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Research Article

A Deep Learning–Based Electronic Module for Global Warming: An Analysis of Validity and Readability to Support Critical Thinking Skills

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ABSTRACT

Purpose of the study: This study aims to analyze the validity and readability of a deep learning–based electronic module (e-module) designed to improve students' critical thinking skills on global warming material.

Methodology: The research employed a Research and Development (R&D) approach using the ADDIE model, consisting of analysis, design, development, implementation, and evaluation stages. The developed e-module integrates deep learning principles—mindful, meaningful, and joyful learning into a Google Sites platform and is enriched with multimedia elements, including videos, animations, interactive worksheets, Padlet, and a carbon footprint calculator. The validity of the e-module was evaluated by six experts, including media experts, subject matter experts, and linguists, using Aiken's V formula.

Main Findings: The results showed that all validation aspects achieved Aiken's V values ranging from 0.83 to 1.00, exceeding the minimum validity threshold (V > 0.78), indicating that the e-module is highly valid. Readability testing involved ten junior high school students and two science teachers and was analyzed using percentage-based criteria. The readability scores ranged from 88% to 100%, categorized as excellent across content, format, presentation, and language aspects. These findings indicate that the deep learning–based e-module is not only valid but also highly readable and user-friendly.

Novelty/Originality of this study: The developed e-module has strong potential to be implemented as an innovative digital teaching material to support science learning and foster students' critical thinking skills, particularly in addressing contextual and global environmental issues such as global warming.

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1. INTRODUCTION

The 21st century has seen tremendous paradigm shifts in the education sector, requiring the need to produce quality human capital endowed with various and complex skills. In a period of unlimited information access and accelerated technological change, the education sector must ensure that their students attain necessary skills in 21st-century century skills, as prescribed in Partnership for 21st Century Skills, in communication,

collaboration, critical thinking skills, and creativity [1]. Of these skills, critical thinking skills take prominence because critical thinking includes such advanced level critical thinking skills such as deductive and inductive reasoning, practical reasoning, decision-making, and problem-solving skills. These skills can be considered basic for effectively dealing with real-world problems since critical thinking skills have been viewed as a multi-dimensional concept necessary for making correct judgments and solving problems, as in PENCRISAL concept [2]. People with excellent critical thinking skills have the opportunity to be better disposed to information analysis, evaluation, and synthesizing for making better decision-making tasks and problem-solving [3].

Science learning in the classroom is an important intervention in developing higher-order thinking abilities, especially critical thinking, in preparing learners to face the increasing demands of the future in terms of addressing societal and environmental needs. A topic in science learning where critical thinking is highly demanded is global warming, which is a major global environmental problem with significant immediate effects on the lives of individuals. Under the Kurikulum Merdeka, the subject of global warming is addressed in Phase D, where learners need to critically analyze the causes, effects, and solutions of global warming using scientific facts and reasoning. Learning science using global issues like climate change has contributed positively to the development of critical thinking skills in learners because it actively engages them in processing facts, scrutinizing arguments, and making sustainable choices [4]. On the other hand, findings from investigations suggest that there is a significant positive link between knowledge on sustainable and environmental concerns and the critical thinking ability of learners, where critical thinking has the capacity to mediate in improving learners' ability to make sustainable choices [5].

Notwithstanding its criticality, the empirical finding shows that the critical thinking level of Indonesian students is surprisingly low. According to PISA Report in 2022 Programme for International Student Assessment, Indonesia's science literacy performance demonstrated an index score of 396, far below the OECD countries' average, with only some 33% of students with an actual level 2 proficiency or higher [6]. The situation now can be attributed to the capability level of the students to use scientific principles in a critical manner within everyday life conditions. In this connection, some studies show that the critical thinking capacity in Indonesia has an average performance level of some 52.15% by most students classified as having a low to moderately low level in critical thinking proficiency.

Among the most important factors that shape the development of students' critical thinking skills is the quality of the learning tools, the approach used, and the methods applied. Effective learning tools are an essential factor in promoting significant learning and the development of higher-order thinking skills. Current studies prove that learning modules created using innovative approaches to teaching can greatly improve students' critical thinking skills [7]. In conjunction with the evolution of modern technology, the 'e-module' has been established as an option for teaching materials and the provision of interactive and engaging learning experiences using the integration of text, images, videos, and graphics in an educational setting [8]. In relation to the printed learning modules, the internet-based web 'e-module,' for instance the use of Google Sites, provides greater flexibility and functionality with the same functionalities and features, and does not require additional applications or advanced devices, hence ideal for wider learning settings.

To address these issues, the Government of Indonesia, through the Ministry of Education, has applied the Deep Learning method as a mechanism to support the development of critical thinking and problem-solving capabilities in students through all levels of education as a nationwide education program. The Deep Learning method not only encourages cognition but also utilizes deep understanding and application in real life. According to [9], the Deep Learning method is developed on the principles of mindful learning, meaningful learning, and joyful learning. Evidence suggests that the adoption of Deep Learning principles has succeeded in enhancing students' interest in learning and critical thinking skills [10]. The Deep Learning method is largely in support of the aims of the Kurikulum Merdeka. This program identifies students' understanding and higher-level thinking.

The application of e-modules in the development of critical thinking skills is also supported by other studies evaluating the procedures of teaching and learning in line with the use of technological innovations. It was found to improve the level of critical thinking skills through the application of repeated exercises utilizing software programs offering intense learning feedback to students to enable them to make corrections on errors found in the solution in an examination, the frequency of use being positively related to performance [11]. Project-based learning, which involves the learning process linked to the application of deep learning strategies, has also been found to promote critical thinking skills while improving the skills of communication and teamwork at the same time [12]. Other studies suggest the need to use learning processes in critical thinking skill development in an integrated manner involving the application of information acquisition skills, conceptual development, application, and creative thinking in line with proven instructional designs [13]. It was also revealed in other studies utilizing creativity strategies in a learning process involving problems to deliver significant results on the scientific creativity level of students in higher-order thinking skills [14], [15].

Learning innovations that link science content to students' everyday experiences have also proved to effectively enhance analytical thinking, creative thinking, problem-solving, and critical thinking skills, with

higher-order thinking results indicating significant improvement after such interventions [16]. In the context of global warming education, the inherently interdisciplinary nature of climate change content provides students with an incentive to investigate complicated interrelationships between scientific ideas and social issues. Previous research does, however, indicate that in trying to implement interdisciplinary climate change education, teachers often experience a number of setbacks, again underlining the need for structured learning resources to support both teachers and their students, while curiosity itself becomes the linchpin that sustains deeper learning trajectories [17].

Despite the increasing number of studies on digital learning media, e-modules, STEM-based learning, and problem-based instruction, several critical gaps still exist. Firstly, science learning modules that have been explicitly designed using the Deep Learning approach-particularly conceptualized in Indonesian education policy (mindful, meaningful, and joyful learning)-remain very limited. Secondly, most studies currently focus on the aspects of learning effectiveness or learning outcomes alone, whereas empirical investigations of the validity and readability of deep learning–based e-modules are still rarely encountered. Thirdly, there is a significant lack of digital learning resources that allow contextual global environmental issues, such as global warming, to be properly integrated into the Kurikulum Merdeka framework. It is notably associated with the need for junior high school students to develop critical thinking skills through contextual and student-centered science learning.

Addressing these gaps, the proposed study concerns the design and empirical validation of a deep learning–based e-module on global warming materials to enhance the critical thinking skills of students. Precisely, this study aims to (1) investigate the validity of the developed e-module from media experts, subject matter experts, and linguists with Aiken's V formula, and (2) examine the readability of the e-module from the teachers and students through small-scale trials. This present study expands on pedagogical validity and practical usability in bridging the gap between policy-driven innovation in education and classroom-level implementations. This present research is expected to contribute both theoretically and practically. Theoretically, this study adds weight to the literature on the development of digital science learning material based on a deep learning approach and its potential role in fostering students' critical thinking skills. The study will produce a deep learning–based, valid, and readable e-module that can potentially act as an alternative innovative teaching resource for global warming topics in junior high school science learning. Furthermore, the research provides a reference framework for educators and researchers interested in developing student-centered, technology-integrated learning tools aligned with Kurikulum Merdeka and the challenges of 21st-century education.

2. RESEARCH METHOD

This research uses the research and development (R&D) method with the ADDIE model which consists of five stages, namely analyze, design, development, implementation, and evaluation. The selection of the ADDIE model is based on its systematic, flexible, and practical characteristics in developing learning products in stages from needs analysis to final evaluation. This model allows researchers to conduct continuous revisions based on the results of validation and trials, so it is very suitable for the development of e-module that are based on the needs of students and contextual to science subjects.

In the analyze stage, a preliminary study was conducted using a teacher and student needs questionnaire and a critical thinking ability test was given to students to identify learning gaps. The design stage includes the preparation of an e-module structure that integrates deep learning principles, namely awareness, meaningful, and encouraging with indicators of critical thinking skills, According to Azwar [18]. The development stage produces a Google Sites-based e-module product that contains global warming material complete with videos, images, animations, live worksheets and padlet. The products that have been developed are then validated by 6 experts consisting of 3 lecturers, 2 master's degree science teachers and 1 professional teacher using a validation instrument with a likert scale of 4 ratings. Validation includes three aspects, namely media expert validation, material expert validation, and linguist validation.

The validity analysis of *the e-module* uses the Aiken's V formula with the formula:

$$V = \frac{\Sigma S}{n(c-1)} \dots (1)$$

Information:
S : The score given by the assessor minus the lowest score
c : Highest assessment score
n: Number of validators

Table 1. Eligibility Categories Based on Aiken Validity

Score	Category
V count > V table	Good
V count < V table	Bad
V count = V table	Revision

E-modul is declared valid and feasible if Aiken's V index > 0.78 based on the V-Aiken coefficient table with 6 validators and 4 ratings. After being declared valid, a readability test was carried out limited to 10 randomly selected students and 2 science teachers using a readability questionnaire. Readability data is analyzed using the percentage formula [19].

$$P = \frac{F}{N} x\ 100\% \ldots (2)$$

Information:
P : Percentage Score
F : Total score obtained
N: maximum score

The readability category was classified as follows table 2.

Table 2. Categories Readability Score

Score Range	Category
81.25% < P ≤ 100%	Excellent
62.5% < P ≤ 81.25%	Good
43.75% < P ≤ 62.50%	Not Good
25% < P≤ 43.75%	Bad

3. RESULTS AND DISCUSSION

3.1 Validity of Deep Learning-Based E-module

The validation process of the deep learning-based e-module on global warming material involved six validators consisting of three expert lecturers, two master's degree science teachers and one professional teacher. Validation was carried out on three main aspects, namely media, learning materials, and language using Aiken's V formula.

Media expert validation includes ten indicators that assess visual, interactivity, and accessibility aspects e-module. The validation results showed that the V value ranged from 0.83 to 1.00 with valid categories on all indicators (Table 3). An indicator with a perfect value of 1.00 was obtained in the aspect of accessibility e-module through various devices and browser, page loading speed without technical glitches, as well as the integration of media such as images, videos, and animations in learning content. This shows that e-module based Google Sites developed has advantages in ease of access and technical responsiveness. The lowest value of 0.83 was obtained in the aspect of consistency of visual elements between pages, which indicates that there is still room for improvement in harmonization font, icons, and layout in some parts e-module . These findings are in line with research showing that the high validity of digital learning media is highly dependent on the quality of visual design and adequate technical functionality [20].

Table 3. Media Expert Validation Results

Indicators	Value	Category
Selection of attractive themes, colors, and page layouts that support the readability of learning content	0.94	Valid
Consistency of visual elements between pages such as fonts, icons, and layouts	0.83	Valid
Text, images, and videos are easy to read and view on a variety of devices	0.89	Valid
Link features, navigation buttons, and interactive elements work well	0.89	Valid
Image, audio, and video quality is clear and relevant to the material	0.89	Valid
The menu structure and links make it easy for users to move between pages	0.89	Valid
Page design is engaging, non-monotonous, and fosters interest in learning	0.94	Valid
E-module are well accessible through a variety of devices and browsers	1.00	Valid
The e-module page can load quickly without any technical glitches	1.00	Valid
Media (images, videos, animations, and links) are well integrated into learning content	1.00	Valid

The expert validation of learning materials includes ten indicators that evaluate the suitability of the content with learning outcomes, the accuracy of the concept, its relevance to real life, and its suitability with the deep learning approach. The validation results showed that the value of V ranged from 0.89 to 1.00 with all indicators being categorized as valid (Table 4). A perfect score of 1.00 was obtained in the aspects of the suitability of the material with learning outcomes, the relevance of the material to daily life and the issue of global warming, as well as the selection of interesting words and sentences. This indicates that the content e-module has successfully integrated the context real-world problems that fit the deep learning approach. The lowest value of 0.89 is found in the aspect of the accuracy of the content of the material and the suitability of examples and illustrations, which shows the need for minor revisions in some parts to improve conceptual accuracy. Previous research confirms that the high validity of learning materials is crucial in ensuring that learners gain an accurate and in-depth understanding of concepts [21].

The technical accessibility and responsiveness of the Google Sites-based e-module demonstrate the importance of user-friendly digital platforms in contemporary education. Research emphasizes that interactive applications including Kahoot, Wooclap, Classflow, and Moodle are essential for maintaining student engagement and increasing participation, with the use of multiple applications leading to improved academic performance by avoiding monotony [22]. The high validity scores for media integration align with findings showing that no-code, accessible tools like waikato environment for knowledge analysis can help students confidently embrace computational methods while enhancing their motivation to learn, though care must be taken to maintain collaborative practices [23]. Additionally, the environmental consideration of digital learning platforms is increasingly relevant in educational decision-making. Both providers and learners share responsibility for minimizing the carbon footprint associated with educational activities, and educators should focus on activities likely to have the greatest environmental impact, whether in face-to-face education or digital learning contexts [24]. This consideration is particularly important for climate change education, where the medium of instruction should align with the environmental values being taught.

Table 4. Validation Results of Learning Material Experts

Indicators	Value	Category
Materials are in accordance with learning outcomes	1.00	Valid
The content of the material is correct, accurate, and does not cause misconceptions	0.89	Valid
The material is easy for junior high school students to understand	0.94	Valid
Material relevant to daily life and global warming issues	1.00	Valid
Examples, data, and illustrations support understanding of the material	0.89	Valid
Presentation of material is concise and clear	0.94	Valid
Learning activities encourage students to think critically	0.94	Valid
Activities in e-module according to the abilities of junior high school students	0.94	Valid
The presentation of learning is consistent and does not give rise to double interpretation	0.94	Valid
Learning activities are in accordance with the principles of the deep learning approach (aware, meaningful and encouraging)	0.94	Valid

The linguistic validation includes five indicators that assess the ease of understanding the language, conformity with the rules of the Indonesian language, the effectiveness of sentences, the attractiveness of word selection, and the communicative nature of the language used. The validation results showed that the value of V ranged from 0.94 to 1.00 with all indicators being categorized as valid (Table 5). A perfect score of 1.00 was obtained on the aspect of word and sentence selection that is interesting and encourages interest in learning, which indicates that *the e-module* has used language that is not only communicative but also motivates learners. The other four indicators obtained a value of 0.94 which indicates excellent language quality in terms of readability and clarity. Previous research has shown that the use of language that is communicative and in accordance with the characteristics of students is an important factor in increasing the effectiveness of digital teaching materials.

The integration of deep learning principles in the e-module is also supported by research demonstrating that innovative learning approaches can significantly enhance students' cognitive abilities. Studies have shown that when students are challenged to engage with higher-order thinking tasks through student-designed assessment problems, their analytical and evaluative skills improve substantially, with students demonstrating all levels of thinking on Bloom's revised taxonomy [15]. The deep learning approach implemented in this e-module aligns with findings indicating that student-centered methods combined with creativity strategies effectively foster critical thinking by encouraging learners to connect theoretical concepts with real-world applications, particularly in science education contexts [14]. Furthermore, research confirms that learning materials designed to promote knowledge application and productive thinking contribute to developing critical learning skills at various educational levels, with frameworks emphasizing information gathering, building understanding, knowledge application, and productive thinking as essential components [13].

The contextual relevance of global warming material in the e-module reflects current educational needs for climate change literacy. Research indicates that secondary students often hold serious misconceptions about climate cl contexts that support understanding, motivation, and data literacy through online int te data and visualizations [25]. The integration of multimedia elements such as v s in this e-module addresses the need for engaging educational tools that combat st t, particularly for digitally native learners who depend on technology and tend to be ith traditional methods [22]. Moreover, holistic climate change education that comb th practical applications has been shown to enhance students' biospheric values and potentially predict lower carbon footprints, though knowledge on mitigative actions requires careful instructional design to achieve meaningful behavioral changes [26]. The interdisciplinary nature of addressing climate change through educational materials also presents challenges for learners as they navigate the complex space between mathematics, technology, and societal issues, with curiosity acting as a potential stimulus for sustained engagement [17].

Table 5. Linguistic Validation Results

Indicators	Value	Category
The langu to understand	0.94	Valid
The use o ntence structure is in accordance with Indonesian rules	0.94	Valid
Sentences d do not give rise to double interpretation	0.94	Valid
Choice of interesting and encourage interest in learning	1.00	Valid
Use of communicative language	0.94	Valid

The overall validation results show that *e-module* developed has met the feasibility standards in terms of media, materials, and language. The achievement of this high validity value shows that the development product has gone through a systematic design process by considering pedagogical, technological, and linguistic aspects. The high validity value is in line with the results of the study which states that *e-module* developed with a structured approach and validated by experts can achieve a very valid category with a percentage above 90% [27]. The high validity also indicates that *deep learning-based e-module* has the potential to improve the quality of science learning, especially in empowering students' critical thinking skills through the exploration of contextual issues such as global warming. The display of the deep learning-based electronic module to improve students' critical thinking skills on global warming material is as follows.

Figure 1. Home Page

Figure 2. Menu

Figure 3. Introduction Page

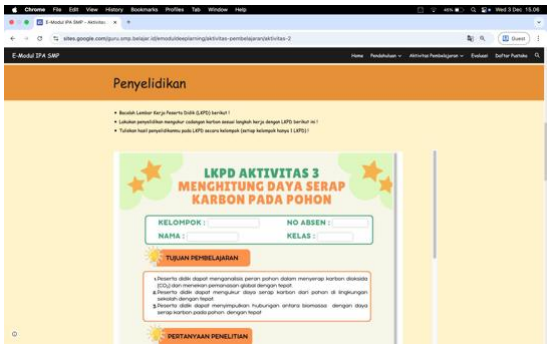

Figure 4. Activity Pages

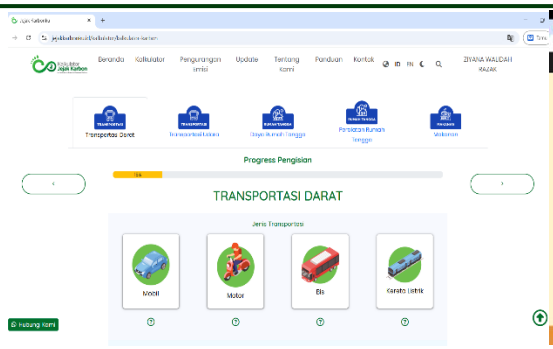

Figure 5. Carbon Calculator

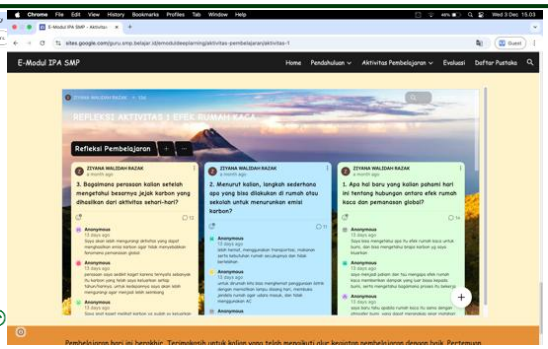

Figure 6. Reflection page

Based on Figure 1-6. The display of *e-modul* design includes layouts, home page, menu, introduction pages, activity pages, reflection pages, and references. *E-modul* can be inserted with text, images, videos, documents, and can be inserted with links another platform such as google forms, google sheets, YouTube, calculator carbon, videos and Padlet.

3.2 Deep Learning-Based E-module Readability

The *e-module readability test* was carried out in a limited trial stage involving ten randomly selected students and two science teachers. Readability was measured using a questionnaire that included 15 assessment items divided into four aspects, namely material content, format, presentation, and language. The results of the readability test showed that all items obtained a very high percentage with a range of 88% to 100%, which indicates that *the e-module* is very easy to understand and interesting for users (Table 6).

Table 6. E-module Readability Test Results

Aspects	No Item	Score	Information
Content	1	94%	Excellent
	2	100%	Excellent
	3	100%	Excellent
Format	4	90%	Excellent
	5	94%	Excellent
	6	92%	Excellent
	7	96%	Excellent
	8	88%	Excellent
	9	96%	Excellent
	10	94%	Excellent
Serving Language	11	98%	Excellent
	12	88%	Excellent
	13	90%	Excellent
	14	92%	Excellent
	15	94%	Excellent

In terms of material content, the three items obtained a very high percentage with two items achieving a perfect score of 100%. This indicates that the content presented in the *e-module* it is very relevant to the learning needs of students and easy to understand. The high readability of the content of the material indicates that the *Deep Learning approach* integrated in *e-module* successfully delivering meaningful learning through activities that relate the concept of global warming to the real lives of students. Previous research has shown that *e-module* with contextual content and presented interactively, it can obtain an excellent level of readability from students [28]-[30]. In terms of format, the eight items obtained percentages between 90% to 98% in the very good category. This shows that the visual design *e-module* developed using *Google Sites* successfully create an attractive, consistent, and responsive display. The use of colors, layouts, and intuitive navigation makes it easier for students to access various learning features. These findings are in line with the results of a study that states that the format *e-module* which is designed with attention to aesthetics and ease of navigation can increase students' interest and motivation to learn [31]-[35]. The high readability of the presentation aspect shows that the integration of multimedia such as video, images, animations, and *Live Worksheet* succeeded, carbon calculator website, padlet in increasing students' attractiveness and understanding of global warming material. Interactive presentations allow students to be actively involved in the learning process in accordance with the principles *deep learning* that is exhilarating and aware. Previous research confirms that the presentation of digital content that integrates various media can significantly increase students' engagement and understanding of concepts

[36]-[39]. In terms of language, the four items obtained percentages between 88% and 94% in the very good category. This shows that the use of language in *e-module* is communicative, in accordance with the characteristics of junior high school students, and easy to understand. Although the two items obtained the lowest score of 88%, this figure still falls into the excellent category and indicates that the overall language ya.ng used does not cause comprehension difficulties for learners. The use of simple but still scientific language is one of the key factors in improving the readability of digital teaching materials, especially for contextual materials such as global warming [40]-[43].

Overall, the results of the excellent readability test on all aspects show that deep learning-based electronic module developed has met the criteria as a teaching material that user-friendly and effective. The combination of relevant content, engaging design, interactive presentation, and communicative language creates an optimal learning experience for learners. The high readability score also indicates that *deep learning-based e-module* has the potential to be widely implemented in science learning at the junior high school level. These findings are in line with research that states that *e-module* with excellent readability levels tend to be more effective in improving students' learning outcomes and high-level thinking skills [44]-[46].

The relationship between the validity and high readability of this *e-module* shows that a systematic development process involving expert validation and user trials results in a quality learning product. The high validity of the expert assessment provides assurance that *deep learning-based e-module* have met academic and pedagogical standards, while good readability from the perspective of learners and teachers ensures that the product is practical and easy to use in a real learning context. The synergy between these two aspects is an important indicator of the feasibility of *e-module* to be implemented in an effort to improve students' critical thinking skills on global warming materials through *a deep learning* approach.

The implementation of technology-enhanced learning materials like this e-module must also consider ethical dimensions and responsible use of digital tools in educational contexts. Research emphasizes the importance of responsible artificial intelligence in education, with essential characteristics including fairness and equity, privacy and security, non-maleficence and beneficence, agency and autonomy, and transparency and intelligibility, requiring collaborative efforts of stakeholders including students, educators, developers, researchers, and policy makers [47], [48]. While the e-module developed in this study does not incorporate artificial intelligence, the principles of responsible technology use, particularly regarding privacy, transparency, and user autonomy, remain relevant considerations for future development and implementation. Additionally, climate change education through digital platforms should address both the learning outcomes and the environmental impact of educational activities, with both providers and learners focusing on minimizing carbon footprints associated with their learning, which is relevant to both face-to-face education and digital learning [49]-[51].

The multidimensional approach of the e-module, combining deep learning principles with contextual environmental issues, addresses the need for holistic education that impacts multiple dimensions of learning. Research demonstrates that climate change courses designed to be multidisciplinary and holistic can significantly increase science knowledge, though knowledge on mitigative actions may remain unchanged despite related course assignments, indicating that different aspects of climate change education require different instructional strategies [52], [53]. The effectiveness of climate change education is enhanced when students engage with novel data through number-line visualizations, with interventions improving climate change knowledge and situated interest, particularly among learners who express more openness to reason with belief-discrepant evidence. The e-module's emphasis on meaningful learning and real-life connections aligns with educational frameworks showing that content design in line with students' knowledge levels, easy to understand, and enabling connections between science content and daily life, supports the development of higher-order thinking skills, though multimedia navigation design and problem scenarios must be carefully structured to support these connections [54], [55].

Furthermore, the blended learning approach implicit in the e-module's design reflects research demonstrating that maximizing the advantages of each teaching method and combining online and face-to-face instruction results in significant increases in learning engagement, with the flex model showing positive impacts on students' academic achievement, self-study skills, and learning attitudes. The interactive and game-based elements incorporated through platforms like live worksheets and padlet align with findings that game-based learning solutions can be used to motivate students and prepare learners to deal with uncertainty, with students' positive and negative perceptions influencing their motivation to study and learn specific subject matter phenomena [56]. The excellent readability scores obtained in the format aspect reflect the effectiveness of well-designed digital learning environments that combine multiple instructional modalities. Research demonstrates that the flex model of blended learning, which maximizes the advantages of online and face-to-face instruction, significantly improves student interactions with teachers, academic achievement, self-study abilities, and learning attitudes compared to traditional methods. The interactive features embedded in the e-module, including live worksheets and padlet, correspond with findings that game-based learning methods can motivate students and prepare learners to deal with uncertainty as in real-life projects, with students reporting positive perceptions

when such methods influence their motivation to study and learn [57], [58]. Moreover, the integration of computational thinking tools and multimedia resources has been shown to enhance learning motivation, with students spending more time focusing on tasks and demonstrating improved algorithmic thinking when exposed to machine learning tools, even without requiring coding skills.

The Novelty of this research lies in the combination of the deep learning strategy (practicing mindfully, meaningfully, and joyfully) into a digital e-module explicitly designed to improve critical thinking abilities among students on global warming topics. Contrary to past research on e-module designs, this research focuses not only on content but also on cognitive engagement, relevance, and joyful learning. Furthermore, the combination of a Google Sites platform and interactive components, such as live worksheets, Padlet, and a carbon footprint calculator, offers a new strategy for teaching global warming. This research also provides new empirical insights by examining both expert-based validity and user-based readability. This implies that the research not only provides intellectual insights but also offers practical ideas and approaches. This research contributes to the existing body of knowledge on digital education in science by providing new empirical insights into the application of deep learning strategies in e-module design. This research will help improve existing perspectives on the significance of meaning and reflective learning strategies as the most important drivers of critical thinking among students, especially regarding global warming. From a practical standpoint, the designed e-module may serve as an alternative teaching innovation for science teachers who adopt the Untuk Curriculum Sciences within the current Indonesian education system. This e-module may serve as an agent that enhances the process between science teachers and their students. It may also act as a reference point among teachers and designers to develop similar e-modules.

Despite the study's benefits, there are still numerous limitations. First, the study focused only on validity and readability. Still, it did not assess the efficacy of the e-module on the critical thinking abilities of the subjects using the experimental method. Second, the aspect of readability involved a small sample of only ten subjects and two teachers, which may limit the study's generalizability. Third, the study focused solely on global warming, so its findings cannot be directly applied to other scientific subjects or levels. Future studies on this topic may conduct experiments or quasi-experimental designs to assess the efficacy of the deep learning algorithm-based e-module in enhancing subjects' critical thinking abilities. Larger-scale experiments should be pursued. Future studies may also expand the development of deep learning algorithm-based e-modules in other science subjects or integrate assessment analytics and adaptive learning functionalities to personalize the e-module further.

4. CONCLUSION

This development study concludes that the deep learning–based e-module on global warming is highly feasible, readable, and pedagogically relevant for junior high school science learning. The validation results demonstrate that the e-module meets rigorous quality standards across media design, content accuracy, and language clarity, indicating that it is well aligned with curricular demands and students' cognitive levels. The very high readability scores further show that the e-module is engaging, easy to understand, and capable of supporting independent learning, which is essential in contemporary science education. The integration of deep learning principles being aware, meaningful, and encouraging—successfully creates a learning environment that connects scientific concepts with real-world environmental issues, thereby fostering students' critical thinking and reflective understanding of global warming.

The implications of these findings suggest that deep learning–based digital modules can serve as effective instructional resources to enrich science learning, particularly for abstract and complex topics such as climate change. Practically, teachers can use this e-module to facilitate more student-centered, contextual, and inquiry-oriented learning experiences that encourage analysis, problem-solving, and environmental awareness. From a broader educational perspective, this study supports the adoption of innovative digital learning materials that emphasize depth of understanding rather than rote memorization, aligning with the goals of 21st-century science education. Future implementation of similar e-modules across other science topics has the potential to strengthen students' higher-order thinking skills and promote meaningful learning that is responsive to global and local challenges.

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CONFLICTS OF INTEREST

The author(s) declare no conflict of interest.

USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declare that no artificial intelligence (AI) tools were used in the generation, analysis, or writing of this manuscript. All aspects of the research, including data collection, interpretation, and manuscript preparation, were carried out entirely by the authors without the assistance of AI-based technologies.

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