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Research article

Implementation of IoT-based STEM-Contextual learning with the MQTT protocol on the digital literacy skills of pre-service science teacher

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Abstract: The Internet of Things (IoT) with the Message Queue Telemetry Transport (MQTT) protocol in learning processes is one of the learning innovations in the digital era which has a significant role in students' digital literacy skills. Moreover, the STEM-contextual approach is in line with the demands of 21st-century learning. The authors attempt to integrate IoT with MQTT protocol in STEM-Contextual learning. This study aims to determine the results of the implementation of STEM-Contextual learning based on the IoT with the MQTT protocol on the digital literacy skills of pre-service science teachers. The research used a one-shot case study design. The research sample was pre-service science teacher students from Universitas Negeri Yogyakarta (UNY), totalling 43, and from Universitas Negeri Malang (UM), totalling 66, determined by convenience sampling technique. The research instruments used were a questionnaire sheet on digital literacy skills and an observation sheet on STEM-Contextual learning implementation. The quality of the instrument was analyzed using the content validity ratio, Fleiss Kappa, confirmatory factor analysis, and Rasch model. Data analysis of digital literacy skills used descriptive statistics, the conversion of quantitative to qualitative scales, and inferential statistics. The finding shows a significant positive effect of implementing IoT-based STEM-contextual learning with the MQTT protocol on the digital literacy skills of pre-service science teachers at UNY and UM. The total score of pre-science teachers of UNY is 70.98 in the High Performers category, while the pre-science teachers of UM are 67.52 in the Above Average Performers category.

Keywords: STEM-Contextual, Internet of Things, Message Queue Telemetry Transport, Digital Literacy Skills

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1 Introduction

Digital literacy skills, especially for pre-service science teachers, are an unavoidable demand. The reason is that all levels of education demand educators to be more creative in teaching students (Kasmaienezhadfard et al., 2015; Xhomara & Uka, 2023). Besides teaching science in the classroom with innovative learning models and approaches, educators also emphasize using digital learning technology. Along with the development of the

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times, education is demanded to move quickly in line with technological advances, especially with the Industrial Revolution 4.0 and Society 5.0, which makes it easier to adjust between technological advances and the human need to continue learning. The revolution has brought changes in various aspects of human life. One of them is that the education system must move quickly in line with technological advances using computer-based learning media, the Internet of Things, big data, entrepreneurship, and internships. Science learning, which integrates these components, will produce graduates with science, digital, and human literacy skills. The authors consider that the curriculum and learning process at the education level must be able to lead and develop students ready to face the era of the Industrial Revolution with an emphasis on the fields of science, technology, engineering, and mathematics (STEM). When associated with contextual science, the authors propose an approach that integrates STEM with context into a new term, STEM-C, to make science learning more meaningful.

Technological advances in the field of artificial intelligence (AI), the Internet of Things (IoT), and 3D printing have a significant impact on learning patterns, which will lead to meaningful science learning (Mantovani et al., 2021). The competencies that must be possessed by in-service science teachers and pre-service science teachers besides the pedagogy and content knowledge (PCK) skills are being able to teach the digital technology that is currently developing, especially how to integrate IoT in the science learning process. On this foundation, knowledge of pedagogy, content, and technology is essential and has resulted in a new approach about a decade ago called technological pedagogical content knowledge (TPACK) (Handayani et al., 2023; Voogt et al., 2013). Mastering TPACK will encourage in-service and pre-service science teachers to integrate technology and pedagogy into the education process. One of the actual forms of TPACK implementation in the current era of digital technological advances is a form of learning by utilizing the Internet of Things (IoT), which is very diverse (Almaiah et al., 2022; Hu et al., 2023). The existing advances must be supported by human resources who can understand and apply how to use technology appropriately. This reason is the trigger that makes digital literacy skills must be mastered by all in-service science teachers and pre-service science teachers.

Digital literacy skills are one indicator of the development of a nation or country in the era of revolution 5.0. The percentage of Indonesia's digital literacy skills in 2023 is still low, with a score of 62%, the weakest in ASEAN countries (Zahra, 2023). This is caused by various factors, including the lack of equitable development and use of Internet-based learning devices, especially the Internet of Things (IoT), combined with the MQTT protocol. Implementing multimedia and using information technology, especially IoT, with the MQTT protocol in schools by teachers is still not optimal (Bahri et al., 2022; Masyhura & Ramadan, 2021). The main problem of general non-optimal utilization of information technology, especially IoT with the MQTT protocol, will significantly impact digital literacy skills. IoT with MQTT protocol is a "Smart Device" system as a form of media innovation or science laboratory tools in the digital era that can connect and communicate with users and other systems in synchronous and asynchronous learning (Dhingra et al., 2019).

The IoT-based science laboratory tool with MQTT protocol can integrate into a computerized system and generate data more efficiently and accurately, indirectly fostering students' digital literacy skills. The author proposes an IoT-based science practicum tool with MQTT protocol to be implemented in STEM-Contextual learning. Although various efforts have been undertaken to make STEM learning more effective, educators face difficulties finding how to teach appropriately (Çevik & Bakioğlu, 2022). Science has four dimensions that must be covered in the learning process: science as a way of thinking, science as a way to investigate, science as knowledge, and science and its relationship with technology and society (Chiappetta & Koballa, 2010). Integrating science, technology, engineering, and mathematics in authentic contexts can be as complex as global challenges that demand a new generation of STEM experts (Kelley & Knowles, 2016). The authors consider that such conditions require new learning patterns that can cover all dimensions of science and integrate TPACK in science learning, namely IoT-based STEM-C learning with the MQTT protocol.

Science learning using IoT is based on TPACK, especially in the digital era, which seamlessly integrates technological, pedagogical, and content knowledge to enhance students' engagement and understanding. The Internet of Things (IoT) is a technology that has developed rapidly and is implemented in various sectors, including science education as a form of scientific progress in a country. IoT is a network of devices interconnected through the internet using sensors to automatically collect, share, and analyze data (Gubbi et al., 2013; Mouha, 2021). In the context of science education, the application of this technology in education not only has an impact on the effectiveness of learning in the short term but also has a long-term impact on educational outcomes, both in terms of improving student skills, the efficiency of the education system, and the readiness of graduates to face the digital-based world of work (Al-Fuqaha et al., 2015). The use of devices based on IoT, such as smartboards, sensors, and wearables, enables more dynamic interactions between students and subject matter (Ghashim & Arshad, 2023; Pogoh et al., 2025). For example, in a science laboratory, IoT sensors can collect real-time data, which students then analyze to improve their understanding of scientific concepts (Al-Ali & Aburukba, 2015).

According to the background description, this study attempts to promote how the TPACK framework is implemented in science learning, especially in the digital era. Its goal is to foster students' digital skills by implementing IoT-based STEM-C learning using the MQTT protocol. The study's questions are as follows.

a. How is the STEM-C learning approach implemented in the science learning model?
b. What is the role of IoT-based science laboratory equipment with MQTT protocol in the science learning model?
c. What are the results of implementing IoT-based STEM-C learning with MQTT protocol on pre-service science teachers' digital literacy skills?

The STEM-C approach has an essential role in the science learning process because besides facilitating higher-order thinking skills, if integrated with the TPACK approach, it will also improve learners' digital skills. However, few formal studies have analyzed the results of STEM-C implementation on digital literacy skills. The findings of this study will be part of a form of science learning innovation in the digital era that science educators can adopt to develop and implement science learning with an IoT-based STEM approach and the MQTT protocol.

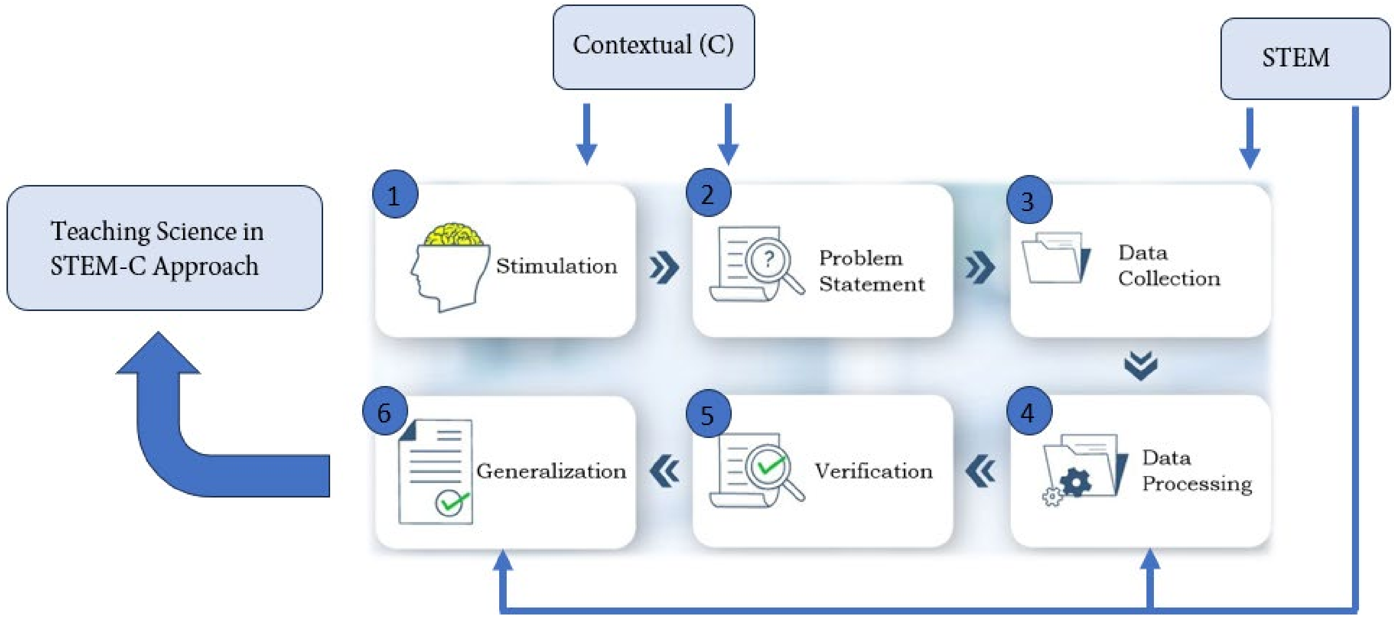
2 Literature review

2.1 Science Learning with STEM - Contextual Approach

Kilbane & Milman (2014) stated that learning design is a systematic and scientific approach to designing and organizing learning materials (Kilbane & Milman, 2014). One of the science approaches that can be used in classroom learning is the STEM approach. The STEM approach is learning by combining four elements: Science, Technology, Engineering, and Mathematics (Ibrahim & Şeker, 2022; Lämsä et al., 2023; Simeon et al., 2022). The STEM approach aims to enhance students' skills to be creative and innovative and to be able to solve problems creatively because STEM integrates learning from various aspects of the surrounding environment. In other terms, aspects of the surrounding environment are known as contextual. Contextual learning integrated with STEM (STEM-C) will enable educators to link the science material that is being taught with the real-world situation of the students and encourage students to make connections between the Science, Technology, Engineering, and Mathematics that they possess and their application in their lives as members of the family and society.

Learning design will be systematic if it is implemented in the form of a learning model. As stated by Joyce et al. (2015), the learning model is a plan used to guide classroom learning or learning in tutorials and to determine learning tools, including books, films, computers, curriculum, and others. The STEM-C approach will be implemented in the discovery learning model. Implementing this learning model will encourage students to develop intellectual potential, have internal motivation, learn to know, and maintain the memory of what is learned (Carin & Sund, 1989; Vysotskaya, et al., 2015). The stages in implementing the discovery learning model are stimulation, problem statement, data collection, data processing, verification, and generalization, as shown in Figure 1.

Figure 1. Stages of Discovery Learning Model



Jerome Bruner introduced Discovery Learning as an inquiry-based learning (Arends, 2012). The rapid development of digital technology in education in the current era has influenced how the discovery learning model is implemented in the classroom. IoT (Internet of Things) with MQTT protocol in the discovery learning model is implemented when students go to the data collection stage, which facilitates the efficient and accurate ease of data collection. The context of this study integrates how STEM-C is taught in a discovery learning model in which there is an element of using IoT with the MQTT protocol as a practical form of TPACK implementation in science learning.

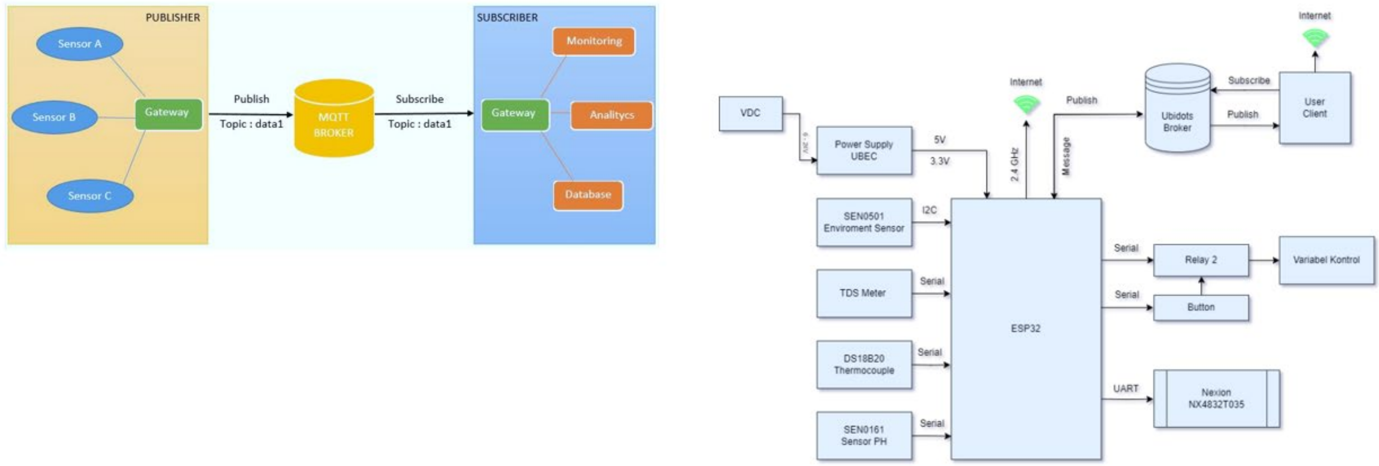
2.2 Internet of Things with Message Queue Telemetry Transport protocol

The Internet of Things (IoT) has emerged as an essential technology with numerous applications in various fields, including the learning process. The IoT originated in several earlier technologies: widespread information systems, sensor networks, and embedded computing (Serpanos & Wolf, 2018). The IoT is the interaction between the physical and digital worlds using many sensors and actuators. Moreover, the IoT is also defined as a paradigm in which computing and networking capabilities are embedded in any comprehensible object (Guptha, 2020; Serpanos & Wolf, 2018). The authors state that the objective of the IoT is to enable physical and virtual 'everything' to be connected anytime, anywhere, with anything and anyone. Various hardware, software, and communication technologies are integrated to provide solutions that allow objects to be sensed or controlled remotely across existing network infrastructure (Sultan, 2019). In general, the IoT can be interpreted as the connection of various objects measured using sensors with an internet network. In its implementation, the IoT requires a communication line like a telephone with a cellular network. One protocol that is suitable for the implementation of IoT is the

MQTT protocol (Bilal et al., 2018).

The MQTT protocol is lightweight because it sends messages with a small header of 2 bytes (Wahyudi et al., 2018). The MQTT protocol uses the publish/subscribe concept (Bilal et al., 2018; Patel & Doshi, 2020). IoT works by utilizing a programming argument where each argument command produces an interaction between fellow machines connected automatically without human intervention and at any distance. The internet links the two machine interactions, while humans, in this case, students, only serve directly as organizers and supervisors of the tool's operation (Kumar et al., 2019). The author introduces the design of an IoT-based science laboratory tool with the MQTT protocol in Figure 2.

Figure 2. The work of the IoT in MQTT protocol (left), Practical Tool Design (right)



The concept of the IoT is straightforward, referring to the three main elements in the IoT architecture, namely: physical items equipped with IoT modules, internet connection devices such as modems and speedy wireless routers, and cloud data centres where applications and databases are stored (Patel & Doshi, 2020). The fundamental working principle of IoT devices is that objects in the real world are given a unique identity that can be multiplied in a computer system and can be represented in the form of data in a computer system (Tedeschini et al., 2022). All activities in IoT are to collect precise and accurate raw data efficiently; however, the more critical aspect in discovery learning is to analyze and process the data into more valuable information, which applies digital technology as a form of TPACK application in science learning.

2.3 Digital Literacy Skills

Digital literacy skills are still changing along with the advancement of digital technology (Phuapan et al., 2015). Educational experts and academics still have different definitions for these skills. Gilster & Gilster (1997) define digital literacy as the skill to understand and use information in various forms and from multiple sources through computers (Gilster

& Gilster, 1997). The definition emphasizes that digital literacy is an individual's skill in accessing, processing, interpreting, communicating, creating, and evaluating information sources through digital media safely and appropriately. Digital literacy is using various digital resources effectively and a form of a specific way of thinking (Eshet, 2002). Digital literacy is also defined as the ability to read and understand information in the form of hypertext or information in multimedia format (Bawden, 2001).

Digital literacy is not only the skill to use digital resources but also the skill to think about information obtained from various multimedia sources effectively. The digital literacy skills framework, created for consensus at the European level, includes five components of digital literacy including:

a. Information, namely identifying, searching, retrieving, storing, organizing, analyzing, and assessing the relevance and purpose of information through digital media.
b. Communication is interacting through digital media by sharing information, collaborating, and participating with groups.
c. Content-creation, namely creating and editing new content, producing creative content, programming, understanding copyright and licenses in creating content, and integrating prior knowledge into content.
d. Safety, namely, the ability to protect digital devices, privacy data, and health against the impact of digital use.
e. Problem-solving, namely analyzing the updates needed by digital media, being innovative in using digital technology, renewing the competence of oneself and others, and solving conceptual problems through digital media (Ferrari et al., 2012; Law et al., 2018)

2.4 Research Objectives

This article describes the results of implementing IoT-based STEM-Contextual learning with the MQTT protocol on the digital literacy skills of pre-science teachers. In addition, it promotes how to implement IoT-based STEM-contextual learning with the MQTT protocol in laboratory activities.

3 Research Methods

3.1 Study Approach and Design

The approach used in this study is quantitative with one-shot case study experimental design (Campbell & Stanley, 1963; Creswell, 2017; Fraenkel et al., 2023). The method is classified as a pre-experimental design method using one experimental class without a control class at Universitas Negeri Yogyakarta (UNY) and Universitas Negeri Malang (UM). This design can be used to determine digital literacy skills by implementing IoT-based STEM-contextual learning with the MQTT protocol, as shown in Figure 3.

Figure 3. Research Design

One-shot case study in the context of this research is used in exploratory research that aims to understand new phenomena before conducting more in-depth research (Creswell, 2017; Hollweck, 2015). Furthermore, this method can be used to observe the initial impact of this technology without having to conduct a pretest or use a control group (Johnson & Christensen, 2019).

3.2 Study Group

The samples used were 43 teachers at Universitas Negeri Yogyakarta (UNY) and 66 at Universitas Negeri Malang (UM). The sampling technique used purposive sampling, which is a sampling technique with specific considerations (Bhattacherjee, 2012; Creswell, 2017; Fraenkel et al., 2023). The consideration is that pre-service science teachers take courses related to factors that affect plant growth. In addition, the number of samples met the statistical tests for the difference and instrument quality tests (Linacre, 1994; P. Louangrath, 2014; P. I. Louangrath, 2017). With a total of 109 participants, this study had a sufficient sample size to conduct various statistical tests, such as instrument validity, reliability, and t-tests.

3.3 Research Instruments

The research instruments used to collect data consisted of an observation sheet for implementing IoT-based STEM-Contextual learning with the MQTT protocol and a questionnaire sheet for digital literacy skills. The teaching is implemented in six stages: stimulation, problem statement, data collection, data processing, verification, and generalization, as shown in Figure 1. The questionnaire sheet to measure students' digital literacy skills consists of five dimensions, as shown in Table 1.

Table 1. Dimensions of digital literacy skills

Dimensions	Indicators	Item	Scale	
			Min	Max
Information	Ability to explore information from the utilization of IoT-based laboratory equipment with MQTT Protocol	1	1	5
	Ability to identify information generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	2	1	5
	Ability to evaluate information generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	3	1	5
Communication	Ability to discuss data generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	4	1	5
	Ability to share data generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	5	1	5
	Ability to collaborate with group friends in completing tasks from the utilization of IoT-based laboratory equipment with MQTT Protocol	6	1	5
Content-creation	Ability to be active online to download data generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	7	1	5
	Ability to create and develop data generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	8	1	5
	Ability to communicate to read and discuss data generated from the utilization of IoT-based laboratory equipment with MQTT Protocol	9	1	5
Problem-Solving	Ability to contribute when dealing with information from the utilization of IoT-based laboratory equipment with MQTT Protocol	10	1	5
	Ability to analyze when dealing with information from the utilization of IoT-based laboratory equipment with MQTT Protocol	11	1	5
	Ability to think critically when dealing with information from the utilization of IoT-based laboratory equipment with MQTT Protocol	12	1	5
Safety	Ability to ensure security when creating with digital technology from the utilization of IoT-based laboratory equipment with MQTT Protocol	13	1	5
	Ability to ensure security when collaborating with digital technology from the utilization of IoT-based laboratory equipment with MQTT Protocol	14	1	5
	Ability to ensure security when exploring information from the utilization of IoT-based laboratory equipment with MQTT Protocol	15	1	5

The questionnaire instrument used was analyzed in terms of validity and reliability. The Content Validity Ratio (CVR) was used to ensure and meet content validity, and the Fleiss Kappa statistic was used for interrater reliability so that agreement between two or more raters on categorical variables was known. The Content Validity Ratio (CVR), according to Lawshe (1975), using the mathematical equation is stated below.

$$CVR = \frac{\left(n_e - \frac{N}{2}\right)}{\frac{N}{2}}$$

Description:

Ne: number of validators who agree and strongly agree or give a score of 3 or 4

N: number of validators or expert team members

The instrument item used is valid if the CVI value is 0.99. In addition, interrater reliability, which denotes agreement between two or more raters on categorical variables, was analyzed using the Fleiss Kappa statistic. The Kappa statistic results provide information about the level of agreement beyond the likelihood (McHugh, 2012; Orts-Cortés et al., 2013). The mathematical equation to calculate the Fleiss Kappa Statistic coefficient is below.

$$K = \frac{Pr(a) - Pr(e)}{1 - Pr(e)}$$

Cohen suggested the Kappa result be interpreted as follows: values ≤ 0 as indicating no agreement and 0.01–0.20 as none to slight, 0.21–0.40 as fair, 0.41–0.60 as moderate, 0.61–0.80 as substantial, and 0.81–1.00 as almost perfect agreement (McHugh, 2012).

The analysis of construct validity uses the Confirmatory Factor Analysis (CFA). The criteria used to determine the CFA's results are shown in Table 2 (Dimitrov, 2012).

Table 2. Criteria for CFA Testing

Criteria	**Recommendation value**
Chi-square (X^2)	Expectedly small
X^2- significance probability	≥ 0.05
Tucker-Lewis Index (TLI)	≥ 0.90
Comparative Fit Index (CFI)	≥ 0.90
Root Mean Square Error of Approximation (RMSEA)	≤ 0.08

Furthermore, the items used to measure digital literacy skills were analyzed using the Rasch Rating Scale Model (Rasch-RSM) (Andrich, 1978). The provision of items that fit Rasch-RSM uses the following criteria (Boone et al., 2014; Dimitrov, 2012; Linacre, 2002; Meyer, 2014).

a. The value of Outfit MNSQ with a range of 0.5 < Outfit MNSQ < 1.5
b. The value of Outfit Z-Standard with a range of -2 < ZSTD < 2,
c. The value of Point Measure Correlation with a range of 0.4 < Pt Mean Corr < 0.85.

3.4 Data Analysis

The data collected in the study are quantitative; therefore, they are analyzed quantitatively. Details of the data analysis in this study are below.

a. Conversion of ordinal scale to interval scale of digital literacy skills data (Harwell & Gatti, 2001).
b. Descriptive statistical analysis to obtain an overview of the research data without generalizing (Bhattacherjee, 2012; Fraenkel et al., 2023). This analysis used computer applications to get an overview of the results of implementing IoT-based STEM-Contextual learning with MQTT protocol on digital literacy skills.
c. The average total score of digital literacy skills is analyzed directly by comparing the norm-referenced curve with the following provisions (Mangal & Mangal, 2019).

Figure 4. Provisions of Digital Literacy Skills in Normal Curve

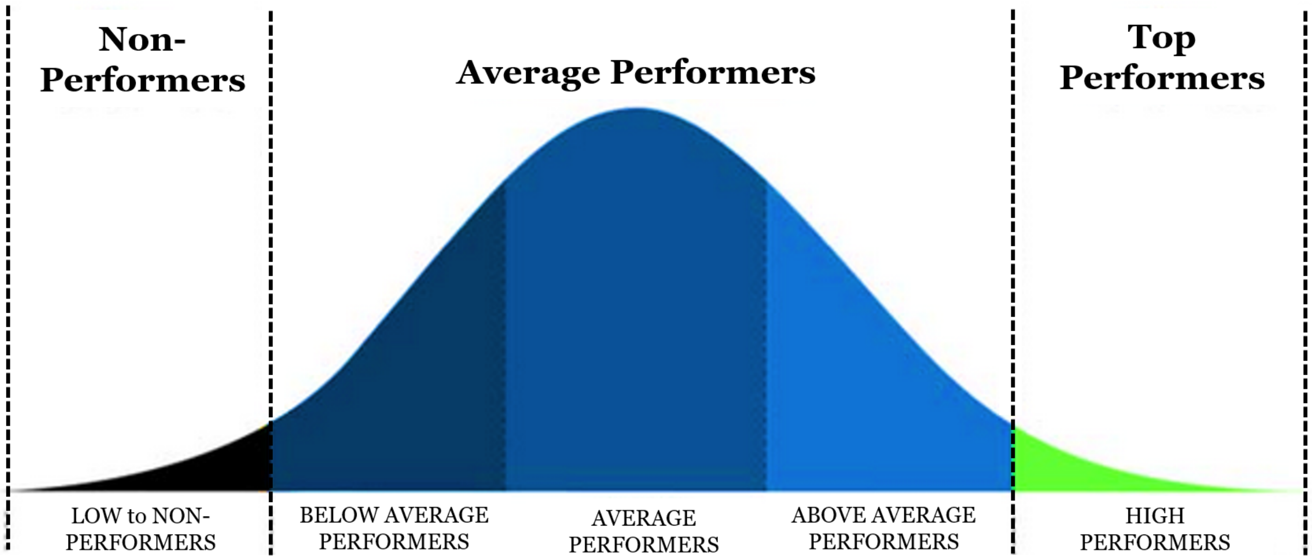


Table 3. Provisions of Conversion from Quantitative to Qualitative Scale

Score	Digital Literacy Skills	Criteria
$x > \bar{x}_i + 1{,}8SD_i$	$x > 68$	High Performers
$\bar{x}_i + 0{,}6SD_i < x \leq \bar{x}_i + 1{,}8SD_i$	$56 < x \leq 68$	Above Average Performers
$\bar{x}_i - 0{,}6SD_i < x \leq \bar{x}_i + 0{,}6SD_i$	$44 < x \leq 56$	Average Performers
$\bar{x}_i - 1{,}8SD_i < x \leq \bar{x}_i - 0{,}6SD_i$	$32 < x \leq 44$	Below Average Performers
$x \leq \bar{x}_i - 1{,}8SD_i$	$x \leq 32$	Low Performers

4 Results

This section presents the results and discussion to answer the objectives of this article, which are organized into three parts. These sections include the quality of the research instruments, the implementation of IoT-based STEM-contextual learning with the MQTT protocol, and digital literacy skills.

4.1 The Quality of the Research Instruments

All instruments used in the study were analyzed by judgment from experts quantitatively and involving empirical tests in the classroom. The first instrument used is the IoT-based STEM-Contextual learning tools with MQTT protocol, which is analyzed from content validity with CVR by engaging five lecturers in science education and physics, with the results shown in Table 4.

Table 4. Results of CVR Analysis of STEM-Contextual Learning Tools

Aspect	**Validators**					**CVR**
	Rater 1	**Rater 2**	**Rater 3**	**Rater 4**	**Rater 5**	
Content	3	4	4	3	3	0.99
Language	4	4	3	3	4	0.99
Presentation	4	4	4	4	4	0.99
Graphics	3	4	4	3	3	0.99
CVI	0.99					

The learning tools used are valid based on Lawshe's provisions if the CVI value is 0.99 (Lawshe, 1975). Table 4 reveals that all IoT-based STEM-Contextual learning tools with MQTT protocol are valid in content, language, presentation, and graphics. In addition, IoT-based measuring instruments with the MQTT protocol connected to the internet network facilitate students to get real-time data digitally and continuously. Integrating learning in laboratory work activities that utilize the internet directly during and beyond learning hours has formed a new learning pattern known as the hybrid model (Setyawarno et al., 2024). Furthermore, the assessment results from the experts were also analyzed by interrater reliability with Fleiss Kappa Statistic, as shown in Table 5.

Table 5. Results of Fleiss Kappa Analysis of STEM-Contextual Learning Tools

		95% CI		
Ratings	**Fleiss' kappa**	**SE**	**Lower**	**Upper**
Overall	0.783	0.148	0.687	0.862
3	0.782	0.148	0.688	0.862
4	0.783	0.148	0.687	0.863

Table 5 reveals that the Fleiss Kappa coefficient is 0.783. The coefficient is in the range of 0.61-0.80, so it is categorized as moderate as substantial and suitable for use in research (McHugh, 2012; Orts-Cortés et al., 2013). The coefficient value reveals that science education experts agreed upon the study's tools.

The second instrument was a questionnaire to measure pre-service science teachers' digital literacy skills. The questionnaire totalled fifteen items developed from digital literacy skills, including information, communication, content-creation, safety, and problem-solving (Ferrari et al., 2012). The digital literacy skills instrument was also analyzed from the validity aspect using the Content Validity Ratio (CVR), with the results as shown in Table 6.

Table 6. The result of content validity ratio analysis of digital literacy skill items

Items	Aspect	Validators					CVR
		Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	
1	Construction	4	4	4	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	3	4	4	4	0.99
2	Construction	3	4	4	4	3	0.99
	Content	4	3	4	3	3	0.99
	Language	3	3	4	4	4	0.99
3	Construction	4	4	3	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	3	4	4	4	0.99
4	Construction	4	3	4	4	3	0.99
	Content	4	4	4	4	3	0.99
	Language	3	4	4	4	3	0.99
5	Construction	4	4	4	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	4	4	4	4	0.99
6	Construction	4	4	4	4	3	0.99
	Content	4	3	4	4	3	0.99
	Language	3	3	4	4	4	0.99
7	Construction	3	4	4	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	4	4	4	4	0.99
8	Construction	4	4	4	4	3	0.99
	Content	4	4	4	3	4	0.99
	Language	3	4	4	4	4	0.99
9	Construction	4	3	4	4	3	0.99
	Content	4	4	4	4	3	0.99
	Language	3	4	4	4	3	0.99

Items	Aspect	Validators					CVR
		Rater 1	Rater 2	Rater 3	Rater 4	Rater 5	
10	Construction	4	4	4	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	4	4	4	4	0.99
11	Construction	4	4	4	4	3	0.99
	Content	4	4	4	3	3	0.99
	Language	3	3	4	4	4	0.99
12	Construction	4	3	4	4	3	0.99
	Content	4	3	4	3	4	0.99
	Language	3	3	4	4	4	0.99
13	Construction	4	4	3	4	4	0.99
	Content	4	4	4	3	3	0.99
	Language	3	4	4	4	4	0.99
14	Construction	4	4	4	4	3	0.99
	Content	4	4	4	4	3	0.99
	Language	4	4	4	4	3	0.99
15	Construction	4	3	4	4	3	0.99
	Content	4	4	4	4	3	0.99
	Language	3	4	3	4	4	0.99
	CVI			0.99			

The questionnaire items used are revealed to be valid based on Lawshe's provisions if the CVI value is 0.99 (Lawshe, 1975). Table 6 shows that all aspects of the questionnaire items were revealed to be valid because they fulfilled these criteria. Furthermore, the assessment results from the experts were analyzed with interrater reliability using Fleiss Kappa Statistic, as shown in Table 7.

Table 7. Results of Fleiss Kappa Analysis of Digital Literacy Skill Items

		95% CI		
Ratings	**Fleiss' kappa**	**SE**	**Lower**	**Upper**
Overall	0.796	0. 082	0. 746	0.816
3	0.796	0. 082	0. 746	0.816
4	0.796	0. 082	0. 746	0.816

Table 7 reveals that the Fleiss Kappa coefficient is 0.796. The coefficient is 0.61-0.80, categorized as moderate, substantial, and suitable for the research. Furthermore, the questionnaire instrument was analyzed empirically using CFA and the Rasch-Rating Scale Model. The results of the analysis using CFA are shown in Table 8.

Table 8. The results of CFA factor loadings analysis

Factor	Indicators	Estimates	SE	Z	p	Stand. Estimate
Factor 1	A1	0.869	0.0671	13.0	< 0.001	0.935
	A2	0.866	0.0657	13.2	< 0.001	0.945
	A3	0.739	0.0633	11.7	< 0.001	0.879
Factor 2	B1	0.821	0.0663	12.4	< 0.001	0.915
	B2	0.736	0.0711	10.4	< 0.001	0.817
	B3	0.798	0.0663	12.0	< 0.001	0.898
Factor 3	C1	0.728	0.0688	10.6	< 0.001	0.830
	C2	0.763	0.0702	10.9	< 0.001	0.850
	C3	0.804	0.0629	12.8	< 0.001	0.931
Factor 4	D1	0.922	0.0711	13.0	< 0.001	0.934
	D2	0.847	0.0655	12.9	< 0.001	0.933
	D3	0.951	0.0748	12.7	< 0.001	0.925
Factor 5	E1	0.921	0.0669	13.8	< 0.001	0.966
	E2	0.915	0.0664	13.8	< 0.001	0.966
	E3	0.789	0.0648	12.2	< 0.001	0.902

Table 8 reveals the CFA factor loading analysis results, in which all standard estimates exceed 0.5. If the standard value of the estimate on factor loading is greater than or equal to 0.5, it means that the indicator in question is valid and significant in measuring a construct, in this case, the digital literacy skills of pre-service science teachers. After the items meet the construct validity, the next analysis examines the fit model, as shown in Table 9.

Table 9. Model Fit on CFA

Chi-Square			CFI	TLI	RMSEA	RMSEA 90% CI	
χ^2	df	P				Lower	Upper
5.32	2	0.140	0.950	0.935	0.119	0.0989	0.139

Table 9 reveals the results of the fit model analysis of CFA, including a Chi-Square value of 5.32 (small) and p-value = 0.140 > 0.05, indicating a fit between the indicators and the measured variable, namely digital literacy skills. In addition, the values of CFI = 0.950 ≥ 0.9, TLI = 0.935 ≥ 0.9 and RMSEA = 0.119 > 0.08.

Figure 5. CFA Model Fit of Digital Literacy Skills

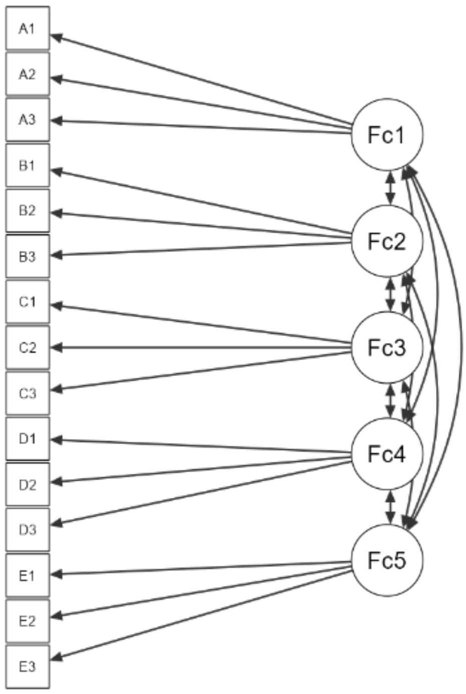


Figure 5 reveals the construction of the digital literacy skills questionnaire items used in the study, with fifteen items covering aspects of information (A1, A2, AND A3), communication (B1, B2, AND B3), content-creation (C1, C2, AND C3), safety (D1, D2, AND D3), and problem-solving (E1, E2, AND E3). In addition, the path diagram indicates the interrelationship between the five dimensions of digital literacy skills that represent digital literacy skills as a whole. The instrument quality analysis of digital literacy skills questionnaire items was also analyzed using Rasch-Rating Scale Model. The summary results of the Rasch Rating Scale Mode analysis of the person and item aspects are provided in Figure 6.

Figure 6. The summary result of Rasch-Rating Scale Model

```
-------------------------------------------------------------------------------
| Person     109 INPUT      109 MEASURED               INFIT          OUTFIT   |
|           TOTAL      COUNT      MEASURE   REALSE      IMNSQ   ZSTD  OMNSQ   ZSTD|
| MEAN       56.8       15.0         3.86      .75        .97    -.2    .93    -.2|
| P.SD       12.4         .0         4.23      .24        .69    1.4    .74    1.4|
| REAL RMSE    .79 TRUE SD    4.16  SEPARATION  5.25  Person RELIABILITY  .96|
|-------------------------------------------------------------------------------|
| Item       15 INPUT       15 MEASURED               INFIT          OUTFIT   |
|           TOTAL      COUNT      MEASURE   REALSE      IMNSQ   ZSTD  OMNSQ   ZSTD|
| MEAN      412.5      109.0          .00      .25       1.00    -.2    .93    -.4|
| P.SD       11.1         .0          .66      .03        .31    1.8    .33    1.5|
| REAL RMSE    .26 TRUE SD     .61  SEPARATION  2.38  Item   RELIABILITY  .85|
-------------------------------------------------------------------------------
```

Figure 6 reveals that the value of Outfit MNSQ for both person and item aspects is 0.93, the Outfit ZSTD for person aspects is -0.2 and item aspects is -0.4. These values are within the Rasch model fit criteria range of 0.5 < Outfit MNSQ < 1.5, -2 < Outfit Z-STANDARD (ZSTD) < 0.85 (Dimitrov, 2012; Linacre, 2002; Meyer, 2014). The summarized results of the instrument analysis of fifteen questionnaire items to measure the digital literacy skills of pre-service science teachers meet the Rasch model fit criteria. In addition, the item reliability value is 0.85 with a very good category (Dimitrov, 2012a; Waugh & Gronlund, 2013). Furthermore, each item was also analyzed to determine if it fit with the Rasch model, as shown in Figure 7.

Figure 7. Analysis Results of Each Item Fit Rasch-Rating Scale Model

ENTRY NUMBER	TOTAL SCORE	TOTAL COUNT	JMLE MEASURE	MODEL S.E.	INFIT MNSQ	INFIT ZSTD	OUTFIT MNSQ	OUTFIT ZSTD	PTMEASUR-AL CORR.	PTMEASUR-AL EXP.	EXACT MATCH OBS%	EXACT MATCH EXP%	Item
1	422	109	-.54	.25	.76	-1.47	.62	-1.74	.83	.80	83.2	80.6	A1
2	420	109	-.42	.25	.61	-2.70	.49	-1.92	.84	.80	86.9	80.1	A2
3	403	109	.56	.23	1.02	.16	.98	-.05	.84	.84	78.5	76.8	A3
4	420	109	-.42	.25	.92	-.43	1.11	.54	.80	.80	83.2	80.1	B1
5	404	109	.51	.23	1.48	2.35	1.46	1.95	.84	.83	62.6	76.9	B2
6	434	109	-1.33	.26	1.18	1.00	.95	-.08	.84	.80	79.4	82.3	B3
7	432	109	-1.19	.26	1.75	2.23	1.43	1.89	.84	.80	76.6	82.1	C1
8	394	109	1.03	.22	1.27	1.83	1.16	.95	.82	.83	75.7	75.0	C2
9	407	109	.34	.24	.68	-2.37	.57	-1.92	.81	.82	80.4	77.6	C3
10	405	109	.45	.23	.77	-1.60	.73	-1.51	.83	.81	84.1	77.0	D1
11	406	109	.40	.23	.63	-2.32	.59	-1.91	.82	.82	90.7	77.3	D2
12	402	109	.62	.23	.97	-.14	1.01	.13	.82	.80	81.3	76.7	D3
13	415	109	-.12	.24	.94	-.34	.78	-1.01	.82	.80	79.4	79.1	E1
14	417	109	-.24	.25	.91	-.52	.76	-1.07	.82	.80	82.2	79.6	E2
15	407	109	.34	.24	1.09	.64	1.03	.22	.80	.82	71.0	77.6	E3
MEAN	412.5	109.0	.00	.24	1.00	-.16	.93	-.45			79.7	78.6	
P.SD	11.1	.0	.66	.01	.31	1.85	.33	1.52			6.4	2.1	

Figure 7 reveals the results of the analysis of each questionnaire item from the digital literacy skills aspect against the Rasch-Rating Scale Model fit all within the range of 0.5 < Outfit MNSQ < 1.5, which means each item is valid and meets the Rasch-Rating Scale Model (Dimitrov, 2012; Linacre, 2002; Meyer, 2014). In addition, -2 < Outfit Z-STANDARD (ZSTD) < 2 and 0.4 < Pt Mean Corr < 0.85 were also met for the fifteen questionnaire items.

4.2 Implementation of IoT-based STEM-Contextual Learning with MQTT Protocol

IoT-based STEM-contextual learning with MQTT protocol in laboratory work is implemented using the discovery learning model. Student worksheets from the implementation of IoT-based STEM-Contextual learning with the MQTT protocol are used as a data collection tool for physical quantities or variables that affect plant growth and development. Two observers at both UNY and UM observed the implementation of learning in the "Biophysics" course. Data on IoT-based STEM-Contextual learning implementation with the MQTT protocol is presented in Table 10.

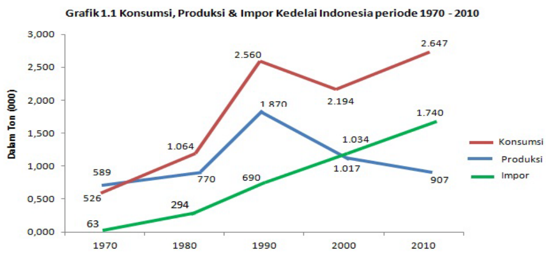
Table 10. Observation Results of IoT-based STEM-Contextual Learning Implementation with MQTT Protocol

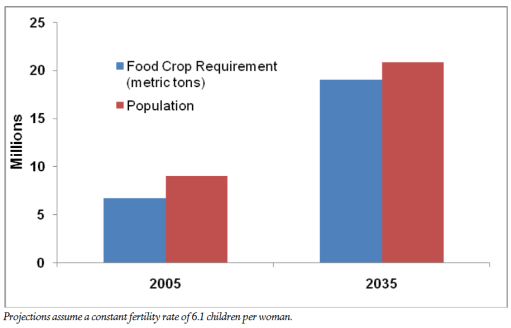
Aspects of the Learning Process	Description	Observasi UNY		Observasi UM	
		Observer 1	Observer 2	Observer 1	Observer 2
Opening	Class conditioning by educators, including the division of laboratory work groups	√	√	√	√
Stimulation	Learners answer contextual questions given by educators as a stimulus to enter into learning factors that affect plant growth and development.	√	√	√	√
Problem Statement	Students discuss to identify problems obtained from the stimulus to be investigated in the application of IoT-based STEM-Contextual learning with the MQTT protocol.	√	√	√	√
Data Collection	Students in groups collect data related to physical quantities that affect plant growth and development using IoT-based practicum tools with the MQTT protocol, accompanied by guidance from educators. Educators also guide and direct students, especially those who have problems collecting data.	√	√	√	√
Data Processing	Students in groups discuss and analyze the results of data findings from using IoT-based practical tools with the MQTT protocol and other information they obtain from various sources. In addition, educators guide and direct learners, especially those with data processing problems.	√	√	√	√
Verification	Students conduct a careful investigation to prove whether or not it is correct using the existing literature, with direction from the educator. In addition, students present the results in front of the class.	√	√	√	√
Generalisation	Students conclude from the data that has been obtained and has been analyzed together to get the correct answer. The conclusion written is related to the physical quantities that influence plant growth and development using STEM-C analysis. In addition, in this stage, the educator directs students to be able to write conclusions correctly.	√	√	√	√
Closing	Educators reinforce the concepts obtained from implementing IoT-based STEM contextual learning with the MQTT protocol, along with reflection activities, by linking digital literacy skills.	√	√	√	√
Total implementation of IoT-based STEM-Contextual learning activities with MQTT protocol		100%		100%	

Table 10 reveals that the implementation of IoT-based STEM-Contextual learning with the MQTT protocol using the discovery learning model both at UNY and UM is adequately implemented (100%), which can be observed from all stages of the opening, core, and closing activities that describe the discovery learning model. The IoT-based laboratory tool with the MQTT protocol is used in data collection. Details of the discovery model stages with the STEM-C approach are shown in Table 11 (Joyce et al., 2015; Kilbane & Milman, 2014).

Table 11. Implementation of STEM-C approach in discovery learning model

<table>
<tr><th>Syntax</th><th colspan="2">STEM-C Approach</th></tr>
<tr><td>Stimulation</td><td>**Contextual:** The educator presents various problems related to crop yields from agriculture which have not been optimized, narrow land, and logistical needs in the current era.




</td><td>**Figure 8.** Some conditions faced today related to logistics needs

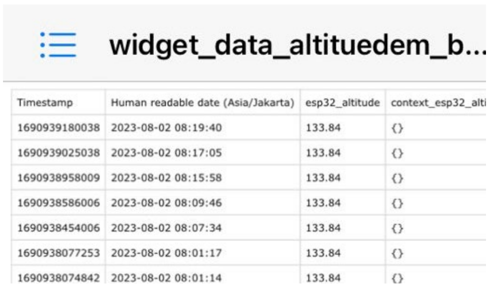
</td></tr>
<tr><td>Problem Statement</td><td>Students discuss to identify problems obtained from the stimulus presented by the educator. The problem that students learn is related to physical quantities in the environment that will optimize plant growth and development.</td><td>For instance. What are the physical variables in the environment that affect plant growth and development and how to optimize the results?</td></tr>
</table>

<table>
<tr><th>Syntax</th><th colspan="2">STEM-C Approach</th></tr>
<tr><td>Data Collection</td><td>

Students in groups collect data related to physical quantities that affect plant growth and development. The physical quantities measured by the IoT-based practicum tool with the MQTT protocol are as follows.

a) Altitude: instrument altitude from sea level (meter)
b) Soil: soil moisture (%)
c) Temp: air temperature (celcius)
d) TemperatureDS: air/water temperature (celcius)
e) UV: ultraviolet radiation (mw/ 〖cm〗 ^2)
f) Hum: air humidity (%)
g) Lux: Light intensity (lux)
h) pH: ph (pH)
i) Press: air pressure (hPa)
j) TDS: tds (ppm)

The data collection activity is related to the process of photosynthesis and the frequency of audiosonic bloom, so that students will be able to find physical quantities that affect plant growth and development.

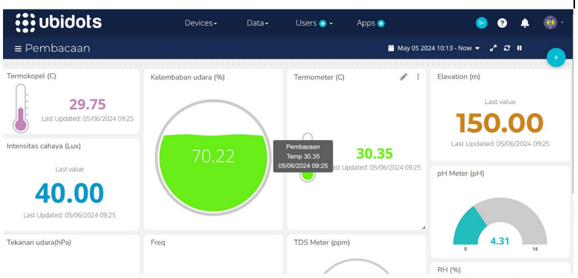


widget_data_altituedem_b...

Timestamp	Human readable date (Asia/Jakarta)	esp32_altitude	context_esp32_alti
1690939180038	2023-08-02 08:19:40	133.84	{}
1690939025038	2023-08-02 08:17:05	133.84	{}
1690938958009	2023-08-02 08:15:58	133.84	{}
1690938586006	2023-08-02 08:09:46	133.84	{}
1690938454006	2023-08-02 08:07:34	133.84	{}
1690938077253	2023-08-02 08:01:17	133.84	{}
1690938074842	2023-08-02 08:01:14	133.84	{}

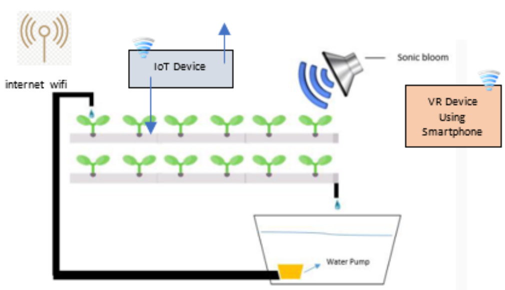
</td><td>

Figure 9. IoT-based laboratory tool with MQTT protocol



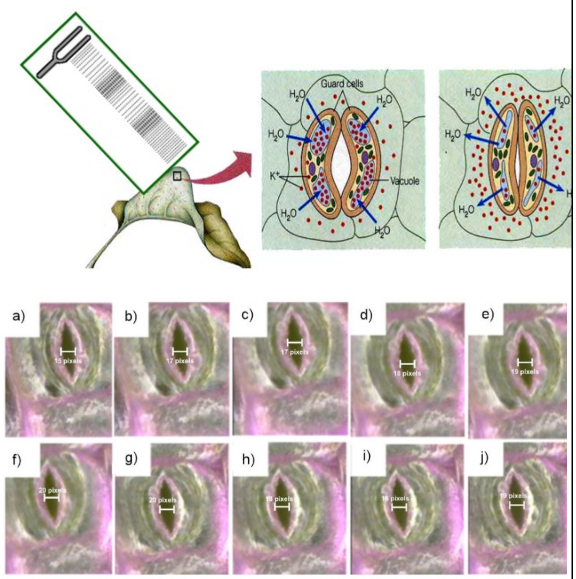
</td></tr>
<tr><td>Data Processing</td><td>

Students in groups discuss and analyze the results of data findings. The data processing is quantitative by correlating physical variables, especially sound frequency variables with stomatal openings in plants.



</td><td>

Figure 10. Data Analysis by Linking Environmental Physical Variables to Plant Stomatal Openings.



</td></tr>
</table>

<table>
<tr><th>Syntax</th><th>STEM-C Approach</th></tr>
<tr><td>Verification</td><td>Students present their work in front of the class.</td></tr>
<tr><td>Generalisation</td><td>The conclusions written are related to the physical quantities that influence plant growth and development using STEM-C analysis.
Table of Analysis. Science, Technology, Engineering, and Mathematics-Contextual (STEM-Contextual)
<table>
<tr><th>Science</th><th>Technology</th><th>Engineering</th><th>Mathematics</th><th>Contextual</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table>
</td></tr>
</table>

Although the data collected is quantitative, students are also encouraged to use a qualitative approach and relate it to the photosynthesis process due to audio sonic bloom applied to the plants associated with stomatal openings on the leaves (Jatmika et al., 2022; Kadarisman et al., 2019; Suryadarma et al., 2020). With limited time in data collection, hybrid learning is also carried out with tools that have been set up. Real-time data can be accessed anywhere and anytime if the IoT-based laboratory equipment has the MQTT protocol and students are connected to the internet.

4.3 Digital Literacy Skill

Students' digital literacy skills in biophysics courses related to physical variables that influence plant growth and development are measured using fifteen questionnaire items, which have been quantitatively analyzed with CFA and Rasch models. Table 12 presents the results of the descriptive statistical analysis of digital literacy skills data from UNY and UM students.

Table 12. Descriptive Statistical Analysis of Digital Literacy Skills

UNY		UM	
Mean	70.98	Mean	67.52
Standard Error	0.54	Standard Error	0.64
Median	69.00	Median	66.00
Mode	69.00	Mode	65.00
Standard Deviation	3.55	Standard Deviation	5.23
Sample Variance	7.59	Sample Variance	8.33
Kurtosis	0.73	Kurtosis	0.04
Skewness	1.68	Skewness	0.62
Range	9.00	Range	8.00
Minimum	63.00	Minimum	62.00
Maximum	72.00	Maximum	70.10

Table 12 reveals the results of a descriptive statistical analysis of the digital literacy skills of pre-service science teachers from both UNY and UM, including mean, median, standard deviation, standard error, and other quantities that describe the general distribution of data. Table 13 presents the average value of each dimension that describes digital literacy skills in detail.

Table 13. Average Score of Digital Literacy Skills

Digital Literacy Skills	Item	Average	
		UNY	**UM**
Information	1, 2, 3	13.38	13.14
Communication	4, 5, 6	14.62	13.43
Content-creation	7, 8, 9	14.33	13.45
Safety	10, 11, 12	13.77	13.42
Problem-solving	13, 14, dan 15	14.88	14.08
Total Average Score of Digital Literacy Skills		70.98	67.52
Category		High Performers	Above Average Performers

Table 13 reveals the mean scores of each dimension of the digital literacy skills of the pre-service science teachers from both UNY and UM. The total average score of digital literacy skills is 70.98 for UNY students and 67.52 for UM students. The score of digital literacy skills in each dimension of the pre-service science teacher students from both UNY and UM is shown in Figure 11.

Figure 11. Comparison Graph of All Dimensions of Digital Literacy Skills of UNY Vs UM Students

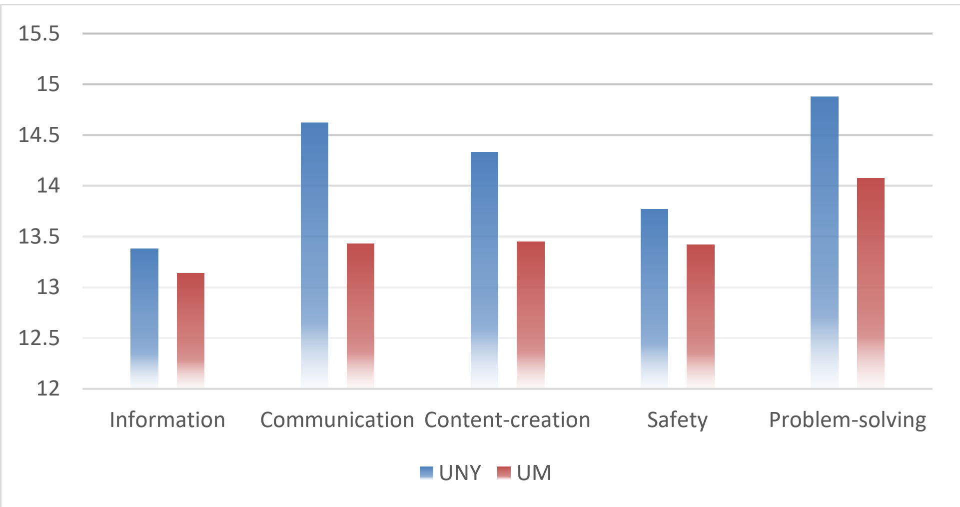
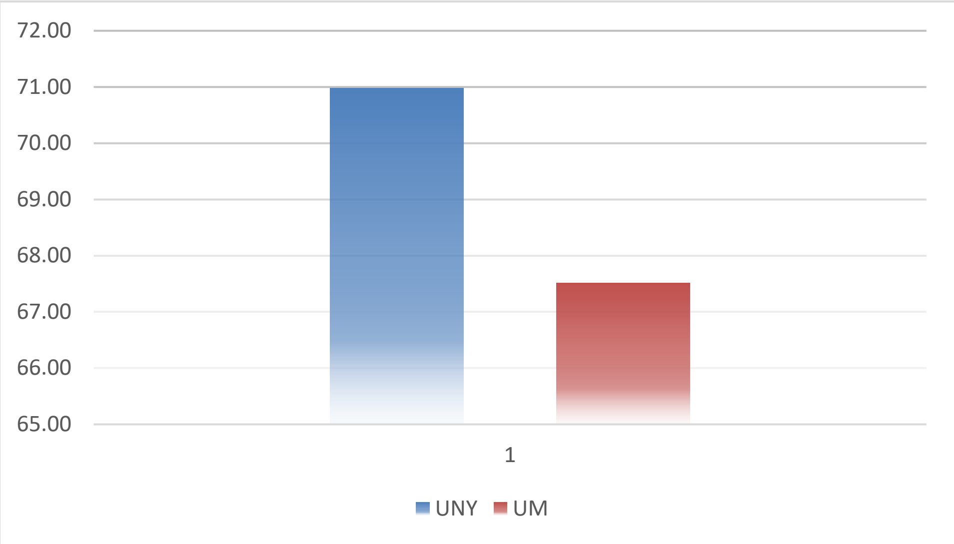


Figure 12 reveals that all items from the digital literacy skills of the pre-service science teachers of UNY have higher scores than those of the pre-service science teachers of UM. The graph's highest to lowest scores are for problem-solving, communication, content creation, safety, and information. Although the scores do not look different in numbers, if they are totalled, they will look significantly different, as shown in Figure 12.

Figure 12. Comparison Graph of Total Score of Digital Literacy Skills of UNY Vs UM Students



Data on digital literacy skills of pre-service science teachers from UNY and UM were analyzed using inferential statistics, namely independent sample t-test, to further determine whether there is a significant difference in digital literacy skills from implementing IoT-based STEM-Contextual learning with MQTT protocol. A normality distribution test precedes this statistical test as a prerequisite test that must be met using Shapiro-Wilk with the results as shown in Table 14.

Table 14. The result of the Normality Test (Shapiro-Wilk)

	W	**p**
Digital Literacy	0.972	0.061

Note. A low p-value suggests a violation of the assumption of normality.

Table 14 reveals the normality test with a probability value of $p = 0.061 > 0.05$, which can be concluded that the data follows a normal distribution, so the first prerequisite test of inferential statistics is met. In addition, Levene's test was used for the homogeneity test, with the results shown in Table 15.

Table 15. The result of the Homogeneity of Variances Test (Levene's)

	F	df	df2	p
Digital Literacy	2.60	1	107	0.107

Note. A low p-value suggests a violation of the assumption of equal variances.

Table 15 reveals the Homogeneity of Variances Test table p-value (0.107) > 0.05, which indicates homogeneity. Therefore, the assumptions of normality and homogeneity are met, and the independent sample t-test can be used. The results of the independent sample t-test analysis of the implementation of IoT-based STEM-Contextual learning with the MQTT protocol are shown in Table 16.

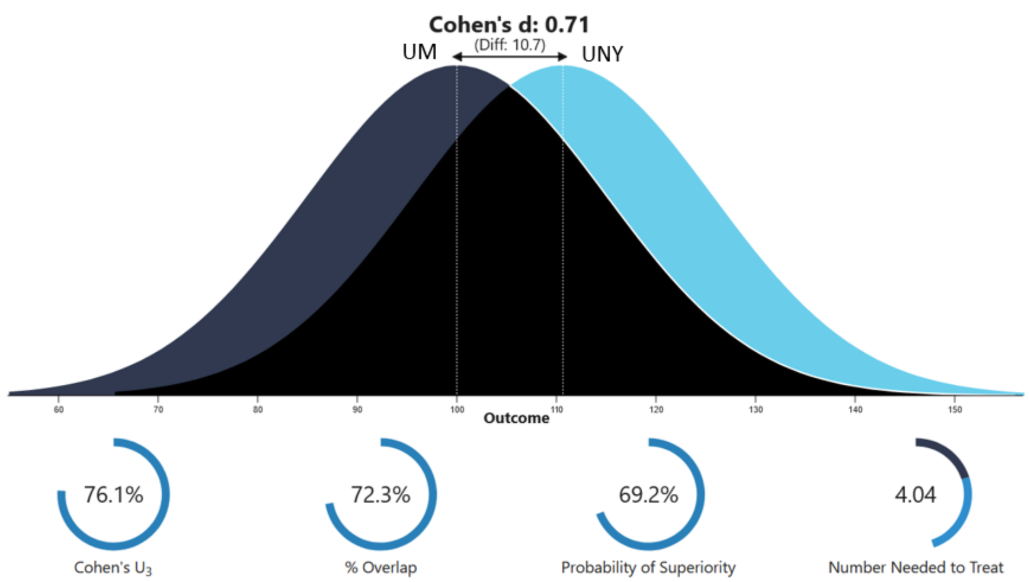
Table 16. The Result of Independent Samples T-Test from Digital Literacy Skills

		Statistic	df	p		Effect Size
Digital Literacy	Student's t	25. [a]	107	< .001	Cohen's d	0.71

[a] Levene's test is significant (p < .05), suggesting a violation of the assumption of equal variances

Table 16 reveals a significance value of p < 0.001, which means p < 0.05. It indicates that there is a significant difference in digital literacy skills between pre-service science teacher students of UNY and UM from the implementation of IoT-based STEM-contextual learning with the MQTT protocol. In addition, the authors conducted additional analysis, namely effect size analysis, as shown in Table 16. If the coefficient is presented in a visualization, it will be presented clearly in Figure 13.

Figure 13. Visualization of Effect Size (Cohen's d)



The results of the effect size analysis reveal that Cohen's coefficient is 0.71 with a medium category. Although the quantitative to qualitative conversion analysis results, as presented in Table 13, indicate excellent achievement results (UNY: high performers and UM: above average performers), other variables achieve digital literacy skills differently. The author underlines that the effect size coefficient is an opportunity for further research with varying research designs to reveal other contributing factors apart from IoT-based STEM-contextual learning with the MQTT protocol. In general, the author states that IoT-based STEM-Contextual with MQTT protocol has a significant positive effect on the digital literacy skills of science teacher candidates of UNY and UM. The implementation of this learning provides more valuable experiences for students apart from concept mastery and digital literacy which are needed in the 21st Century (Çoban & Goksu, 2022; Eija et al., 2024; Hu-Au & Lee, 2017). Furthermore, this learning can improve the performance and activeness of collaborative learners (Ghory & Ghafory, 2021; Lee et al., 2009; Zhang et al., 2023).

5 Discussion

Every research requires a data collection tool called a research instrument, which must meet the eligibility and validity criteria (Canals, 2017; Sudaryono et al., 2019). The standard coefficient of the Aiken Formula with five experts, namely with a minimum limit of 0.80, was met because the analysis results obtained 0.99, as shown in Tables 4 and 6. In addition, the rater agreement shows that the level of reliability has been met substantially, as shown in Table 5 and Table 7. In addition, empirical tests were conducted to strengthen the quality of the instrument, in this case, the confirmatory factor analysis (CFA) and Rasch model. The results of the fit model analysis in CFA from five criteria, namely Chi-Square (X2), probability (p), CFI, TLI, and RMSEA, have all been met as Table 9, so it can be concluded that the items developed have met the criteria for construct validity in the path diagram path can be seen in Figure 6 (Dimitrov, 2012; Teo, 2013). The results of the Rasch model fit item test analysis with the provisions of the Outfit MNSQ value with a range of $0.5 < \text{Outfit MNSQ} < 1.5$, the Outfit Z-Standard value with a range of $-2 < \text{ZSTD} < 2$, and the Point Measure Correlation value with a range of $0.4 < \text{Pt Mean Corr} < 0.85$ have also been met for fifteen digital literacy skills items (Boone et al., 2014; Dimitrov, 2012; Linacre, 2002). According to this description, the quality standards of the instruments used in this study have been met; therefore, the conclusions obtained have good accuracy.

The research instruments that have been met are implemented in classroom learning. The author implemented IoT-based STEM-contextual learning with the MQTT protocol for two synchronous and asynchronous meetings for the first-year pre-service science teacher at UNY and UM. The model used in the implementation of IoT-based STEM-Contextual learning with the MQTT protocol is discovery learning because this model is not only based on the scientific method but also emphasizes how students work in groups in the form of direct (synchronous) or indirect (asynchronous) laboratory work (Carin & Sund, 1989; Nurcahyo et al., 2018). The learning context used in classroom learning is one of the topics in biophysics related to factors that influence plant growth and development. Students use IoT-based laboratory tools with the MQTT protocol in the morning, afternoon, and evening synchronously and asynchronously to get digital data with a duration of sending data every 30 seconds. The sensors embedded in the device make it easy to study the physical quantities of the environment that influence plant growth and development as shown in Figure 10, namely altitude/height from sea level, soil/soil moisture (%), temp/air temperature (centigrade), temperature DS/air/water temperature (centigrade), UV / ultraviolet radiation (mw / 〖cm〗 ^2), hum / air humidity (%), lux / light intensity (lux), pH/acid-base level, press/air pressure (hPa), TDS, and frequency of sound. Table 10 indicates that the results of observations of the implementation of IoT-based STEM learning with the MQTT protocol are maximally implemented or 100%, which means that the stages of the discovery model have been taught optimally.

IoT-based STEM-contextual learning with MQTT protocol as a model of learning innovation in the 21st century is closely related to digital technology. Therefore, the author is interested in measuring students' digital literacy skills. This study's digital skills dimensions include information, communication, content-creation, problem-solving, and safety (Ferrari et al., 2012; Phuapan et al., 2015). The summary of the results of the implementation of IoT-based STEM-Contextual learning with the MQTT protocol on digital literacy skills is presented in Table 12, which shows the average total score of 70.98 with the category of high performers for pre-service science teachers of UNY and 67.52 with the category of above average performers for pre-service science teachers of UM. IoT-based STEM-Contextual learning with the MQTT protocol can encourage students to solve problems actively and be able to improve high-level thinking skills with a scientific approach (Ibrahim & Şeker, 2022; Inde et al., 2020; Nurcahyo et al., 2018). Although the achievement results are classified as good, further analysis using an independent sample t-test shows a significant difference between students from UNY and UM, with an effect size coefficient of 0.71 and a medium category (Brydges, 2019).

Several factors that may cause differences in the implementation of IoT-based STEM learning and its impact on students' digital literacy skills include curriculum factors, technological readiness, student experience, learning environment, and socio-cultural and pedagogical factors (Timotheou et al., 2023; Tutkyshbayeva & Zakirova, 2024). UNY has a curriculum that is more oriented towards technology and digitalization in science education; students from this university may have an advantage in implementing IoT-based STEM learning with the MQTT protocol because they have gained a stronger foundation in computing, data analysis and the use of technology in learning. In contrast, UM focuses more on conventional experimental aspects in science and theory-based pedagogical approaches; students from this university may take longer to adapt to new technologies such as IoT and MQTT, thus impacting their digital literacy outcomes. This finding is very interesting and an opportunity for further research to explore what variables contribute to learners' digital literacy skills in addition to IoT-based STEM-Contextual learning with MQTT protocol.

6 Conclusion and Further Research

This study's conclusion reveals a significant positive effect of the implementation of IoT-based STEM-Contextual learning with MQTT protocol on the digital literacy skills of pre-science teacher candidates both at UNY and UM. The total score of pre-service science teacher students at UNY is 70.98 in the High Performers category, while pre-service science teacher students at UM are 67.52 in the Above Average Performers category. Although all categories are classified as good, the T-test analysis results indicate significant differences in the implementation of both UNY and UM. The effect size coefficient is 0.71 with a moderate category. Moreover, implementing IoT-based STEM-contextual learning with the MQTT protocol has great potential to improve the digital literacy of science teacher candidates. Still, its success depends mainly on the strategies used by educators. By integrating technology into the curriculum, enhancing digital skills training, implementing project-based approaches, and utilizing blended learning, educators can ensure that students have the skills needed to teach in the digital age. In addition, collaboration with the industry and ongoing evaluation will further strengthen the effectiveness of IoT-based learning in STEM education. The limitations of this study are that it was only conducted on a small scale, consisting of one class at both UNY and UM and on one topic: plant growth and development. Further research can be developed with a quick experiment design involving control classes in each research location with broader dependent variables. In addition, further research can be conducted to explore other variables that contribute to students' digital literacy skills other than IoT-based STEM-Contextual learning with the MQTT protocol.

Research Ethics

Author Contributions

D.S.: conceptualization, writing – original draft preparation, formal analysis, writing – review and editing
D.R.: methodology, validation, writing – original draft preparation, formal analysis, and funding acquisition.
I.: conceptualization
E.H.: conceptualization, investigation, validation, writing – review and editing.
A.A.: conceptualization, investigation, methodology, project administration, validation, and data curation.

All authors have read and approved the published version of the manuscript.

Artificial Intelligence

This manuscript utilized artificial intelligence software, including: (i) Winstep (licensed), (ii) R Program (open source), and (iii) Grammarly to assist with grammar checking.

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Institutional Review Board Statement

The Ethical Committee of the Universitas Negeri Yogyakarta, Indonesia has granted approval for this study (Ref. No. B/617/UN34.13/TU/2023).

Informed Consent Statement

Informed consent was obtained from all research participants.

Data Availability Statement

The research dataset is currently confidential as it involves collaboration among three universities in Indonesia and forms part of a multi-year study. Additionally, further investigations are still underway on several variables related to the implementation of STEM-C in science education. The dataset has been fully anonymized to ensure confidentiality.

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Conflicts of Interest

The authors declare no conflicts of interest.

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