Fostering Critical Thinking Skills through Augmented Reality: Insights from Higher Education Engineering Students

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***Abstract*—This study aims to explore the use of Augmented Reality (AR) technology in relation to digital literacy, learning strategies, and perceived ease of use of Technology Acceptance Model (TAM), on students' critical thinking skills. This research employs a quantitative correlational method to examine the relationships among these variables. The sample of this study consisted of 221 students majoring in Electronic Engineering at the Engineering Faculty, Universitas Negeri Padang, obtained through purposive sampling technique. The collected data were analyzed using Structural Equation Modeling (SEM) using SmartPLS 3 to examine the relationships between variables, and network analysis using Jeffreys's Amazing Statistics Program (JASP) to map and visualize the interactions among them. The results showed that digital literacy has a significant positive influence on students' critical thinking skills. In addition, learning strategies also have a positive and significant impact on students' critical thinking skills. This finding shows that perceived ease of use contributes significantly and can moderate the relationship between digital literacy and learning strategies in improving students' critical thinking skills. Therefore, improving digital literacy and strengthening learning strategies need to be considered in curriculum design. In addition, the development of user-friendly AR applications can increase technology acceptance and support the improvement of critical thinking skills. Further research is recommended, to consider how children's emotional intelligence, technological support, and environmental influences are factors related to AR use and students' critical thinking, both quantitatively and qualitatively.**

***Keywords*—augmented reality, critical thinking skills, digital literacy, learning strategies, perceived ease of use**

I. Introduction

Over the past two decades, Critical Thinking Skills (CTS) have been a prominent topic of discussion in the field of education [1]. CTS in the modern education era is one of the main abilities that students must possess. Every country strongly recommends and supports the development of this skill [2]. However, developing and enhancing a skill is not easy to achieve in a short period. There are many steps and reforms that must be taken to pursue this skill. In general, cognitive and intelligence differences can affect the level of ability to criticize something. In addition, different teaching methods and approaches will lead to varying levels of critical thinking development.

In fact, there is no completely valid tool for accurately measuring a person's level of critical thinking. This is because critical thinking is subjective and multidimensional, encompassing various aspects such as analysis, inference, and diverse perspectives unique to each individual [3–5]. However, a critical person can be characterized by their ability to analyze arguments, structure and organize work in a structured and logical manner, have questions that are sometimes beyond reason, and be able to solve problems appropriately.

Several factors contribute to an individual's level of critical thinking, including psychological factors (personality, experience, beliefs) and sociological factors (social adaptation, culture, and access to education) [6]. Based on Aston's research [7], an external factor that affects a person's critical thinking is the use of technology. Specifically, this study focuses on Augmented Reality (AR) as the proposed technology. AR is a technology that transforms 2D objects into 3D visualizations [8]. It marked the first step in the development of AR. Over time, AR has evolved, with many new features being introduced. A key milestone occurred in 2016, with the launch of the highly popular Pokémon GO game [9].

Originally popularized in the gaming world, AR is now being increasingly developed for educational application [10, 11]. A new opportunity has emerged to provide an interactive learning experience for students. Although its potential in education is recognized, successful implementation largely depends on students' acceptance of the technology. Based on the Technology Acceptance Model (TAM) theory, individuals are more likely to adopt a technology if they feel that the technology is easy to use and easy to understand (perceived ease of use) [12]. Therefore, this study will analyze how students' perceptions of the ease of use of AR contribute to the adoption of this technology in educational environments.

In addition, there are still few studies that examine the relationship between AR and factors such as digital literacy and learning strategies to improve critical thinking skills, especially in Indonesia. Meanwhile, these factors are closely related to AR and digital technology. Numerous previous studies have examined the contribution of this technology to enhancing students' digital literacy and learning strategies. First, Blevins [13] and Hsu [14] argued that AR has a positive influence on students' digital literacy. Digital literacy is the

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ability to evaluate any information obtained from technology including AR. Second, the influence of AR on student learning strategies. This technology encourages students to learn with curiosity [15, 16]. AR has the capability to transform virtual objects and bring them closer to the realm of science fiction, bridging the gap between imagination and reality. The curiosity that arises fosters a sense of inquiry and a desire to explore and utilize the technology. Ultimately, it transforms their learning approach, shifting the focus toward questioning and problem-solving.

Previous studies have demonstrated that the implementation of AR can influence critical thinking skills [17]. Additionally, the use of AR also impacts digital literacy [18, 19]. These studies were conducted in general education settings, such as elementary schools. To support these theories, further investigation is needed at other educational levels, such as universities. Another variable involved is learning strategies, which differ across educational levels, particularly because university students have different characteristics compared to students in primary or secondary education. Therefore, further exploration is necessary to understand how learning strategies specifically designed for university students can optimize the use of AR technology, then enhancing their critical thinking skills. The objective of this study is to analyze the combined influence of digital literacy gained through AR, the ease of use of AR, and the implementation of AR-based learning strategies in contributing to the improvement of university students' critical thinking skills. This combined influence is consolidated into a single comprehensive study, expected to contribute to advancing previous theories for the progression of knowledge and to offer new insights in a different context. Furthermore, this study is anticipated to serve as a recommendation for educators and policymakers in designing more effective AR-based learning strategies. Thus, several research hypotheses are presented in Fig. 1.

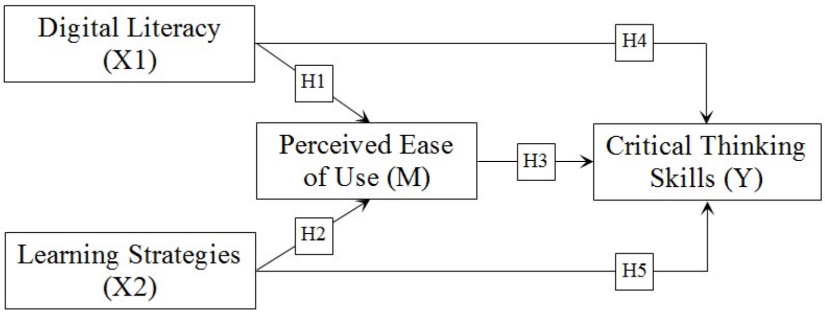

Fig. 1. Research hypothesis.

Additionally, beyond the empirical contributions outlined above, the practical implications of this research are expected to provide a strategic framework for educators and educational institutions in designing AR-based learning experiences. The findings from the review and study of the influence of digital literacy, learning strategies, and perceptions of the ease of use of technology on students' critical thinking skills will serve as a foundation for developing pedagogical approaches that align more closely with the evolving dynamics of education in the digital era. These results also hold the potential to guide educational technology developers in creating AR applications that are user-friendly, intuitive, and easy to navigate, thereby optimizing cognitive engagement, fostering independent learning, and significantly enhancing technology acceptance. As a result, students are likely to become more engaged in utilizing technology for their learning.

II. Literature Review

A. Digital Literacy

Digital literacy refers to the ability of students to understand their role and purpose in utilizing technology [20, 21]. Students are able to critically assess and to evaluate the technology they use, ensuring its appropriateness for their learning needs. For instance, when asked, 'What benefits do I gain from using this technology in learning?', they can readily explain the rationale behind its use, identify its strengths and weaknesses, and predict its long-term impact on their learning process. From the perspective of digital ethics, the responsible use of technology, rooted in digital literacy, will guide users toward improved digital security [22]. Enhanced digital security, in turn, minimizes the risks associated with the misuse of personal data and cyberattacks, particularly those affecting learning devices.

Digital literacy skills are very important for electronic engineering students, particularly in understanding complex electronic components that can often be challenging. Electronics has a strong theoretical concept [23, 24]. The theory underlying it is a compilation of various branches of science, including physics, chemistry, and mathematics, integrated into a unified framework. Therefore, it takes a strong understanding of flow and literacy to understand every inch of scientific facts from this field. This skill can be done by actively looking for relevant reference sources, utilizing the latest technology such as electronic simulation software, and following online communities that discuss the latest innovations in electronics. The more you practice, the better and more honed your digital skills will be.

B. Learning Strategies

Learning strategies are ways or methods used by students to acquire knowledge and skills. Strategy is also defined as tactics and self-control over the process that is passed to get the results as expected [25, 26]. The learning process is not just remembering, but being able to explain and understand. In this case, Raweewan (2020) [27] suggests that the development of effective learning strategies requires an understanding of the cognitive levels that students can achieve. Therefore, there are four basic steps in developing strategies: 1) setting objectives, 2) determining the approach system, 3) selecting techniques and methods, and 4) determining success criteria.

Some common learning strategies include metacognitive strategies, self-regulated learning, and many more. In the field of electronic engineering, metacognitive strategies are used in the process of reflection and evaluation of the understanding of basic concepts and the application of theory in practical situations [28, 29]. Students are asked to identify their strengths and weaknesses in understanding theory and practice, such as basic electronic circuits. With common questions such as 'What have I understood?' or 'What do I need to learn more?', they will realize their own abilities, that they know which learning approach to cock to increase the effectiveness of understanding. In addition, self-regulated learning is a learning strategy that gives students complete freedom and control over their own learning. Especially in electronics, self-regulated learning is applied during practicum. They are free to choose the project that will be made. The result of the project is an original work that they appreciate that has gone through an independent process.

C. Perceived Ease of Use (PEU)

A technology is useful if it is easy to use. This statement is one of the two main elements of the theory of Technology Acceptance Model (TAM) [30]. Developed in 1989 by Fred Davis [31], an American researcher, each dimension of this theory has been tested to predict a person will adopt technology. 1) a person will adopt technology if the technology is useful. 2) a person will adopt technology if the technology is easy to control and learn. Along with its development, TAM has added three other elements, namely 3) attitude towards using, if the easier and more useful a technology is, someone will have a positive attitude towards the technology. 4) behavioral intention to use, the more useful and easier a technology is to use, the more likely someone will use it in the long term. 5) actual system use, the level at which someone has actually used and adopted technology in real life.

D. Critical Thinking Skills

The concept of critical thinking has its roots in the thought of Socrates, an ancient Greek philosopher in the 5th century BC. Socrates was known for his dialectical method, called the 'Socratic Method,' in which he used questions to encourage others to consider and reflect on their views [32]. This method encourages analysis and evaluation of arguments, which are essential components of critical thinking. Later, in the early 20th century, American philosopher John Dewey developed this idea of thinking. In his book 'How We Think' published in 1933. Dewey introduced the concept of 'reflective thinking' which emphasized the importance of analysis, evaluation, and decision-making based on careful consideration. Later, in 1990, Peter Facione suggested that critical thinking is 'a purposeful and self-regulating judgment'. Critical thinking is a process of evaluation and analysis carried out with a clear purpose, as well as the ability to regulate and reflect on the thinking process itself. Until entering the 21st century, one of the qualities advocated in 21st century education is critical thinking. Amidst the rapid development of information technology and the complexity of global challenges, critical thinking is an indispensable skill for analyzing information, making informed decisions, and solving problems effectively.

In the field of electronics, critical thinking is applied in all aspects of learning, both theory and practice. Students who are able to master this ability will be adept at analyzing conditions, using logic, and predicting the long-term impact of each step taken. In addition, critical thinking also reflects a spirit of great responsibility, because this ability encourages a person to consider every decision carefully, not instantly, and dare to face the consequences that might occur.

III. Materials and Methods

This research was conducted with structured scientific steps. In line with Snyder (2019) [33], there are several scientific steps in research. The first step in this research is to conduct a literature analysis to identify research gaps. This stage is carried out to review various previous studies so that areas or variables that have not been widely explored are found. Based on the results of the literature analysis, hypotheses were formulated to test the relationship between relevant variables. Furthermore, methodology selection is carried out in accordance with the research objectives. Once the method is established, data is collected and analyzed systematically, where to analyze the relationship between existing variables, the correlation method is applied.

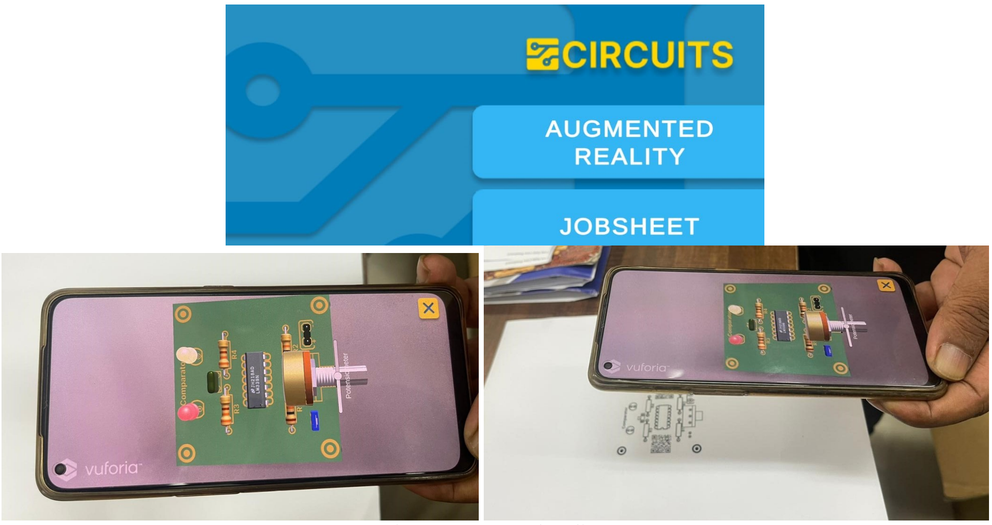

Fig. 2. Augmented reality.

This research is a quantitative study with a correlational approach. According to Creswell (2017) [34], a correlation study is quantitative research that uses statistical methods to measure the relationship between two or more variables [34]. Therefore, this research aims to identify the relationship between digital literacy, learning strategies using AR, and perceived ease of use of AR, on students' critical thinking skills. The population in this study were all students of the Engineering Faculty, Universitas Negeri Padang, while the sample focused on students majoring in Electronic Engineering at the Engineering Faculty, Universitas Negeri Padang. The research sample consisted of 221 students selected by purposive sampling technique.

In the first step, AR technology was implemented through practicum sessions in the basic electronic components course. In this practicum, an m-learning strategy is applied, where students are given the opportunity to use the AR application using a smartphone. The applied AR contains materials about basic electronic components. Then in the display that AR appears, there are also animations such as electric current and lights that turn on. After they used AR in the learning process, data collection was conducted to assess their digital literacy, learning strategies, perceived ease of use, and critical thinking skills. Fig. 2 shows an overview of the AR technology implemented.

A. Data Collection

The data collection stage of the research was carried out in several stages. Starting from determining the instrument of each variable, conducting trials to validate the instrument, collecting the main data, then analyzing and interpreting the data.

The research instrument was adopted from prior research that has been valid. The measurement of students' digital literacy used statement items from Reddy [35] and Lukitasari [36]. The instrument to evaluate student learning strategies was adopted from McCord's study [37]. Furthermore, the instrument used to evaluate student perceptions in the ease of using AR was adopted from the research of Thi Uyen Nguyen [38] and Yao [39]. Then, the instrument to measure the level of students' critical thinking skills was adopted from Ni'mah research [40]. All of these instruments have been proven valid in measuring related factors in previous studies. However, there are differences in population and sample characteristics between previous studies with the current study. Therefore, the validity and reliability test of the instrument is still carried out through a pilot study to validate the adopted instrument [41]. The pilot test was conducted on 30 students outside the main sample. After the instrument was declared valid, then the research was carried out on the set sample.

After the instrument was declared valid through an initial trial, the measuring instrument was loaded into a Google Form digital questionnaire. Data collection was carried out using a cross-sectional survey, which is a survey conducted immediately to students shortly after they use AR applications for learning, so that the responses given can describe their perceptions directly [42]. The measurement scale used is a 5-level Likert (1–5), to assess their level of agreement or disagreement with each statement [43].

Subsequent to obtaining the necessary data, it was analyzed and processed for interpretation. Table 1 shows the demographic data of respondents consisting of gender, domicile or region of residence, and daily mobile usage.

Table 1. Respondents profile

Sample characterization		Frequency	Percent
Gender	Male	146	66.06%
	Female	75	33.94%
	Total	221	100%
Domicile	Urban	197	89.14%
	Rural	24	10.86%
	Total	221	100%
Daily mobile usage	<= 3 h	68	30.77%
	4–6 h	100	45.25%
	> 6 h	53	23.98%
	Total	221	100%

Table 1 shows the profile of respondents consisting of gender, domicile, and duration of mobile usage per day. First, gender. There were 146 male respondents, and 75 female respondents. This comparison makes a significant percentage ratio of 66.06% and 33.94%. Gender differences can cause different perspectives in terms of technology adoption and acceptance of AR in the learning process. Men and women may have different preferences towards the use of technology, which may affect how they utilize AR in improving critical thinking skills. Seen in the table, male respondents dominate.

The two domiciles are urban and rural. There are 197 respondents or 89.14% who live in urban areas, and 24 respondents or 10.86% who live in rural areas. It should be noted that although the majority of respondents live in urban areas, this is due to the location of the campus in the middle of the city. However, many of them actually come from rural areas, so their original residential backgrounds remain varied. Neighborhoods differ in terms of access to technology, educational infrastructure, and exposure to digital innovations. Respondents from urban areas may be more accustomed to using digital technologies, including AR, compared to those living in rural areas, which may affect the effectiveness and adoption rate of AR in education.

Lastly, there is the duration of mobile usage per day. Respondents who use mobile phones for less than or equal to three hours totaled 68 respondents or 30.77%, four to six hours per day totaled 100 respondents or 42.52%, and 53 respondents around 23.98% used mobile phones for more than six hours per day. These characteristics will cause differences in the level of digital literacy and technology usage habits, which measure the extent to which respondents are familiar with technology, and how this can impact their readiness to use AR to improve critical thinking skills.

B. Data Analysis

After the data was collected, initial analysis was carried out through data tabulation using Microsoft Excel, then continued with Structural Equation Modeling (SEM) analysis using SmartPLS 3 software. The strong reason for choosing SEM with SmartPLS is because this method is built on the basis of measurement models and structural models [44]. Previous researchers have also proven the superiority of PLS-SEM, with some of its practices even exceeding the standard. In addition, this analysis does not require classical assumption tests such as normality, homogeneity, and linearity of data, because the SEM model is based on correlation, not on causality models [45].

Network analysis was applied to visualize the relationships between dimensions in the system using Jeffreys's Amazing Statistics Program (JASP) software. This type of analysis was chosen because it is able to identify multidimensional interaction structures [46]. Dimensions in network analysis refer to research variables. The variables are represented as nodes, while the relationships between nodes are described as edges [47]. So that the specific results obtained are known relationship patterns and the strength and direction of association between variables. That is the advantage of this analysis compared to conventional statistics which tend to focus on linear or direct relationships.

Edges are connections between nodes that indicate relationships or associations between them. Patterns between systems can be recognized through this analysis, where the strength and direction of the relationship are indicated by the thickness and color of the edges. The measure used to determine the importance of a node in the network, referred to as centrality, consists of betweenness, closeness, and strength indices. The strength index is considered the most reliable due to its ability to show the extent to which a node is directly connected to other nodes, thus illustrating how much influence it has in influencing the network as a whole. Meanwhile, closeness measures how close or connected a node is to other nodes in the network.

Nodes with high closeness values can be accessed faster than other nodes, indicating that they are strategically positioned to spread information or influence throughout the network efficiently. Then, betweenness indicates how often a node is in the path between two other nodes in the network. In other words, betweenness measures a node's role as an intermediary or connecting different parts of the network.

Nodes with high betweenness have important influence because they are often the main link between nodes, so changes to these nodes can affect the flow of information or influence within the network. The last category, expected influence, in network analysis predicts the potential impact or spread of a node's influence across the network, taking into account not only its direct connections, but also the strength and reach of those connections through secondary or indirect pathways. Nodes with high expected influence are expected to have a broader or more significant impact on network dynamics, as their connections can influence or spread effects to different parts of the network.

IV. Result and Discussion

In this section, the results of the study are presented. The data obtained is analyzed to interpret the findings and relate them to relevant literature. The instruments used in data collection have gone through a validation process according to scientific research procedures, thus ensuring that the data is reliable, valid and accurate. The findings of this study are then compared with previous research to evaluate their compatibility or identify any differences that may exist.

A. Validity and Reliability

The first analysis is the construct validity test, which aims to ensure that the research instrument actually measures the intended concept or construct [48]. At this stage, there are two types of validity tests, namely convergent validity assessed through outer loading and Average Variance Extracted (AVE), and discriminant validity examined through the Fornell-Larcker and Heterotrait-Monotrait Ratio (HTMT) [49]. In addition, a reliability test was also conducted which included Composite Reliability (CR) and Cronbach's alpha.

Table 2. Convergent validity and reliability

Variable	Item	Outer loading	Cronbach's alpha	CR	AVE
Digital literacy (DL)	DL1	0.814	0.800	0.870	0.626
	DL2	0.846			
	DL3	0.739			
	DL4	0.761			
Learning strategy (LS)	LS1	0.769	0.820	0.874	0.581
	LS2	0.766			
	LS3	0.762			
	LS4	0.788			
	LS5	0.723			
Perceived ease of use (PEU)	PEU1	0.785	0.865	0.909	0.713
	PEU2	0.882			
	PEU3	0.875			
	PEU4	0.833			
Critical Thinking Skills (CTS)	CTS1	0.779	0.897	0.919	0.619
	CTS2	0.811			
	CTS3	0.810			
	CTS4	0.779			
	CTS5	0.784			
	CTS6	0.746			
	CTS7	0.798			

Table 2 shows that convergent validity and data reliability have been met, as evidenced by the outer loading value above 0.7, Cronbach's alpha and Composite Reliability (CR) above 0.7, and Average Variance Extracted (AVE) above 0.5 [50]. This indicates that each construct is able to measure the variable in question consistently and accurately, and has good validity in explaining the variance of the related indicators.

Table 3 displays the results of the discriminant validity analysis that is in accordance with the Fornell-Larcker criteria [24]. This can be seen from the square root value of the Average Variance Extracted (AVE) of each construct, namely Critical Thinking Skills (CTS) = 0.787, Digital Literacy (DL) = 0.791, Learning Strategies (LS) = 0.762, and Perceived Ease of Use (PEU) = 0.845, which are on the diagonal of the table. These values are greater than the correlations between constructs that are off the diagonal, such as the correlation between CTS and DL (0.670) or between PEU and LS (0.553). Thus, each construct is better able to explain its own indicators than other variables, indicating that discriminant validity has been achieved. This indicates that the model can distinguish well between different constructs.

Table 3. Discriminant validity

Variable	CTS	DL	LS	PEU
CTS	0.787			
DL	0.670	0.791		
LS	0.722	0.588	0.762	
PEU	0.591	0.485	0.553	0.845

Table 4. Heterotrait-Monotrait Ratio (HTMT)

Variable	CTS	DL	LS	PEU
CTS				
DL	0.787			
LS	0.835	0.722		
PEU	0.665	0.581	0.653	

HTMT represents the ratio between the average correlation of items measuring different constructs and the geometric mean correlation of items measuring the same construct, thus providing an indicator of discriminant clarity between constructs. The value of the requirement for the fulfillment of this test is below 0.9 [51]. However, a value below 0.85 better illustrates that the constructs are conceptually completely different, so the discriminant validity is stronger. As seen in Table 4, the highest construct value is 0.835. It can be concluded that this value is sufficient to prove that discriminant validity has been achieved, and the constructs in the study are different from each other.

B. Hypothesis Testing

Following the validity and reliability tests, data analysis was continued with hypothesis testing using Partial Least Squares Structural Equation Modeling (PLS-SEM). This test aims to test the relationship between the variables in the research model, both direct and indirect relationships, and measure the strength and significance of the relationship. The results of this hypothesis testing are presented in Fig. 3 (T-Statistic result) and Fig. 4 (P-Value result).

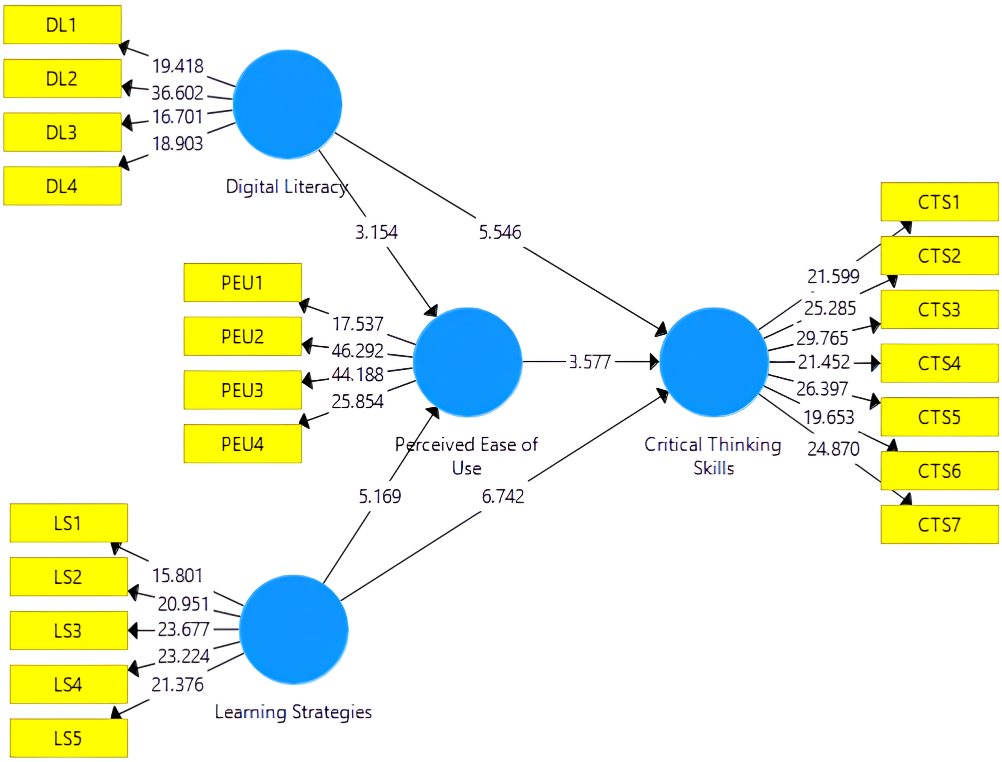

Fig. 3. T-Statistic result.

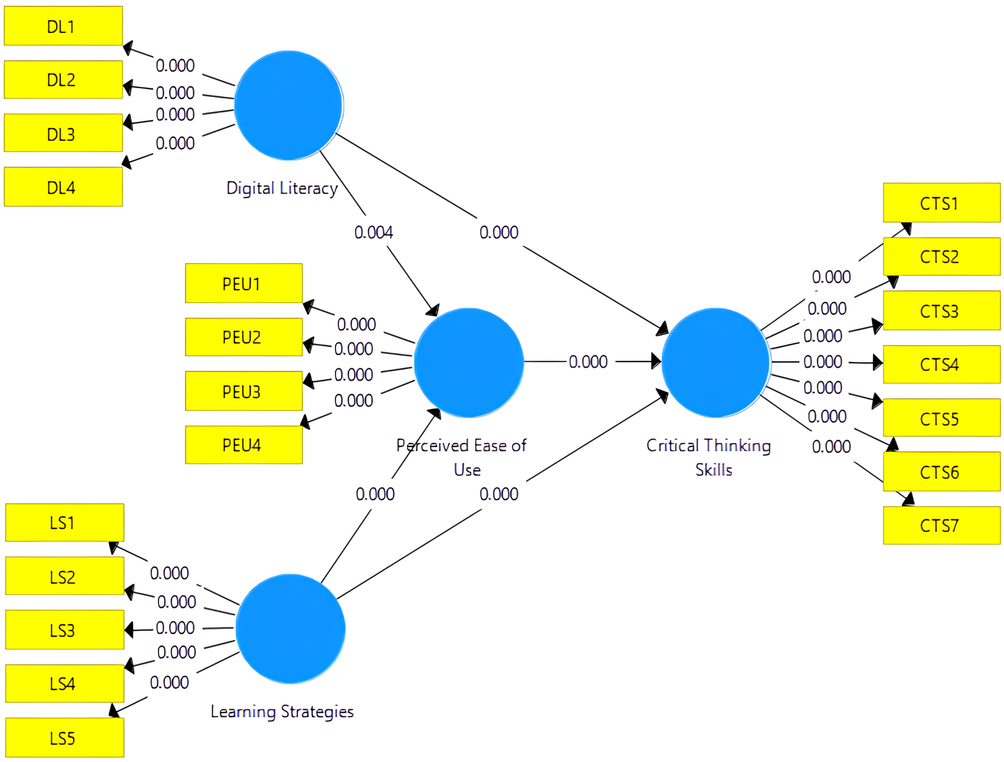

Fig. 4. P-Value result.

Table 5. Direct hypothesis result

Hypothesis	β	T-Statistic	P-Value	Result
H1: Digital literacy > Perceived Ease of Use	0.245	3.154	0.004	Accepted
H2: Learning strategies > Perceived Ease of Use	0.408	5.169	0.000	Accepted
H3: Perceived Ease of Use > Critical Thinking Skill	0.201	3.577	0.000	Accepted
H4: Digital literacy > Critical Thinking Skill	0.326	5.546	0.000	Accepted
H5: Learning strategies > Critical Thinking Skill	0.419	6.742	0.000	Accepted

Based on the results of direct hypothesis testing displayed in Table 5, all proposed hypotheses are accepted, because the T-Statistic value of each hypothesis is greater than 1.96 and the P-Value is smaller than 0.05 [52], which indicates the significance of the relationship between variables. H1: Digital Literacy has a significant influence on Perceived Ease of Use with a coefficient value $\beta = 0.245$, T-Statistic 3.154, and P-Value 0.004, so this hypothesis is accepted. This means that the higher the digital literacy, the more positive the perceived ease of use of technology. These results support the research of Net *et al.* [53]. Given the positive influence of digital literacy on perceived ease of use of technology, programs that improve digital literacy in the learning process and campus environment activities can help in the adoption of new technologies, including AR technology.

H2: Learning Strategies also have a significant influence on Perceived Ease of Use with a coefficient value β = 0.408, T-Statistic 5.169, and P-Value 0.000, indicating that effective learning strategies contribute to increase perceived ease of use of technology. This finding has important implications for the development of digital learning programs. By understanding that effective learning strategies can increase perceived ease of use, educators and technology developers can design better curriculum and learning tools. For example, Kimathi and Zhang [54] showed that positive experiences with learning strategies can increase students' beliefs in the ease of use of e-learning systems.

H3: Perceived Ease of Use has a significant effect on Critical Thinking Skills with a coefficient value β = 0.201, T-Statistic 3.577, and P-Value 0.000, indicating that the perceived ease of use of AR can support the improvement of critical thinking skills. Research by Tennakoon [55], supports these findings by showing that students who have a positive perception of the ease of use of technology tend to be more able to apply critical thinking skills in the context of learning. In addition, research by Tennakoon showed that the use of technology that supports interaction and collaboration can improve students' critical thinking skills. These findings have important implications for the development of digital learning programs. By understanding that PEU can improve critical thinking skills, educators and technology developers can design better curriculum and learning tools. For example, the use of intuitive and easy-to-use technologies can encourage students to more actively participate in discussions and analyses, which are important components of critical thinking.

H4: Digital Literacy also has a direct influence on Critical Thinking Skills with a coefficient value $\beta = 0.326$, T-Statistic 5.546, and P-Value 0.000, which means that the better one's digital literacy, the higher the critical thinking skills. Research by Amin [56] supports these findings by showing that good digital literacy is positively related to students' critical thinking skills in the context of online learning. In addition, research by Indah [57], showed that students who have high digital literacy are better able to apply critical thinking skills in complex situations.

H5: Learning Strategies have the greatest influence on Critical Thinking Skills with a coefficient value β = 0.419, T-Statistic 6.742, and P-Value 0.000, indicating that good learning strategies significantly improve critical thinking skills. Research by Palloan [58], supports these findings by showing that good learning strategies are positively related to students' critical thinking skills in the context of online learning. By understanding that good learning strategies can improve critical thinking skills, educators can design programs that focus more on developing effective learning strategies. For example, the integration of project-based and collaborative learning methods can help students to be more active in analysing and evaluating information [59].

In addition to the direct effect tested in the previous hypothesis, the results also showed that perceived ease of use managed to become a significant moderator variable in the relationship of digital literacy and learning strategies to critical thinking skills through indirect effects. These results are shown in Table 6.

The relationship between digital literacy and critical thinking skills is significantly moderated by perceived ease of use with coefficient $\beta = 0.049$, T-Statistic 2.438, and P-Value 0.015. These results indicate that perceived ease of use strengthens the influence of digital literacy on critical thinking skills. That is, when students have a better perception of the ease of use of AR, the influence of digital literacy on improving critical thinking skills becomes stronger. The relationship between learning strategies and critical thinking skills is also significantly moderated by perceived ease of use with coefficient β = 0.082, T-Statistic 2.830, and P-Value 0.005. This indicates that perceived ease of use of AR strengthens the influence of learning strategies on critical thinking skills. The higher the perceived ease of use of technology, the stronger the influence of learning strategies on students' critical thinking skills.

Table 6. Indirect hypothesis result

Hypothesis	β	T-Statistic	P-Value	Result
H1: Digital literacy > Perceived Ease of Use > Critical Thinking Skills	0.049	2.438	0.015	Accepted
H2: Learning strategies > Perceived Ease of Use > Critical Thinking Skills	0.082	2.830	0.005	Accepted

C. Network Analysis

The network analysis conducted produces centrality plot data that shows the role of each variable in the network. The results are displayed in Fig. 5 and explained in more detail with specific numbers in Table 7. Additionally, Fig. 6 presents a network visualization that illustrates the relationships between the analyzed variables. Centrality plot, there are four centrality metrics, namely betweenness, closeness, strength, and expected influence [60, 61].

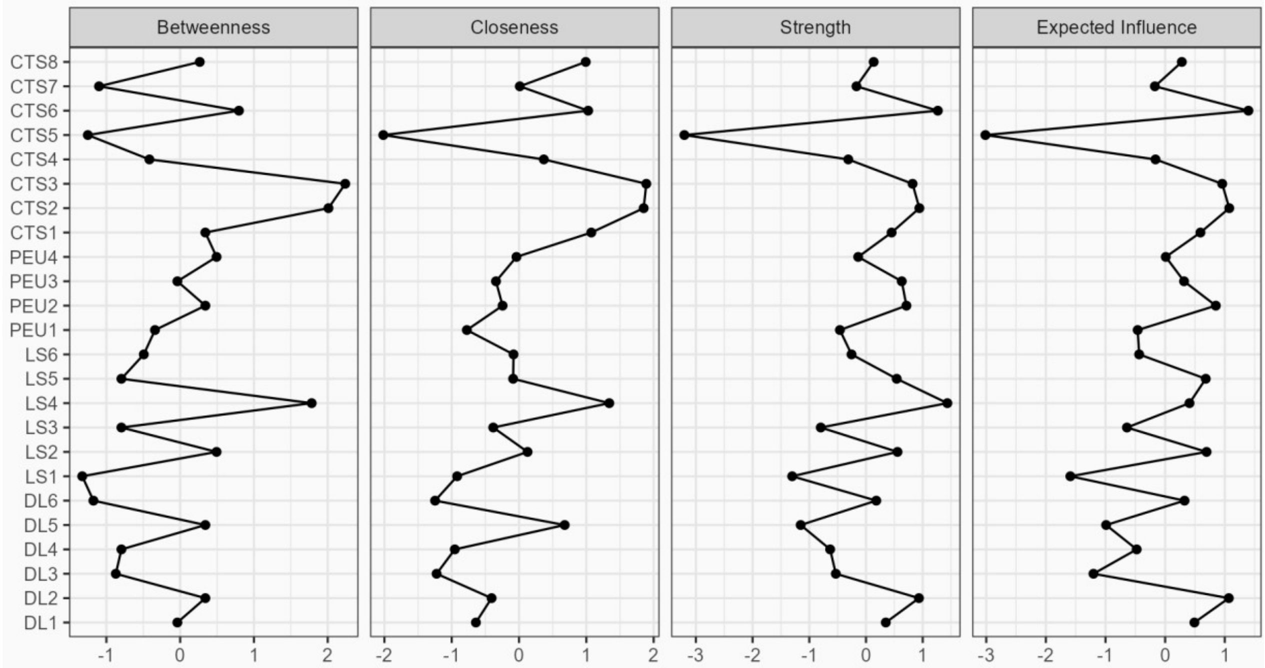

Fig. 5. Centrality plot.

First, in the betweenness metric, the item with the highest value is CTS3, which has a value of 2.238. Then CTS2 with a value of 2.010. Critical thinking skills act as a dependent variable, but still show an important position in the network with a high betweenness value, meaning that this ability is strongly influenced by its connection with other variables in the network. The betweenness category shows how often a node is the shortest path between two other nodes. Nodes that have a high betweenness value are inferred to be strategic links, so influence flows between other nodes. The CTS3 item statement is "I strive to learn as many professional skills as possible, even though I don't know when they will be used." This sentence leads to a student's desire to continue learning and developing professional skills, which are very important in the development of critical thinking skills even though they do not know when they will be implemented. The AR application used gradually provides professional training for students. Its features are designed to direct users to practice. Scenarios in AR will lead to a critique of technology, which in turn makes students more challenged and try to prepare for things to come [62, 63]. Meanwhile, CTS2 has an indicator that reads, "I am open to various opinions and try to find common ground from differences." This indicator describes the attitude of openness and the ability to adapt in discussions, because with the discussion a critic will be born and develop.

Second, the closeness metric shows that the most highly positioned items are CTS3 and CTS2, with values of 1.891 and 1.852 respectively. This result is consistent with the findings on the betweenness metric, where these two items also show significant values. The strong connection between CTS3 and CTS2 in the network reflects how these indicators act as efficient interaction points. Although CTS has a position as the dependent variable, its centrality in the network proves that this ability is significantly influenced by other independent variables, such as digital literacy, learning strategies, and perceived ease of use. Good connectivity will effectively flow information, thus enhancing the overall development of students' critical thinking skills [64]. The consistent values of these two metrics make it clear that the CTS not only reacts to the influence of other variables, but also becomes the center of interaction within the network.

Table 7. Centrality measures per variable

Variable	Betweenness	Closeness	Strength	Expected influence
DL1	−0.038	−0.641	0.349	0.491
DL2	0.341	−0.408	0.933	1.067
DL3	−0.872	−1.225	−0.532	−1.202
DL4	−0.796	−0.954	−0.632	−0.477
DL5	0.341	0.679	−1.152	−0.990
DL6	−1.176	−1.247	0.181	0.325
LS1	−1.327	−0.919	−1.302	−1.589
LS2	0.493	0.126	0.555	0.694
LS3	−0.796	−0.383	−0.798	−0.641
LS4	1.782	1.341	1.435	0.408
LS5	−0.796	−0.087	0.541	0.681
LS6	−0.493	−0.082	−0.255	−0.436
PEU1	−0.341	−0.775	−0.460	−0.461
PEU2	0.341	−0.244	0.712	0.849
PEU3	−0.038	−0.342	0.630	0.317
PEU4	0.493	−0.038	−0.138	0.011
CTS1	0.341	1.074	0.451	0.592
CTS2	2.010	1.852	0.941	1.075
CTS3	2.238	1.891	0.821	0.957
CTS4	−0.417	0.368	−0.312	−0.162
CTS5	−1.251	−2.016	−3.203	−3.014
CTS6	0.796	1.027	1.267	1.396
CTS7	−1.100	0.012	−0.168	−0.172
CTS8	0.265	0.991	0.135	0.280

Third on the strength metric, the item with the highest value is LS4, having a value of 1,435. Below it, there is item CTS6 with a value of 1,267. The strength metric measures the number of direct connections a node has, showing how much interaction the item has in the network. A high value on LS4 indicates that this item has many direct connections, thus acting as a strong node in the network. As an indicator of the learning strategy variable, LS4 "When I am confused about something I read, I go back and try to figure it out myself" reflects the ability to map and manage self-understanding, which is closely related to metacognition. In utilizing AR, students actively try to solve problems through reflection on their understanding of knowledge [65]. A fair chance is given to each user to prove their curiosity through simulations provided in this technology [66]. The proof is unlimited, so all possibilities are possible and will generate new curiosity [67]. This cycle repeats itself, indicating that they are thinking critically. On the other hand, although CTS6 has a slightly lower score, its position remains significant. The indicator "I conduct systematic and comprehensive analysis from various points of view in learning" reflects that Critical Thinking Skills have some important connections that support interactions with other variables.

The high expected influence value of CTS6 indicates that this item has great potential to influence interactions in the network, not only on its immediate connections, but also on other more distant nodes. The indicator CTS6, which reads "I conduct systematic and comprehensive analysis from various points of view in learning", is a sign of depth of thinking, so it has a strong influence on thinking patterns across the network. The high expected influence value indicates that this item has a pervasive impact, affecting both direct and indirect connections. Thus there is a kind of "center of understanding," where influence flows through and strengthens the connectivity of other items related to learning strategies and digital literacy.

Based on the centrality metric analysis, there are several recommendations that are worth considering. First, with the strategic position indicated by the high betweenness value in CTS, strengthening critical thinking skills should be the main pillar in curriculum transformation. Training programs to hone the development of these skills should be introduced preventively to improve connectivity and digital literacy factors and student learning strategies. Given the influence of the independent variables digital literacy, learning strategies, and perceived ease of use on CTS, it is important to design learning activities that synergize these three variables. In addition, the high strength value of item LS4, it is recommended to strengthen the connection between these variables by providing more opportunities for interaction, through collaborative activities, group discussions, or team-based projects in accordance with the LS4 indicator, because the way to find a solution to a problem is to question and analyze the problem. CTS6 indicator of sharing views and opinions shows the potential to influence other variables in the network, it is best to utilize CTS6 in teaching strategies that promote interaction and collaboration between students. Another recommendation is to conduct periodic evaluations of the development of students' critical thinking power and independent variables. Careful monitoring of students' progress in critical thinking skills.

Fig. 6 illustrates the network of relationships between various variables that fall into four groups, consisting of: group 1 visualized in red is the digital literacy variable, group 2 represented by blue is the learning strategies variable, group 3 marked in green is the critical thinking skills variable, and group 4 in yellow is the perceived ease of use variable, with a total of 24 nodes. Interconnections are clearly visible between the variables of each group based on the thickness and thinness of the lines connecting each node consisting of variable items. Each node is represented by a colored circle corresponding to its group, and the connecting lines show the relationship or association between the nodes [68]. The connecting lines indicate the strength of the relationship between the nodes. Thicker lines indicate stronger relationships, while thinner lines indicate weaker relationships.

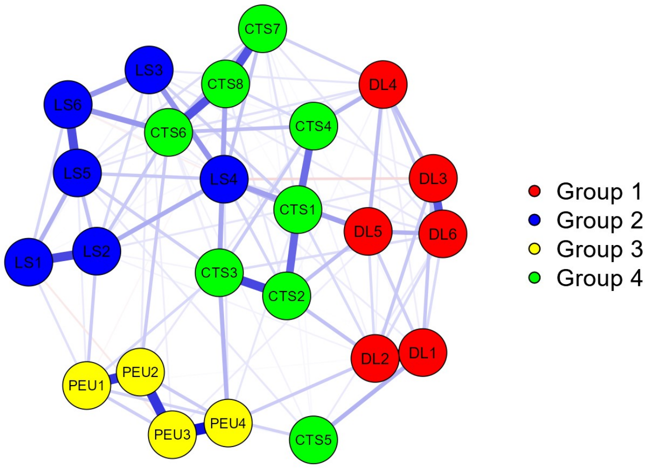

Fig. 6. Network visualization.

It can be seen that the nodes of the CTS group are highly connected to the learning strategies group. Nodes from the learning strategies group (blue) have many strong and dominant relationships, both with fellow nodes in the group and with other groups. This means that the use of AR applications in learning not only supports the development of the critical power of the mind directly, but also strengthens its connection with learning strategies. Vale [69] suggests active learning strategies that simultaneously integrate intellectual, social, and physical. The AR application used not only engages cognitively through analysis and reflection, but also collaborates with peers, establishes social relationships and fun is also obtained. In addition, the physical elements of using AR technology, such as moving around in an interactive learning space, add to the learning experience. In addition, the link between CTS skills and digital literacy is also very close. AR provides a great opportunity to practice digital literacy skills. In simulations or interactive tasks, students are faced with challenges that require sharp problem solving, careful evaluation of information, and the formation of arguments based on relevant data [70]. The deepest meaning that can be taken is that a technology presented to them is not only a learning tool, but more than that it aims to make students able to recognize, assess, and sort out the information obtained. This technology encourages students to not only passively receive information, but also actively engage in the process of data criticism, because the smarter the user, the more benefits that can be obtained [71]. Thus, AR not only serves as a learning tool, but also as a reminder that critical thinking skills and digital literacy are two things that cannot be separated, especially in an increasingly complex and digitally connected world.

Furthermore, nodes from the perceived ease of use group (yellow) have more limited connections compared to the other groups. However, despite their fewer connections, they are still connected to some nodes from the learning strategies and CTS groups. Perceived ease of use has some influence in the network, although not as strong as the other groups, according to its role as a moderator variable in the TAM model [72]. As a moderator variable, perceived ease of use affects the relationship between other variables, so its presence is still important even though it is not directly connected to many nodes, because its function is more to strengthen or weaken the influence of other variables in the technology acceptance process [73].

Learning strategies and critical thinking skills are important factors in this network as they have strong connections with other groups of variables. Digital literacy also shows strong connections with variables from other groups, suggesting that digital literacy plays a role in supporting critical thinking skills and learning strategies. Perceived ease of use had less influence in the network, but was still related to the other variables, which may suggest that ease of use of technology or learning tools influences, but does not directly dominate, the learning and critical thinking processes. Based on this analysis, learning strategies and critical thinking skills should be emphasized in interventions or training designed to improve digital skills and perceived ease of use of technology. The influence of digital skills in networks is predicted to increase the domino effect, improving critical thinking skills and supporting more effective learning strategies.

The analysis conducted both through Structural Equation Modeling (SEM) and network analysis, has successfully answered the objectives of this study. The results showed that digital literacy and learning strategies have a positive influence on students' critical thinking skills, both directly and indirectly through the perceived ease of use variable. The better students' digital literacy skills, the more their critical thinking skills improve. The more effective the learning strategy applied by students, the better the level of critical thinking skills in using AR. In addition, the ease of use of technology, described in the Technology Acceptance Model (TAM), while improving critical thinking skills directly, also affects students' digital literacy and learning strategies, making these variables interconnected.

Based on the findings of this study, there are several practical implications addressed to all parties involved in the learning process, be it lecturers as educators, educational staff, and AR application developers. Lecturers need to pay attention to the role of digital literacy and suitable learning strategies in improving students' critical thinking skills. Digital literacy training can also be a consideration to improve students' ability to utilize technology. In addition, learning strategies that are suitable for student abilities need to be adjusted. AR developers also need to design AR that is user-friendly and easily accessible. Therefore, developing policies that support the integration of technology in the curriculum and providing adequate technical support for students and lecturers will maximize students' critical thinking skills in a sustainable manner.

V. Conclusion

There is a positive reciprocal relationship cycle between digital literacy and students' critical thinking. The higher the digital literacy, the higher the critical thinking. The same applies to learning strategies. The better the strategy used, the higher the students' critical thinking. The model developed by Fred Davis, the Technology Acceptance Model (TAM), successfully moderates the relationship between digital literacy and learning strategies. There is an expansion of the theoretical understanding of TAM, especially in the context of technology-based learning in electronics engineering colleges generated through this study. Results show that perceived ease of use not only mediates the relationship between digital literacy and learning strategies, but also strengthens this relationship by improving students' critical thinking skills. All variables associated with perceived ease of use from TAM contribute positively to improving students' critical thinking. Thus, several suggestions and practical implications can be applied, such as consideration of the effective use of AR technology, curriculum development that incorporates the values of increasing digital literacy and appropriate learning strategies, and the development of AR applications that are user-friendly and easy to use.

The meaning that can be taken is that the technology presented to a learner is not only a tool in the learning process, but also useful to encourage students to be able to evaluate and criticize the technology, so that they can use it wisely. As the link between scientific ideas and students, educators must ensure that students not only learn but are also able to teach and develop them. Future research is recommended to discuss other factors that are very possibly related to AR in improving students' critical thinking that have not been widely explored in previous studies. Suggested factors such as students' emotional intelligence, technological support, environment, both quantitatively and qualitatively.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Thamrin Thamrin: Writing - original draft. Giatman: Methodology and Formal analysis. Muhammad Anwar: Writing - review & editing. Khairi Budayawan: Data curation. Delsina Faiza and Nur Diyana Kamarudin: original draft and Data curation. Alwen Bentri and Ernawati: Writing - review & editing. All authors have accepted the final version of the manuscript.

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