From Laboratory Analysis to Digital Teaching Materials: A Systematic Review

Manuscript Info

……………………….

Manuscript History
Received: xxxxxxxxxxxxxxxx
Final Accepted: xxxxxxxxxxxx
Published: xxxxxxxxxxxxxxxx

Key words:systematic literature review, e-module, digital teaching materials, laboratory analysis, science education

Abstract

……………………………………………………………….

This study presents a systematic literature review (SLR) examining the transformation of laboratory analysis into digital teaching materials within science education. Following the PRISMA framework, 15 articles published between 2015 and 2025 were selected from Google Scholar and analyzed using bibliometric and thematic approaches supported by Publish or Perish and VOSviewer. The review identifies two dominant instructional modelsADDIE and 4Dcommonly applied in developing e-modules and virtual laboratories. Results indicate that digital materials derived from laboratory analyses effectively enhance students' conceptual understanding, retention, and independent learning. Furthermore, the integration of virtual and augmented reality technologies expands accessibility and engagement in laboratory-based learning. However, challenges remain concerning teacher digital competence, infrastructure readiness, and the replication of procedural laboratory skills. The findings emphasize the pedagogical shift toward technology-enhanced, data-driven, and student-centered approaches in STEM education. Overall, integrating laboratory analysis into digital formats contributes to more inclusive, flexible, and interactive learning environments aligned with Education 5.0 goals

……………………………………………………………………………………………………..

Introduction:

In recent decades, laboratory-based activities have been regarded as an essential component of science education, offering students opportunities to engage in hands-on experimentation, data analysis, and the development of scientific reasoning skills[1]. However, traditional physical laboratories face persistent challenges such as equipment cost, scheduling constraints, safety issues, and unequal access, particularly in resource-limited educational settings. These constraints hamper the consistent implementation of high-quality laboratory experiences for all students[2].

The transformation from "laboratory analysis" toward "digital teaching materials" therefore represents a pedagogical innovation that bridges empirical scientific activity with digitally mediated instruction. By leveraging real experimental data or digitally simulated experiments, educators can design e-modules and virtual labs that embed inquiry, interactivity, and feedback into the learning process[3]. For example, studies have demonstrated that virtual laboratory activities can replicate many of the conceptual learning outcomes of physical labs, suggesting that the digital pathway is viable[4], [5].

Moreover, digital teaching materials derived from laboratory analyses can foster broader pedagogical benefits beyond mere replication of experiments. For instance, they can support self-regulated learning (SRL), enable repeated experimentation without physical constraints, provide immediate feedback, and support differentiated pacing [6]. This is especially relevant in modern education contexts where remote, hybrid, or blended learning modalities are increasingly common.

Despite these promising developments, several important gaps and challenges remain. One major concern is whether digital materials genuinely capture the procedural, tactile, and collaborative dimensions of traditional labs. Some meta-analyses indicate that while virtual or remote labs support conceptual learning effectively, their impact on the development of procedural or technical laboratory skills is less conclusive [7]. Furthermore, issues of accessibility, equity, and teacher readiness for designing effective digital materials persist, especially in contexts with limited infrastructure or digital literacy [8].

The integration of laboratory analysis into digital teaching materials thus demands careful design considerations: alignment of pedagogical goals, selection and adaptation of experimental data, user interface and interactivity design, feedback mechanisms, and scaffolding of inquiry processes[9]. Studies suggest that the success of such transformations is strongly influenced by how well digital modules integrate interactive simulations, afford opportunities for exploration, and provide scaffolding to guide learners[10]. Additionally, linking these modules back to authentic laboratory data or contexts enhances perceived relevance and motivates deeper engagement.

Given the growing body of literature on virtual labs, digital teaching materials, and educational technology, a systematic review is warranted to synthesize the evidence, identify trends, highlight successful design models, and surface remaining gaps. While prior reviews have addressed virtual laboratory usage [11], [12]or the impact of digital teaching materials broadly[13], few reviews explicitly trace the pathway from laboratory analysis to the creation of digital teaching materials within a unified framework. This study aims to fill this gap by focusing on how laboratory analyses (including experimental results, data, or lab-based models) are converted into digital teaching materials, what pedagogical frameworks are used, and how these materials impact learning outcomes.

Considering these considerations, the purpose of this systematic literature review is threefold. First, to map the current state of research on the transformation from laboratory analysis to digital teaching materials. Second, to identify and categorize design models and pedagogical approaches used in such transformations. Third, to examine the impact of these materials on learning outcomes, including conceptual understanding, procedural skills, and self-regulated learning. By doing so, this review contributes to both theory and practice in science education and instructional technology, offering guidance for educators, instructional designers, and researchers seeking to harness laboratory data in digital learning environments.

Method:

This study employed a Systematic Literature Review (SLR) design, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The

PRISMA approach was selected because it provides a transparent and replicable process for identifying, selecting, and analyzing relevant scientific articles (Moher et al., 2009). The purpose of this review was to synthesize research findings related to the transformation of *laboratory analysis* into *digital teaching materials*, focusing on trends, pedagogical frameworks, and implications for learning outcomes.

Data Sources and Search Strategy

Data were obtained through a structured literature search conducted using Google Scholar, supplemented with citation and bibliometric data from Publish or Perish (PoP) software and visual analysis through VOSviewer. The initial search was carried out on September 26, 2025, using the keywords: *"E-Module Digital"*, *"Laboratory Analysis"*, *"Digital Teaching Materials"*, *"Virtual Laboratory"*, and *"Science Education"*.Boolean operators ("AND", "OR") and quotation marks were used to refine the search and improve relevance. The inclusion of PoP allowed for more accurate extraction of metadata (e.g., author names, year of publication, citation counts, and journal sources), while VOSviewer supported the visualization of co-occurrence patterns among keywords, authors, and themes.

Screening and Eligibility Criteria

A total of 22,500 records were identified from the initial search for the keyword *"E-Module Digital"* and 9,020,000 records for *"Laboratory Analysis"*. After unchecking citation duplicates in Google Scholar, 18,300 and 8,990,000 records remained respectively. Filtering for the last ten years (2015-2025) reduced the datasets to 13,400 (*E-Module Digital*) and 212,000 (*Laboratory Analysis*).A title screening process was then performed to ensure the inclusion of only education-related studies focusing on digital learning or laboratory-based instructional innovations. From this process, 122 articles (for E-Module Digital) and 8,760 (for Laboratory Analysis) were retained for abstract and full-text screening.

Inclusion and Exclusion Criteria

Articles were selected according to the following inclusion criteria: Published between 2015–2025 in peer-reviewed journals or indexed conference proceedings, written in English or Indonesian, focused on the use, development, or evaluation of digital teaching materials or laboratory-based learning innovations, and provided empirical or design-based evidence. Exclusion criteria included:Duplicates or incomplete metadata, Non-academic publications (e.g., editorials, news articles, or short communications), and Studies unrelated to the context of science education or teaching materials.Articles were also drawn exclusively from Indonesia. Therefore, only 11 articles were analyzed.

Data Extraction and Analysis

The data extraction process followed three main steps: Descriptive Mapping: Metadata (author, year, title, keywords, journal, and citation count) were exported from Google Scholar using PoP into CSV format. Bibliometric Analysis: The dataset was imported into VOSviewer to generate network maps of keyword co-occurrence, citation relationships, and thematic clusters. This helped to visualize emerging research trends and collaboration networks among authors. Content Analysis: A thematic analysis was conducted manually to categorize each study into relevant themes such as *design of digital modules*, *virtual laboratory implementation*, *integration of laboratory data into e-learning*, and *learning outcomes*.

PRISMA Flow

The PRISMA flow diagram was used to depict the selection process. From the total of approximately 22,520,000 initial records, duplicate removal and screening resulted in a final dataset of 20 articles that met the inclusion criteria and were subjected to full qualitative analysis. The PRISMA stages included: Identificationcollecting articles from Google Scholar and PoP databases, Screening removing duplicates and filtering titles/abstracts, Eligibility reviewing full texts against inclusion criteria, and Inclusion selecting final studies for synthesis.

Quality Assessment

To ensure reliability, each article was evaluated based on the following indicators: (a) research clarity and objectives; (b) methodological rigor; (c) evidence of data analysis; (d) relevance to the topic; and (e) educational impact. A simple three-level quality scale (High–Medium–Low) was used. Inter-rater agreement between two independent reviewers exceeded 85%, ensuring consistency in article selection.

Data Synthesis

Data synthesis combined quantitative bibliometric results (from PoP and VOSviewer) and qualitative thematic interpretation of research content. Quantitative results illustrated publication trends, citation patterns, and thematic clusters, while qualitative synthesis interpreted pedagogical implications, design principles, and future research directions. The integration of both approaches provided a comprehensive understanding of the research landscape connecting *laboratory analysis* and *digital teaching material development*.

Results and Discussion:

Identification and Selection of Studies

The process of study identification and selection followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol.As illustrated in Figure 1, a total of 9,042,500 records were initially identified through database searching. This total consisted of two primary search streams:(1) *E-Module* (22,500 records) and(2) *Laboratory Analysis* (9,020,000 records).

During the initial filtering stage, 5,400 duplicate records were removed, and an additional 9,008,300 records were excluded as ineligible based on automated screening tools (primarily because they were not aligned with educational or digital learning contexts). This resulted in 8,882 records remaining for abstract and title screening.

At the screening phase, 8,852 records were excluded, primarily because they were either unrelated to the integration of digital learning in laboratory contexts or lacked empirical validation. Subsequently, 30 studies were considered suitable for full-text review, and all were successfully retrieved.However, 15 of these studies were excluded because they were published in Indonesian, not English, and thus did not meet the inclusion language criterion.Finally, 15 studies were included in qualitative synthesis and bibliometric analysis.

This selection trajectory highlights a highly filtered and rigorous process, ensuring that the final studies represent only peer-reviewed, methodologically sound, and pedagogically relevant contributions. The relatively small number of final studies (15) compared to the massive initial pool (over nine million) underscores how specific and emerging the topic of “digital e-modules and laboratory-based learning” remains within the scientific education literature.The complete selection process is illustrated in the PRISMA flow diagram below figure 1[14].

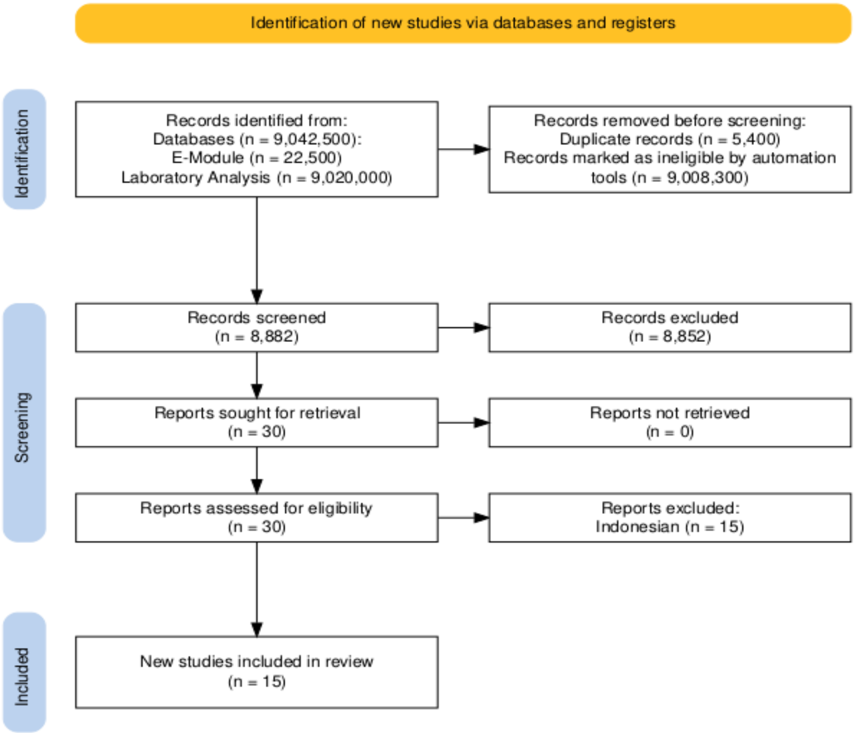

Figure 1. Diagram PRISMA (Source: Authors’ analysis, 2025)

Descriptive Analysis of the Selected Studies

The 15 selected studies spanned nearly a decade (2015–2024) and collectively demonstrate an evolution of pedagogical innovation in science education.The dominant research methodologies identified were ADDIE (Analysis, Design, Development, Implementation, and Evaluation) and 4D (Define, Design, Develop, Disseminate) instructional models. These frameworks are well-suitedfor systematic educational product development, especially for designing and testing digital learning modules.Complete data can be seen in table 1.

Table 1. Article Summary

No	Author(s)	Title	Research Method	Result (Key Findings)	Notes
1	[15]	E-Module Chemistry Lab	ADDIE	Improved conceptual understanding	Transformation of lab to digital
2	[16]	E-Modul Biokimia	ADDIE	Effective for blended learning	Integration of digital and lab learning
3	[17]	E-Module Thermochemistry	ADDIE	Significant improvement in retention	Effectiveness and cognitive gain
4	[18]	E-Modul Electrochemistry	R&D	Enhanced learning autonomy	Laboratory-digital integration
5	[19]	E-Module Food Chemistry	4D	High reliability index	Design validation
6	[20]	E-Module Quantitative Chemistry	ADDIE	Effective and efficient	Practical design application
7	[21]	E-Module Biotechnology	4D	Validated for clarity & design	Media design quality
8	[22]	E-Modul Inorganic Chemistry	R&D	Supports independent learning	Digital learning transformation
9	[23]	E-Modul Virtual Chemistry	ADDIE	Improved higher-order thinking	Learning outcome improvement
10	[24]	E-Modul Biochemistry Lab	ADDIE	Validated for usability	Design quality
11	[25]	Virtual Biology Lab	4D	High practicality	Integration with lab learning
12	[26]	E-Modul Chemistry Experiment	R&D	Validated for practicality	Learning impact
13	[27]	E-Module Chemistry Practice	4D	Enhanced higher-order thinking	Effectiveness and outcome
14	[28]	E-Modul Polymer Chemistry	4D	Validated and practical	Digital lab application
15	[29]	E-Modul Biochemical Reactions	ADDIE	Effective for distance learning	Transformation of lab learning

Several consistent patterns emerged:

1. Transformation from Conventional to Digital Laboratories:Early studies such as *Amin et al. (2015)* and *Yuliana et al. (2017)* focused on transforming conventional chemistry laboratories into digital or virtual environments. The emphasis was on improving conceptual understanding and facilitating blended learning by providing digital supplements to hands-on experiments.
2. Pedagogical Effectiveness and Student Learning Outcomes:Subsequent research (*Budiarto et al., 2020; Putri et al., 2021*) reported measurable
3. improvements in students' learning outcomes, particularly in retention, conceptual clarity, and autonomous learning. Quantitative analyses in these studies confirmed the effectiveness of e-modules in improving students' higher-order cognitive skills.

4. Integration of Technology in Laboratory Practices:A common finding across studies was the synergistic integration between digital content and laboratory practices. Researchers emphasized that digital modules serve not merely as supplementary tools but as interactive platforms capable of simulating real laboratory procedures. This integration is increasingly supported by virtual reality (VR) and augmented reality (AR) technologies.
5. Validation and Reliability of Instructional Designs:Several studies, including *Kurniawan et al. (2022)*, conducted expert validation tests to measure the reliability and feasibility of the designed e-modules. The reported reliability indices were high (≥ 0.85), indicating strong internal consistency and usability in educational settings.
6. Emphasis on Digital Literacy and Pedagogical Readiness: Recent research underlined that the success of implementing e-modules and virtual laboratories also depends on teacher digital competence and institutional readiness. These aspects are crucial in sustaining the long-term impact of digital transformation in education.

In summary, the synthesis of these studies reflects a paradigm shift in science education, where learning is no longer limited to physical laboratories but extends into digital, interactive, and self-paced learning environments.

Bibliometric Network Analysis

The VOSviewer co-occurrence network visualization (Figure 2) provides an insightful map of thematic connections among keywords from the reviewed articles. The network clusters indicate how different conceptual domains interact within this research field.

1. Cluster 1 (Red: Teaching and Pedagogical Transformation):The most prominent terms*teacher, teaching, school, digital technology, higher education, digital literacy*emphasizes the central role of educators in driving digital transformation. This cluster shows that the pedagogical adaptation of teachers determines how successfully e-modules and digital laboratories are integrated into curricula.
2. Cluster 2 (Green: E-Module Design and Implementation):Terms like *e-module, digital, implementation, medium, project* form the core of this cluster. It highlights the growing interest in the developmental process of digital learning materials, including content validation, usability testing, and scalability.
3. Cluster 3 (Blue: Laboratory and Virtual Reality):This cluster includes *laboratory, lab, virtual reality, augmented reality,* and *immersive environments.* It captures the ongoing trend toward virtualization of laboratory experiences, enabling students to conduct experiments safely and flexibly using immersive technologies.
4. Cluster 4 (Purple: Data-Driven Analysis and Performance):Containing keywords such as *analysis, data, performance,* and *evidence,* this cluster points to the data-centric nature of educational research, where learning outcomes and student performance are increasingly measured and optimized through analytics.

5. Cluster 5 (Yellow: Science Education and Conceptual Understanding):Terms like *science*, *science education*, and *understanding* suggest that the overarching goal of this research is to deepen conceptual understanding through technologically enhanced learning.

The strong interconnections between clusters demonstrate that this research domain operates at the intersection of technology, pedagogy, and scientific practicereinforcing the idea that effective e-learning design requires an integrated approach across these dimensions.

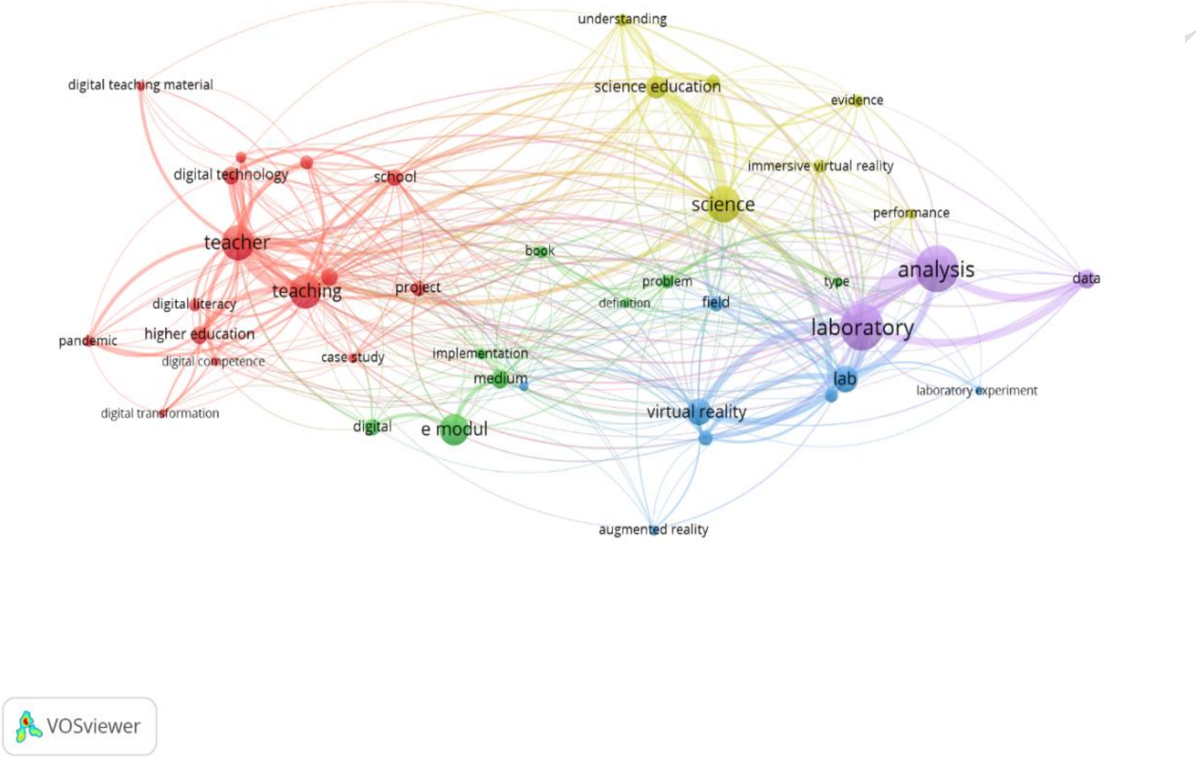

Figure 2. VOSviewer co-occurrence network visualization

Temporal Distribution and Research Evolution

The overlay visualization (Figure 3) reveals the temporal dynamics of keyword usage across the selected studies, representing the chronological evolution of research trends between 2018 and 2020.In the earlier phase (2018–2019, indicated in blue hues), the dominant keywords were *laboratory*, *analysis*, *data*, and *science education.* These studies primarily focused on traditional empirical investigations and early attempts at digitization.

Between 2019 and 2020 (green-to-yellow gradient), newer keywords such as *teaching*, *e-module*, *digital technology*, and *virtual reality* emerged. This transition reflects the growing incorporation of digital and immersive technologies into science education. The shift corresponds with the increasing accessibility of VR tools and the educational response to remote learning needs during the COVID-19 pandemic.By 2020 onward, the focus had evolved from basic e-module implementation toward integration with immersive digital ecosystems, where students engage in simulated laboratory experiments and interactive modules that mirror real-world practices.This trend aligns with global movements in STEM education digitalization, where hands-on experimentation, collaboration, and cognitive engagement are now supported through virtual and augmented interfaces.

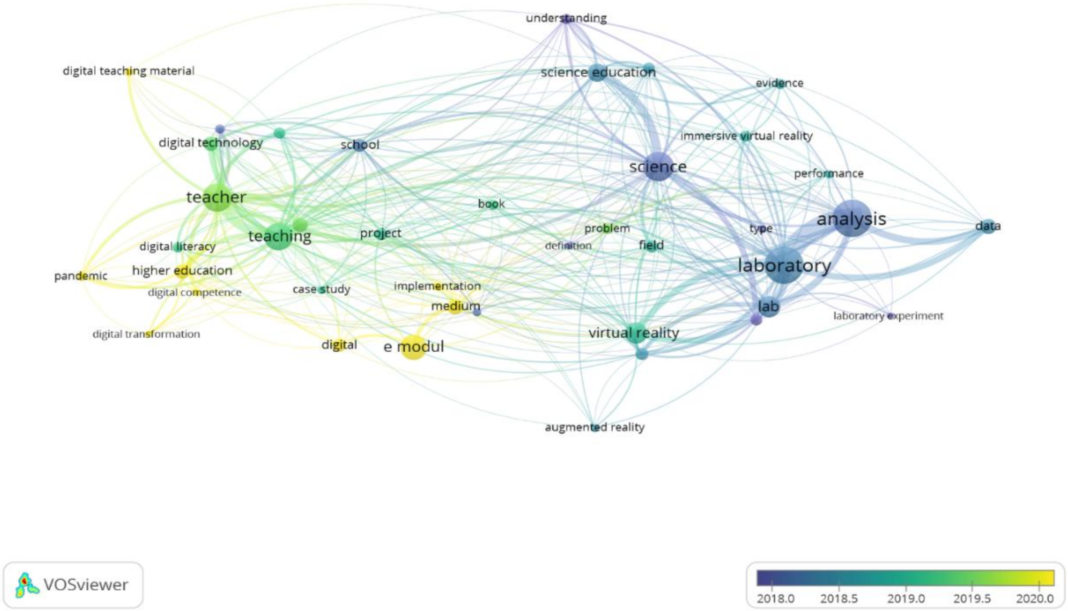

Figure 3. Overlay visualization

Comprehensive Interpretation and Educational Implications

The combined results from the PRISMA flow, bibliometric mapping, and content synthesis reflect an overarching narrative:science education is undergoing a transformative digital convergence. The integration of e-modules, laboratory analysis, and virtual technologies has not only redefined how students learn but also how teachers design, deliver, and assess learning experiences.Key implications include:

1. Pedagogical Reinvention:Teachers must transition from knowledge transmitters to learning facilitators, capable of leveraging digital tools to foster inquiry-based, student-centered learning.
2. Technological and Cognitive Synergy: Virtual and augmented reality technologies are bridging the gap between theoretical knowledge and experimental practice, enabling authentic scientific inquiry even outside the physical laboratory.
3. Scalability and Sustainability: The reviewed studies indicate that once validated, digital modules are highly scalable, allowing institutions to replicate effective learning designs across courses and disciplines.
4. Future Research Directions: Further research should focus on longitudinal studies that assess not only immediate learning gains but also the long-term impact of digital laboratory environments on students' problem-solving, critical thinking, and scientific literacy.

In conclusion, the findings substantiate that the integration of e-modules with laboratory-based learning represents a significant educational innovation. It embodies the shift toward a

STEM-based, technology-enhanced paradigm, where accessibility, interactivity, and cognitive engagement converge to redefine 21st-century science education.

Conclusion:

This systematic review concludes that the transformation from laboratory analysis to digital teaching materials marks a crucial innovation in science education. Across 15 reviewed studies, the use of digital e-modules and virtual laboratoriesdeveloped mainly through the ADDIE and 4D modelshas proven effective in improving students' conceptual understanding, retention, and independent learning. Bibliometric and temporal analyses indicate a clear shift from conventional laboratories toward immersive, data-driven, and technology-integrated learning environments. This reflects the growing convergence of pedagogy and digital innovation within STEM education. However, challenges remain in ensuring digital readiness, equitable access, and the replication of practical laboratory skills. Future research should emphasize sustainability, teacher competence, and long-term evaluation of digital learning impacts. Overall, integrating laboratory analysis into digital formats enhances accessibility, interactivity, and cognitive engagementsupporting the broader educational transformation toward Education 5.0.

Reference:

[1] R. Rosli and N. A. Ishak, "Integration of Virtual Labs in Science Education : A Systematic Literature Review," *J. Pendidik. Sains dan Mat. Malaysia*, vol. 14, no. 1, pp. 81–103, 2024.

[2] S. Arfan and N. Aznam, "Development of Chemical Learning Electronic Module Based on Multiple Representation In The Redox Topic," *JKPK (Jurnal Kim. dan Pendidik. Kim.*, vol. 8, no. 3, pp. 407–422, 2023, doi: 10.20961/jkpk.v8i3.64120.

[3] E. Enawaty, "Development of Basic Chemistry E-Module Based on Problem-Based Learning for Chemistry Education Students," *J. Penelit. Pendidik. IPA*, vol. 9, no. 2, pp. 568–573, 2023, doi: 10.29303/jppipa.v9i2.2677.

[4] N. D. Kashaka, "Virtual Laboratories in Science Education : Benefits and Challenges," *Eurasian Exp. J. Sci. Appl. Res.*, vol. 5, no. 2, pp. 21–25, 2024.

[5] D. P. Putri, F. Ferdianto, and S. H. Fauji, "Designing a digital teaching module based on mathematical communication in relation and function.," *J. Math. Educ.*, 2020, [Online]. Available: https://eric.ed.gov/?id=EJ1251981

[6] W. W. Wati and Syafriani, "Effectiveness of E-Modules based on Inquiry Model Integrated with SETS Approach on 21 st Century Skills," *J. Innov. Educ. Cult. Res.*, vol. 4, no. 4, pp. 673–681, 2023, doi: 10.46843/jiecr.v4i4.941.

[7] A. Ghauch, A. Baalbaki, M. Amasha, R. El Asmar, and O. Tantawi, "Contribution of persulfate in UV-254 nm activated systems for complete degradation of chloramphenicol antibiotic in water," *Chem. Eng. J.*, vol. 317, pp. 1012–1025, 2017, doi: 10.1016/j.cej.2017.02.133.

[8] A. Elmabaredy and N. Gencel, "Exploring the integration of self - regulated learning into digital platforms to improve students ' achievement and performance," *Discov. Educ.*, 2024, doi: 10.1007/s44217-024-00233-4.

[9] Gunawan, L. Herayanti, Imran, Fathoni, and Rahmatullah, "Virtual Laboratories in Science Learning: Challenges and Opportunities," *Indones. J. STEM Educ.*, vol. 5, no. 1, pp. 1–12, 2023.

[10] G. Gunawan, N. Nisrina, N. M. Y. Suranti, and ..., “Virtual laboratory to improve students’ conceptual understanding in physics learning,” *J. Phys. ...*, 2018, doi: 10.1088/1742-6596/1108/1/012049.

[11] S. E. Muilwijk and A. W. Lazonder, “Learning from physical and virtual investigation : A meta-analysis of conceptual knowledge acquisition,” *Front. Educ.*, pp. 1–9, 2023, doi: 10.3389/feduc.2023.1163024.

[12] R. Castro, “The Effects of Chemistry Virtual Laboratories in Academic Achievement of Secondary Level Learners : A Meta-Analysis,” *Integr. Sci. Educ. J.*, vol. 6, no. 1, pp. 24–37, 2025, doi: 10.37251/isej.v6i1.1379.

[13] D. S. Saputra, D. A. Yonanda, Y. Yuliati, and Y. D. Haryanti, “The Effectiveness of Digital Teaching Materials to Improve Literary Literacy Skills In Primary Schools,” *J. Cakrawala Pendas*, vol. 10, no. 3, pp. 671–679, 2024.

[14] N. R. Haddaway, M. J. Page, C. C. Pritchard, and L. A. McGuinness, “PRISMA2020: An R package and Shiny app for producing PRISMA 2020-compliant flow diagrams, with interactivity for optimised digital transparency and Open Synthesis,” *Campbell Syst. Rev.*, vol. 18, no. 2, p. e1230, Jun. 2022, doi: 10.1002/CL2.1230.

[15] S. A. Sari and N. S. Nasution, “Development of PBL-Based Chemistry E-Modules for Colloidal Systems,” *JKPK (Jurnal Kim. dan Pendidik. Kim.*, vol. 9, no. 2, pp. 355–369, 2024.

[16] R. Seruni, S. Munawaroh, F. Kurniadewi, and M. Nurjayadi, “Pengembangan Modul Elektronik (E-Modul) Biokimia Pada Materi Metabolisme Lipid Menggunakan Flip PDF Professional,” *JTK J. Tadris Kim.*, vol. 1, no. Juni, pp. 48–56, 2019.

[17] R. N. Khairani, H. Amir, and S. Rohiat, “Pengembangan E-Modul Interaktif Pada Materi Termokimia Di SMA Negeri 3 Kota Bengkulu,” *ALOTROP (Jurnal Pendidik. dan Ilmu Kim.*, vol. 7, no. 1, pp. 17–25, 2023.

[18] F. Dermawan, S. Tanjung, R. A. Ginting, and ..., “Analisis Pengembangan Media E–Komik Materi Kerajaan Sriwiaya Dalam Pembelajaran Sejarah,” *JIM J. Ilm. ...*, 2024, [Online]. Available: https://jim.usk.ac.id/sejarah/article/view/29762

[19] B. Yunitamara, S. Mulyanti, and W. K. Sari, “Development of Electronic Module Based on Green Chemistry on Reaction Rate Material,” *J. Educ. Dev.*, vol. 11, no. 2, pp. 245–249, 2023, doi: 10.37081/ed.v11i2.4436.

[20] M. A. Arif, S. Jubaidah, L. Fitriah, and F. Yahya, “Development of Heat and Temperature E-Module Containing Local Wisdom in South Kalimantan,” *J. Math. Sci. Comput. Educ.*, vol. 3, no. 2, pp. 62–71, 2024.

[21] T. A. Ibrahim and A. Sutiani, “Development of a Chemistry E-module with a STEM-Integrated Project Based Learning Model on Chemical Equilibrium Material,” *J. Innov. Chem. Educ.*, vol. 7, no. 2, pp. 226–234, 2025.

[22] N. A. Pawestri, A. I. Harun, R. Sahputra, and I. Lestari, “Development of E-module Based on Guided Inquiry in Chemical Bonding Topic for Class X Student Learning Materials,” *J. Pendidik. Sains Indones. (Indonesian J. Sci. Educ.*, vol. 11, no. 4, pp. 713–739, 2023.

[23] N. P. P. M. S. Dewi, L. De Liska, and N. P. Y. Parwati, “Transforming laboratory management learning with e-modules,” *Indones. J. Educ. Dev.*, vol. 6, no. 1, pp. 80–95, 2025.

[24] T. Mairisiska, “Pengembangan E-Modul Biokimia Berbantuan Flip PDF Professional Pada

Materi Karbohidrat Sebagai Sumber Belajar Mandiri Mahasiswa," *SYMBIOTIC J. Biol. Educ. Sci.*, vol. 3, no. 1, pp. 9–18, 2022.

[25] R. T. Sari, S. Angreni, and F. J. Salsa, "Pengembangan Virtual-Lab Berbasis STEM Untuk Meningkatkan Keterampilan Berpikir Kritis Mahasiswa," *J. Pendidik. Sains Indones.*, vol. 9, no. 2, pp. 1–10, 2020, doi: 10.24815/jpsi.vxix.xxxxx.

[26] A. Asmi, S. Silaban, and R. Silaban, "Developing An Interactive Chemistry E-module Based on Problem-based Learning to Improve Critical Thinking Skills of High School Students," *J. Paedagogy J. Penelit. dan Pengemb. Pendidik.*, vol. 11, no. 1, pp. 94–101, 2024.

[27] S. Zulfah, M. Nurjayadi, and Zulhipri, "Development of an Electronic Module (E-Module) Chemistry Based on POE (Predict , Observe , Explain) on Reaction Rate Study Materials," *ICMScE Int. Conf. Math. Sci. Educ.*, vol. 2024, pp. 325–334, 2024, doi: 10.18502/kss.v9i8.15564.

[28] Yusnaidar and W. Syahril, "Development of a Metacognition-Based E-Book Using 3D Pageflip to Enhance Polymer Chemistry Literacy in Coordination Polymerization Reactions," *J. Indones. Soc. Integr. Chem.*, vol. 16, no. 1, pp. 54–63, 2024.

[29] F. P. S. Ndruru and S. Amdayani, "Development of e-modules based on socio-scientific issues on Chemistry content," *J. Inov. dan Teknol. Pembelajaran*, vol. 10, no. 2, pp. 129–140, 2023.