result, students become more actively involved in learning activities and demonstrate stronger interest in science education.

The effectiveness of virtual laboratories can also be understood through inquiry-based learning perspectives. Inquiry learning emphasizes exploration, questioning, experimentation, and evidence-based reasoning during the learning process. Virtual laboratories naturally support inquiry-oriented instruction because students are encouraged to manipulate variables, observe outcomes, and investigate scientific phenomena independently. Through inquiry-based virtual laboratory activities, students become active participants in constructing scientific understanding rather than passive recipients of information. Tsai et al. (2021) explained that virtual chemistry laboratories encouraged elementary students to explore concepts actively and engage more deeply in inquiry processes. Similarly, Syar et al. (2023) reported that virtual laboratory implementation improved students' experimental independence and scientific investigation skills. These findings suggest that combining inquiry learning models with virtual laboratories creates highly effective science learning environments that support both conceptual understanding and inquiry competence. Despite the positive findings regarding virtual laboratory implementation, several challenges and limitations remain important considerations. One significant challenge concerns unequal access to

technological infrastructure, internet connectivity, and digital devices among schools and students. Virtual laboratory implementation depends heavily on stable technological resources, which may not always be available in all educational contexts. Reyes et al. (2024) and Polihito et al. (2025) noted that disparities in digital access and technological readiness may affect the sustainability and effectiveness of virtual laboratory utilization. In addition, teachers' digital literacy and instructional competencies also influence the success of technology-enhanced science learning. Teachers need adequate training and pedagogical support to integrate virtual laboratories effectively into inquiry-based learning environments. Without proper instructional design and guidance, virtual laboratories may become merely technological tools without significantly improving students' learning experiences.

Another important issue concerns the balance between virtual and real laboratory experiences in science education. Although virtual laboratories provide many advantages, they may not fully replace hands-on experimentation experiences that involve direct manipulation of physical objects and materials. Kapıcı et al. (2022) explained that future studies should explore the optimal sequence and combination between virtual and traditional laboratory activities to maximize science learning effectiveness. In elementary education, direct sensory experiences and collaborative experimentation remain important for developing practical scientific skills and social interaction competencies. Therefore, virtual laboratories should ideally complement rather than entirely replace traditional practical science activities. Combining virtual and physical laboratories may create more comprehensive science learning experiences that integrate conceptual understanding, inquiry skills, and practical experimentation abilities.

Overall, the findings of this Systematic Literature Review indicate that virtual laboratories are effective instructional tools for improving elementary school students' science learning outcomes. Virtual laboratory implementation contributes positively to conceptual understanding, science literacy, science process skills, analytical thinking, motivation, and inquiry competence. The integration of interactive simulations, immersive technologies, and inquiry-based learning approaches creates meaningful and student-centered science learning environments that support active participation and scientific exploration. Furthermore, virtual laboratories offer practical solutions to limitations related to laboratory facilities, safety concerns, and instructional resources in elementary schools. However, successful implementation requires adequate technological infrastructure, teacher readiness, and appropriate instructional design to maximize learning effectiveness. Therefore, virtual laboratories can be considered promising educational technologies for supporting innovative, interactive, and inquiry-oriented science learning in elementary education contexts.

5. CONCLUSION

In conclusion, the findings of this study demonstrate that the utilization of virtual laboratories is effective in improving elementary school students' science learning outcomes. The reviewed studies consistently showed that virtual laboratory-based learning enhances students' conceptual understanding, science literacy, science process skills, critical thinking abilities, and learning motivation compared to conventional instructional methods. Interactive technologies such as PhET simulations, augmented reality, immersive virtual reality, and inquiry-based virtual laboratories provide meaningful, safe, and engaging learning experiences that help students visualize abstract scientific concepts and participate actively in scientific exploration activities. Furthermore, virtual laboratories offer practical solutions to limitations related to laboratory facilities, safety concerns, and instructional resources in elementary schools while supporting student-centered and inquiry-oriented learning environments. Therefore, virtual laboratories can be considered an effective and innovative educational technology for enhancing science learning quality and promoting active scientific learning experiences among elementary school students.

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