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## From Laboratory Analysis to Digital Teaching Materials: A Systematic Review

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trn:oid::1:3434299516

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IJAR-55074.pdf

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## From Laboratory Analysis to Digital Teaching Materials: A Systematic Review

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### Manuscript Info

#### Manuscript History

Received: xxxxxxxxxxxxxxxx

Final Accepted: xxxxxxxxxxxxxxxx

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 models ADDIE and 4D commonly 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

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### Introduction:

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

9  
10 The transformation from “laboratory analysis” toward “digital teaching materials”  
11 therefore represents a pedagogical innovation that bridges empirical scientific activity with  
12 digitally mediated instruction. By leveraging real experimental data or digitally simulated  
13 experiments, educators can design e-modules and virtual labs that embed inquiry, interactivity,  
14 and feedback into the learning process[3]. For example, studies have demonstrated that virtual  
15 laboratory activities can replicate many of the conceptual learning outcomes of physical labs,  
16 suggesting that the digital pathway is viable[4], [5].

17 Moreover, digital teaching materials derived from laboratory analyses can foster broader  
18 pedagogical benefits beyond mere replication of experiments. For instance, they can support self-

19 regulated learning (SRL), enable repeated experimentation without physical constraints, provide  
20 immediate feedback, and support differentiated pacing [6]. This is especially relevant in modern  
21 education contexts where remote, hybrid, or blended learning modalities are increasingly  
22 common.

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

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

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

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

55

## 56 **Method:**

57 **1** **16** **This study employed a Systematic Literature Review (SLR) design, following the Preferred  
58 Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. The**

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

### 64 65 **Data Sources and Search Strategy**

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

### 75 76 **Screening and Eligibility Criteria**

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

### 85 86 **Inclusion and Exclusion Criteria**

87 Articles were selected according to the following inclusion criteria: Published between  
88 2015–2025 in peer-reviewed journals or indexed conference proceedings, written in English or  
89 Indonesian, focused on the use, development, or evaluation of digital teaching materials or  
90 laboratory-based learning innovations, and provided empirical or design-based evidence.  
91 Exclusion criteria included: Duplicates or incomplete metadata, Non-academic publications (e.g.,  
92 editorials, news articles, or short communications), and Studies unrelated to the context of  
93 science education or teaching materials. Articles were also drawn exclusively from Indonesia.  
94 Therefore, only 11 articles were analyzed.

### 95 96 **Data Extraction and Analysis**

97 The data extraction process followed three main steps: Descriptive Mapping: Metadata  
98 (author, year, title, keywords, journal, and citation count) were exported from Google Scholar

99 using PoP into CSV format. Bibliometric Analysis: The dataset was imported into VOSviewer to  
100 generate network maps of keyword co-occurrence, citation relationships, and thematic clusters.  
101 This helped to visualize emerging research trends and collaboration networks among authors.  
102 Content Analysis: A thematic analysis was conducted manually to categorize each study into  
103 relevant themes such as *design of digital modules*, *virtual laboratory implementation*, *integration*  
104 *of laboratory data into e-learning*, and *learning outcomes*.

105

## 106 PRISMA Flow

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

113

## 114 Quality Assessment

115 To ensure reliability, each article was evaluated based on the following indicators: (a)  
116 research clarity and objectives; (b) methodological rigor; (c) evidence of data analysis; (d)  
117 relevance to the topic; and (e) educational impact. A simple three-level quality scale (High–  
118 Medium–Low) was used. Inter-rater agreement between two independent reviewers exceeded  
119 85%, ensuring consistency in article selection.

120

## 121 Data Synthesis

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

128

## 129 Results and Discussion:

### 130 Identification and Selection of Studies

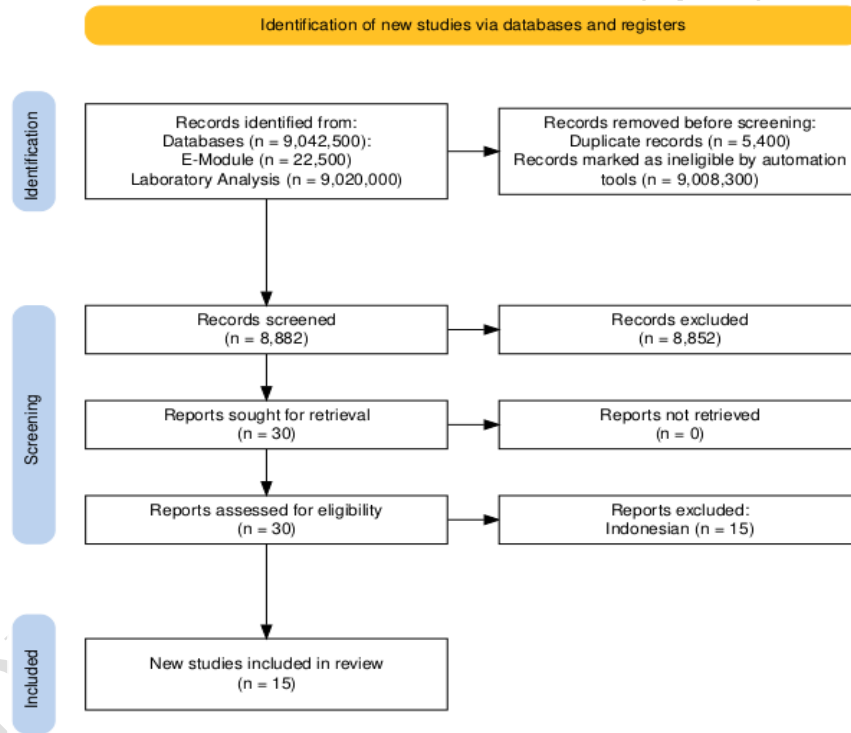
131 The process of study identification and selection followed the PRISMA (Preferred Reporting  
132 Items for Systematic Reviews and Meta-Analyses) protocol. As illustrated in Figure 1, a total of  
133 9,042,500 records were initially identified through database searching. This total consisted of  
134 two primary search streams: (1) *E-Module* (22,500 records) and (2) *Laboratory Analysis*  
135 (9,020,000 records).

136 During the initial filtering stage, 5,400 duplicate records were removed, and an additional  
137 9,008,300 records were excluded as ineligible based on automated screening tools (primarily

138 because they were not aligned with educational or digital learning contexts). This resulted in  
 139 8,882 records remaining for abstract and title screening.

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

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



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

153  
 154 ***Descriptive Analysis of the Selected Studies***

155 The 15 selected studies spanned nearly a decade (2015–2024) and collectively demonstrate an  
 156 evolution of pedagogical innovation in science education. The dominant research methodologies  
 157 identified were **ADDIE (Analysis, Design, Development, Implementation, and Evaluation)** and  
 158 **4D (Define, Design, Develop, Disseminate)** instructional models. These frameworks are well-  
 159 suited for systematic educational product development, especially for designing and testing  
 160 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

161

162

Several consistent patterns emerged:

163

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.

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2. Pedagogical Effectiveness and Student Learning Outcomes: Subsequent research (*Budiarto et al., 2020; Putri et al., 2021*) reported measurable

169

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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.

171

172

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

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

189

### 190 ***Bibliometric Network Analysis***

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

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

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

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

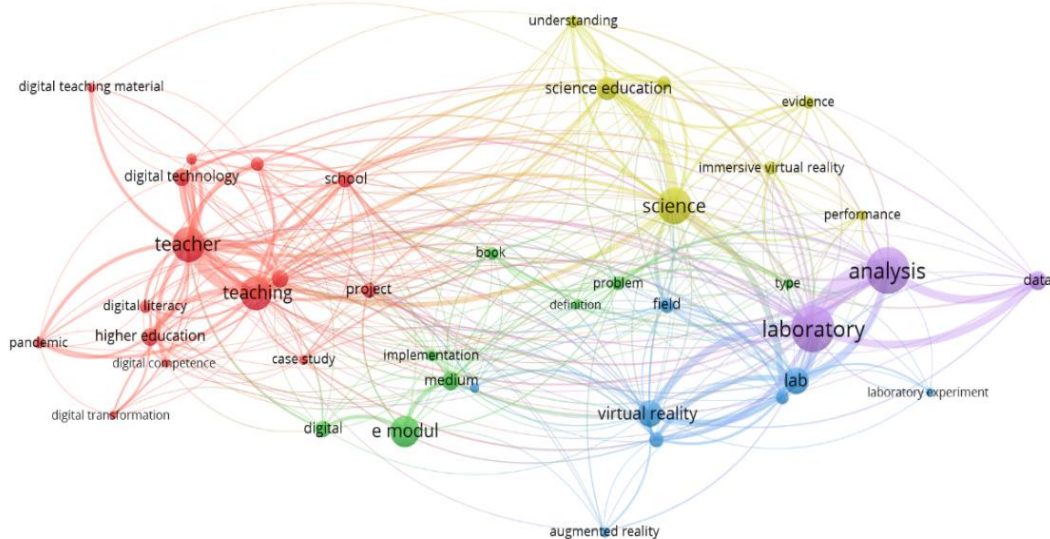


Figure 2. VOSviewer co-occurrence network visualization

217  
 218 **Temporal Distribution and Research Evolution**

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

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

232 where hands-on experimentation, collaboration, and cognitive engagement are now supported  
 233 through virtual and augmented interfaces.

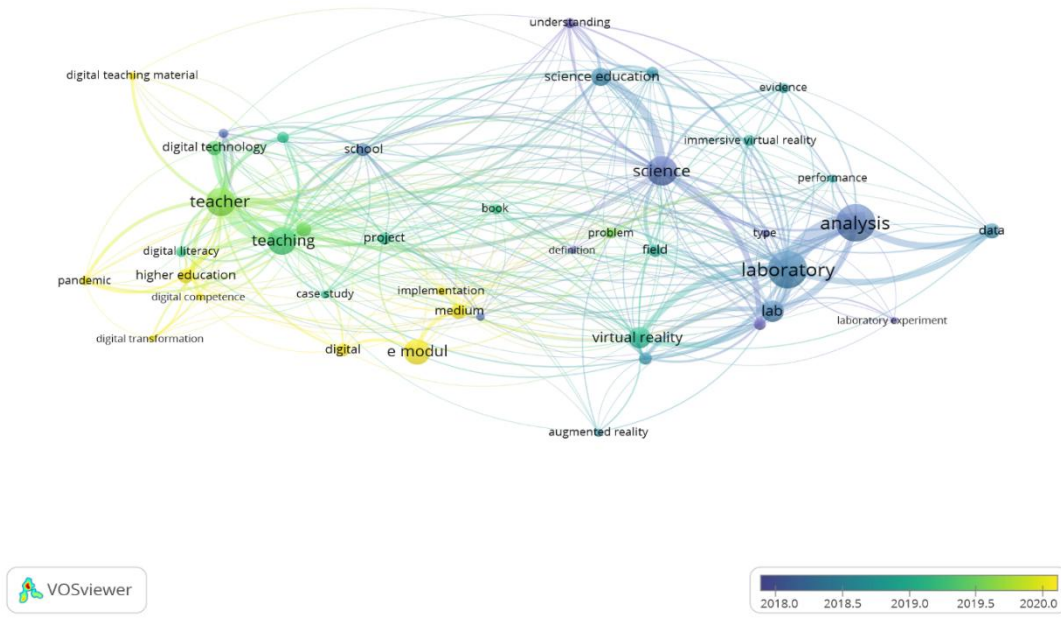


Figure 3. Overlay visualization

234

235 ***Comprehensive Interpretation and Educational Implications***

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

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

254

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

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

259

### 260 **Conclusion:**

261 This systematic review concludes that the transformation from laboratory analysis to digital  
262 teaching materials marks a crucial innovation in science education. Across 15 reviewed studies,  
263 the use of digital e-modules and virtual laboratories developed mainly through the ADDIE and  
264 4D models has proven effective in improving students' conceptual understanding, retention, and  
265 independent learning. Bibliometric and temporal analyses indicate a clear shift from  
266 conventional laboratories toward immersive, data-driven, and technology-integrated learning  
267 environments. This reflects the growing convergence of pedagogy and digital innovation within  
268 STEM education. However, challenges remain in ensuring digital readiness, equitable access,  
269 and the replication of practical laboratory skills. Future research should emphasize sustainability,  
270 teacher competence, and long-term evaluation of digital learning impacts. Overall, integrating  
271 laboratory analysis into digital formats enhances accessibility, interactivity, and cognitive  
272 engagements supporting the broader educational transformation toward Education 5.0.

273

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