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The relationship between information literacy, learning space, and TPACK on prospective teachers' digital mathematics literacy

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ABSTRACT

This study aims to examine the relationship between information literacy, optimized learning spaces, and TPACK Skills on the mathematical digital literacy skills of prospective mathematics teachers. The method is non-experimental research with a causal correlation design and a quantitative approach using the Structural Equation Modeling (SEM) analysis method. The population in this study were undergraduate mathematics teacher candidates. The sample was obtained from as many as 216 respondents using purposive sampling from public and private universities in Riau, West Sumatra, Bengkulu, Banten, Jakarta, West Java, Yogyakarta, and East Java. The instrument used is a Likert scale on a scale of 1-5, which consists of 24 indicators representing 4 variables. Based on the results of the assumption test, validity test, and model fit test, it can be concluded that the SEM model in this study is suitable and feasible and can describe the theory and findings in the field. Based on the inner model test, it can be concluded that information literacy (LT), Optimize Learning Spaces (LS), and TPACK Skills (TK) have significant effects on mathematical digital literacy (DL) in terms of estimates and P <0.05. The results of this research indicate that the increasing need for the application of learning technology, especially in mathematics learning, requires increasing the competence of teachers and students in integrating technology in mathematics learning and digital mathematics literacy needs to be the focus of further research.

INTRODUCTION

The role of technology integration in the world of work continues to increase along with the Industrial Revolution 4.0. Today, like never before, rapid technological changes demand excellence in our education and school systems in adapting to global demands and competition. The presence of the industrial revolution 4.0 has eliminated some conventional jobs but has also given rise to new jobs as a result of the needs in this 4.0 industrial revolution era (Sima et al., 2020). For example, new jobs are emerging in robotics, smart computers, artificial intelligence, digital finance, the Internet of Things, big data analytics, and relevant fields. This raises the question of what skills and abilitites are needed by students to compete competitively in the world of work that requires effective and efficient mastery of technology (Alatas & Yakin, 2021).

Various kinds of ICT devices are growing increasingly large and varied, as well as the ability to collect, organize, synthesize, analyze, and communicate information continues to change and adapt more quickly and efficiently (Abel et al., 2018). The implementation of digital technology has

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significantly changed the traditional pattern of teaching. Facts on the ground show that nowadays students have the possibility of accessing an unlimited number of required information with the click of a button, which is a special challenge for the structure of the education curriculum system. Because of the constructivist-teaching concept, The role of the teacher has changed, where previously he played a central role but is now a facilitator, apart from that the role of ICT will be a potential learning media, (Boholano, 2017; Nurjanah et al., 2020). As educators, we must help students connect learning with real life and equip them with the skills needed to prepare them for success in facing the digital era of the 21st century (Boholano, 2017).

Mathematics learning is one area that needs the integration of technology in learning. The National Council of Mathematics (NCTM) states that computers can teach concepts, develop abstract thinking from concrete modeling, and be used in problem-solving (NCTM, 2014). In the digital era, the ability to interact with mathematical content through technological means—commonly referred to as digital mathematics literacy—has become an essential competency for both learners and educators. However, many studies have shown that students still struggle to apply mathematical knowledge in digital contexts, especially when it comes to evaluating, representing, and communicating mathematical ideas using digital tools (Borba et al., 2016; Walshaw, 2012). The lack of integration between digital tools and mathematical reasoning often leads to shallow understanding and limited transferability of mathematical knowledge to real-world digital environments. These issues highlight the growing concern that digital mathematics literacy remains underdeveloped, despite the increasing availability of technological resources in education. As future educators, they are expected to be well-prepared not only in mathematics content but also in the pedagogical and technological dimensions of teaching. In this context, three critical aspects must be considered: (1) information literacy, which enables teachers to search, assess, and utilize digital mathematical information effectively; (2) learning space optimization, which includes the ability to create or adapt physical and virtual environments that support active, technology-integrated learning; and (3) Technological Pedagogical Content Knowledge (TPACK), a theoretical framework that captures how teachers integrate technology into their pedagogical practice effectively (Koehler et al., 2014; Koehler & Mishra, 2008). These three aspects are interconnected and play a substantial role in shaping how future teachers engage with and develop students' digital mathematical literacy.

This requires the need for prospective teachers to master mathematics content, and pedagogical skills as well as integrate them with ICT technology capabilities. The intersection of these three aspects is further named technological pedagogical content knowledge (TPACK) proposed by Mishra and Kohler (Ariani et al., 2014; Durdu & Dag, 2017). Several studies on digital literacy and its relationship with mathematics learning and mathematical abilities in ICT have been revealed by several researchers, including Machaba (Machaba, 2018) regarding the urgency of the pedagogical skills needed in mathematical literacy, including ICT mastery skills in learning. (Zulkarnain et al., 2020) researched students' digital literacy abilities in using E-Learning in mathematics learning, then Pradana and Sholikhah (Pradana & Sholikhah, 2019) connected the virtual mathematics kits learning media to mathematical literacy (Dofková, 2016) examine the relationship between mathematical digital literacy in teacher candidate training, then (Abel et al., 2018) which reviews literature studies regarding the characteristics of mathematical digital literacy.

Although there is increasing emphasis on the integration of ICT tools in mathematics learning, the ability to combine digital literacy skills and mathematical literacy is still not widely studied (Abel et al., 2018; Dofková, 2016; Machaba, 2018), several recent studies have begun to define the term digital mathematics literacy as a combination of digital literacy and mathematical literacy. DigCom 2.0 has comprehensively mapped the relationship between ICT and digital literacy by competencies in the 21st century in developing countries. Digital Mathematics Literacy is an emerging interdisciplinary competence that integrates the conceptual frameworks of digital literacy and mathematical literacy, particularly relevant in the context of 21st-century education. It refers to an individual's ability to understand, evaluate, and effectively use digital tools to engage with mathematical content, solve problems, and communicate mathematical ideas in diverse digital contexts. According to (Ng, 2012), digital literacy involves the awareness, attitude, and ability to use digital tools to identify, access, manage, evaluate, and synthesize digital information critically and productively. When applied to mathematics education, this literacy extends to the use of technologies such as GeoGebra, Desmos, spreadsheets, and computer algebra systems that facilitate dynamic, visual, and interactive learning (Borba et al., 2016; Walshaw, 2012).

Therefore, digital mathematics literacy can be conceptualized through five core components: mathematical reasoning through digital tools, digital representation, digital mathematical communication, critical evaluation of digital mathematical content, and tool proficiency. This integrative literacy is essential for preparing both students and teachers to navigate and contribute effectively in technologically enriched learning environments that demand a synergy between content knowledge, pedagogical strategies, and technological competence.

The digital literacy competencies that must be mastered include information and data literacy, communication, collaboration and sharing, digital content skills, data safety, and problem-solving (UNESCO, 2018). It is time for special ICT literacy competencies to develop mathematical skills called mathematical digital literacy to become a special concern for educators, curriculum developers, and many other stakeholders in the field (Dowling, 2012; Harrison, 2018; Wu, 2018). Therefore, this research examines the relationship between factors and the influence of information literacy, learning spaces (as part of the collaboration and sharing aspect), and TPACK (as part of the digital content skills aspect) on the variable mathematics digital literacy (as part of the problem-solving aspect) of prospective mathematics teachers.

The integration of TPACK (Technological Pedagogical Content Knowledge) and digital literacy remains fragmented in the current literature, particularly in studies concerning mathematics education. TPACK, as conceptualized by (Koehler et al., 2014), emphasizes the complex interplay between technology, pedagogy, and content knowledge. However, its implementation is not isolated from contextual factors such as learning spaces—whether physical or virtual. Optimized learning environments, including well-equipped classrooms and digital platforms, act as enablers that facilitate or hinder the enactment of TPACK in practice (Voogt et al., 2015). In this study, learning spaces are conceptualized not merely as physical settings but as dynamic affordances that mediate teachers' capacity to apply TPACK effectively. A digitally enriched learning environment enhances opportunities for prospective teachers to integrate technology meaningfully in mathematical instruction, which in turn supports the development of students' digital mathematics literacy ((Koehler et al., 2014; Zelkowski et al., 2013)). Moreover, information literacy functions as a foundational cognitive skill that enables pre-service teachers to critically assess, select, and apply digital tools and content in line with TPACK principles. Therefore, we propose a holistic framework where learning spaces provide the infrastructural support, information literacy provides cognitive readiness, and TPACK operationalizes the integration process, collectively fostering mathematical digital literacy.

Despite growing interest in both digital and mathematical literacy, research combining these domains remains limited. Studies have often addressed them as separate competencies, thereby neglecting their synergetic potential—particularly in the training of mathematics teachers who are expected to navigate digital tools in discipline-specific contexts (Borba et al., 2016; Zelkowski et al., 2013)). The urgency of this integration is underscored by the increasing demand for technologically competent educators in the digital era. Mathematical digital literacy encompasses the ability to use digital tools to solve mathematical problems, represent mathematical ideas, and communicate solutions effectively—competencies essential for 21st-century learning (Ng, 2012). This study contributes to the field by empirically examining how information literacy, learning spaces, and TPACK jointly influence the digital mathematics literacy of prospective teachers using a Structural Equation Modeling (SEM) approach. This model offers a novel lens to understand how these competencies interact within teacher education programs and provides evidence-based insights for curriculum designers aiming to integrate digital competency into mathematics education.

Information literacy

The rise of information technology is a big part of the digital revolution era. It's growing fast and can have a big impact on all aspects of people's lives, especially in education. In today's world, it's important to have skills for the 21st century because of all the new technology and changes happening. This includes being good with computers and understanding digital literacy. These skills are important for learning, working, and working with others to create new ideas (Erdogan, 2019). Digital literacy is a key skill in education today. Digital literacy includes various types of literacy, such as information literacy, computer literacy, media literacy, communication literacy, visual literacy, and technological literacy (Çam & Kiyici, 2017).

One of the skills needed today is information literacy, Admiko (Suharto, 2014) says that information literacy is the skill to recognize information needs, and sources of information, and find, use, and evaluate it. Every individual needs information literacy (IFL) skills combined with problem-solving and communication skills as part of the integrated skills needed by adults to effectively communicate and solve problems in their lives. The benefit of considering IFL as a specific skill is that it allows a person to provide information and access to information effectively to create the right solutions. Adopted by UNESCO's Information for All Programme (IFAP), information literacy is people's capacity to distinguish data needs, discover and assess the quality of data, store and recover data, utilize data successfully and ethically, and communicate information (Catss, Ralph; Lau, 2012).

There's an agreement that digital and information literacy includes the interaction and integration of a few abilities, such as procedural competence with ICT devices, cognitive abilities are required to utilize them successfully, and social and communication abilities are moreover required to utilize them more viably (Aviram & Eshet-Alkalai, 2006; Nawaz & Kundi, 2010). This information and digital literacy can help young people benefit from information sources connected to digital technology and prepare themselves to face today's technological challenges (Nawaz & Kundi, 2010). In the field of education, digital literacy is increasingly emphasized in general to be more optimized in learning spaces in the classroom (Zulkarnain et al., 2020). Likewise, the field of mathematics education, specifically NCTM, has integrated the application of ICT in mathematics learning and has been shown to have a positive impact on student achievement (National Council of Teacher Mathematics, 2000). ICT tools are also increasingly integrated into mathematical research, as evidenced by ICT-assisted mathematics learning studies which have experienced an increasing trend in recent years (Monroe, 2014).

To determine the level of students' information literacy skills, this research applies the Big Six Skills Model developed by Michael B. Eisenberg and Robert E. Berkowitz in 1987(Iriani & Wicaksono, 2021). The big 6 skills model consists of six components, namely: formulate the problem (LT1), information search strategy (LT2), allocation and access utilization of information (LT4), synthesis (LT5) and evaluate (LT6) (Catss, Ralph; Lau, 2012; Iriani & Wicaksono, 2021; Wijaya, 2016)

Technological pedagogical and content knowledge (TPACK)

Mastering pedagogy and content knowledge is enough for teachers in the past, but in this digital era, teachers not only have to master pedagogy and content knowledge but also technological competence. Using technology in mathematics learning is becoming a trend. This is driven by a belief that technology can improve learning outcomes (Imania et al., 2022). Moreover, technology has a positive effect on students' learning when it is properly integrated (Schrum et al., 2007). To address this issue, Mishra and Koehler (Koehler & Mishra, 2008) suggested a structure for TPACK that includes theoretical frameworks that can be used to help teachers carry out self-assessments and understand the growth of their professional knowledge through technology-based teaching practices. TPACK is introduced as a framework for the understanding of teacher skills needed for technology integration (Koehler & Mishra, 2008). There are seven sub-domains in TPACK (Koehler et al., 2013; Koehler & Mishra, 2008):

1) Content knowledge refers to knowledge of the subject matter to be studied (TK1)
2) Technological knowledge refers to knowledge about various technological tools that can be utilized in learning (TK2)
3) Pedagogical knowledge refers to knowledge about effective teaching methods in learning a concept (TK3)
4) Technological content knowledge refers to knowledge of subject matter that is suitable to be presented using technological assistance. (TK4)
5) Technological pedagogical knowledge refers to knowledge of how to effectively integrate technology with different teaching methods (TK5)

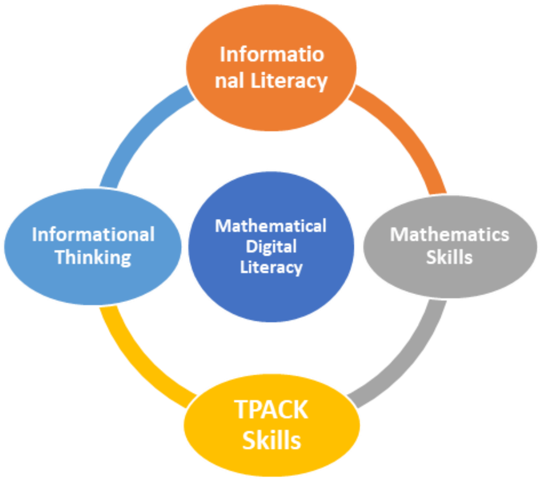

Figure 1: The relationship between mathematical digital literacy and its supporting components

6) Pedagogical content knowledge refers to knowledge of appropriate teaching methods for teaching various types of subject matter (TK6)
7) Technological pedagogical content knowledge is understood as knowledge about the appropriate use of technology in effectively applying teaching methods to various types of subject matter (TK7)

Mathematical digital literacy

Literacy is one of the mathematical abilities. Mathematical literacy is the individual's ability to formulate, use, interpret, and solve mathematics problems in various ways. The context for describing, explaining, and predicting phenomena related to the use of mathematics in life (Malasari et al., 2017). Mathematical literacy involves more than just carrying out procedures. Mathematical literacy includes mathematical reasoning and using mathematical concepts, procedures, facts, and tools. Individuals who are mathematicians can measure, describe information, understand everyday problems, reason in numerical, realistic, and geometric situations, and communicate using arithmetic (Ojose, 2011).

Computers have become a common part of our daily lives. Computer-based systems have dominated the needs of individuals and society, the need for global information depends on the ability to obtain, analyze, and utilize information rather than on the actual amount of factual encyclopedia knowledge (Donaldson & Alker, 2019a). That is why digital technology is one of the possible tools for the development of mathematical literacy, because digital technology offers a very efficient tool for learning, expressing oneself, and building, preserving, and sharing one's identity (Pradana et al., 2020). Although there is an increasing emphasis on the integration of ICT tools in mathematics learning, the ability to combine digital literacy skills and mathematical literacy is still not widely studied, several recent studies have begun to define the term digital mathematical literacy as a combination of digital literacy and mathematical literacy, although it is still not found a standard definition/consensus in general. It is time for special ICT literacy competencies to develop mathematical skills to be of special concern to educators, curriculum developers, and many other stakeholders in the field (Smart, 2017).

Students' digital mathematical literacy skills can be seen from five constructs, namely: basic, scientific, informational, technological, and visual (Zulkarnain et al., 2020). These components relate to the seven skills with ICT tools described by ETS (2003), but their use is specific to mathematics. More specific and detailed analysis is needed to find the intersection between digital literacy in mathematics learning. That is why digital technology is one of the possible tools of mathematical literacy development because digital technology offers a very efficient tool for learning, self-expression, and building a more comprehensive mathematical understanding. Digital mathematical literacy is a slice of several concepts, namely information literacy, informational thinking, literacy ability (mathematical literacy, science, social, etc.), and digital literacy, illustrated by Figure 1 (Dofková, 2016).

Although there are many variations in how students engage in certain mathematics learning activities using ICT, in general, there are 5 categorizations of indicators for the implementation of digital mathematical literacy development, namely: selecting and determining software/ ICT media that can be used to solve mathematical problems (DL1); understand and apply the syntax (steps to use) software needed in solving mathematical problems (DL2); translate and model mathematical problems using software (DL3); Interpreting software output results in finding the proposed mathematical solution (DL4); able to use software to prove that the proposed solution is correct (DL5) (Abel et al., 2018).

Learning spaces

Learning Management System (LMS) is the lifeblood of online learning in managing the learning process in class, both in delivering material, discussions, tests, and assignments (Bradley, 2020). The role of LMS in the educational environment has been studied by Jamal and Shanaah (Jamal & Shanaah, 2011), their research concluded that its use facilitates learning activities while helping students to learn from their friends. LMS leverages data and communications technology to develop creative approaches to learning. Furthermore, various educational processes are supported by the system; which is a full-scale learning platform (Alfailakawi, 2022).

Digital learning spaces (DLS) are a refinement of traditional LMS that have the advantage of using web technology to build flexible, inexpensive, and open-access personal teaching environments (PTEs) and personal learning environments (PLEs) within larger digital learning spaces that can be connecting students and educators from various regions in one integrated platform. These PTEs and PLEs contain the features educators and students need to make their online teaching and learning more interactive and effective (Dowling, 2012). DLS is made when people connect with each other and with the course material in this learning space. These PTE, PLE, and DLS can be used by people to help with their learning for a long time, and they do not have a specific time or course (Dowling, 2012; Moore-Russo et al., 2015; Wu, 2018).

As Alduwayrish (Alduraywish et al., 2022) make a report on what success factors will optimize the use of digital learning spaces, including management support (SL1), strengthening and standardization of IT(SL2), level of computer skills (SL3), proper training programs (SL4), human competencies (SL5), and networking space (SL6).

Information literacy and mathematical digital literacy

Since 2016, the Ministry of Education and Culture has programmed and intensified the school literacy movement to improve students' literacy skills in Indonesia which are still low (Pendidikan et al., 2019). The school literacy movement is a program to improve literacy culture in the school environment which is integrated into all subjects. The main goal of the school literacy movement is to create a society that is aware of the importance of literacy in the school environment, as well as creating quality students, and producing active learning by forming reading habits that are directed at developing learning in the revised 2013 curriculum. Information literacy skills are also very much needed, especially when the world is facing the COVID-19 pandemic where teachers require students to be able to search for references online independently. Learning that is almost completely carried out online requires students' skills to read, write, analyze, and make reports accurately (Iriani & Wicaksono, 2021).

Other empirical studies show that literacy information is related to the level of teacher readiness in preparing learning. A mathematics teacher must be able to prepare relevant teaching materials, literature sources, and both printed and video materials that support the learning process in the classroom. Without good literacy skills from a teacher, a teacher can't be able to create a conducive learning atmosphere and achieve the learning objectives to be achieved. Information literacy indicators are by the big 6 characters. The literacy model proposed by Eisenberg and Berkowitz (1987) includes: formulating the problem, information search strategy, allocation and access utilization of information, synthesis, and evaluate are also related to indicators of mathematical digital literacy abilities (Catss, Ralph; Lau, 2012; Iriani & Wicaksono, 2021; Wijaya, 2016).

Learning space and mathematical digital literacy

Lane (2016) wrote that the limitations of a teacher in online learning above are caused by the limited pedagogical features inherent in the LMS. He believes that LMSs were originally designed based on the traditional approach of one-way presentation and assessment. The main features educators encounter in a traditional LMS are tools that allow them to present content, assess learning, and create discussion forums. After teachers learn how to use these tools well, they might stop trying new ways to use their learning system. This means they might miss out on other cool tools that could help their students learn in different ways. Dowling (2012) stated that a more creative and advanced LMS can make online learning better. It can help teachers and students communicate better and improve the quality of learning. It can also help students learn math better by providing helpful features created by math teachers. Digital Learning Spaces (DLS) is a refinement of traditional LMS, DLS can provide features that can help students learn the material that has been provided which was designed by mathematics teachers.

Technological pedagogical and content knowledge (TPACK) skills and mathematical digital literacy

The conceptual framework of this study is grounded in the understanding that effective mathematics teaching in the digital age requires a comprehensive integration of content knowledge, pedagogical knowledge, and technological knowledge, as captured by the TPACK framework (Koehler et al., 2014). TPACK is a theoretical model that describes how teachers integrate technology into their instruction in ways that are contextually appropriate and pedagogically sound. In this model, the intersection of these knowledge domains—Technology (TK), Pedagogy (PK), and Content (CK)—produces TPACK, a unique form of teacher knowledge required for teaching effectively with technology.

In this study, TPACK skills are conceptualized as a critical antecedent to Mathematical Digital Literacy (MDL**)** among prospective mathematics teachers. MDL refers to the ability to understand, represent, evaluate, and communicate mathematical ideas using digital tools and resources. This includes competencies such as using dynamic geometry software, spreadsheets for data analysis, digital graphing tools, and online platforms for collaborative mathematical problem-solving (Borba et al., 2016; Walshaw, 2012). The central premise of the framework is that TPACK skills empower teachers not only to use technology, but to use it in ways that align with mathematical content and sound pedagogy. Teachers who possess strong TPACK are expected to design instructional activities that leverage digital tools to enhance mathematical understanding, foster student engagement, and facilitate meaningful assessment. As such, TPACK acts as a catalyst for developing MDL, enabling teachers to guide students in using technology to explore mathematical concepts critically and creatively.

This relationship is especially relevant in the context of digital transformation in education, where prospective teachers are expected to navigate complex digital environments while maintaining high standards of mathematical instruction. By situating TPACK as a key predictor of MDL, the study offers a conceptual pathway that connects teacher preparation to 21st-century learning outcomes. Furthermore, the framework incorporates information literacy and learning space optimization as additional factors that support the development of both TPACK and MDL. Information literacy enables teachers to search, evaluate, and apply digital mathematical resources effectively, while optimized learning spaces—whether physical or virtual—create the environmental conditions necessary for implementing TPACK-based instruction. Together, these constructs form a multidimensional model that reflects the interconnected nature of teacher competencies in a digitally mediated mathematics education landscape.

To address the aforementioned issues, this study proposes a solution by examining the relationships among information literacy, optimized learning spaces, TPACK, and digital mathematics literacy. Analyzing these relationships is essential because it can reveal the degree to which each factor contributes to the development of digital mathematics literacy and whether their interactions form a coherent framework that supports teacher readiness. Moreover, understanding these dynamics provides empirical insights for improving teacher education programs and equipping future teachers with the competencies needed to integrate digital technologies into mathematics education meaningfully. By doing so, this study seeks to fill the gap in current research, which often treats these variables in isolation rather than as part of a holistic model that reflects the complex realities of digital teaching and learning.

The contribution of this research is threefold. First, this research will contribute to the literature on information literacy, TPACK, and the role of Learning Spaces as well as mathematical digital literacy, which has not been studied much in previous research. Second, this research contributes to strengthening the importance of the mathematical digital literacy model as a model that can strengthen the skills of a mathematics teacher before the teacher is sent to school to teach. Eventually, it is trusted that this examination will make a noteworthy commitment to the approach changes being arranged by the government and the private segment. The following research questions are directed to achieve the aims of this recent study, such as:

1) Does information literacy have a positive effect on mathematical digital literacy?
2) Does learning space have a positive effect on mathematical digital literacy?
3) Does TPACK have a positive effect on mathematical digital literacy?
4) Does information literacy have a positive and significant effect on digital mathematics literacy skills through TPACK Skills?
5) Does information literacy have a positive and significant effect on digital mathematical literacy skills through learning space optimization?

METHODS

Research design, population, and sample

The method is non-experimental research with a causal correlation design and a quantitative approach using the Structural Equation Modeling (SEM) analysis method. The population in this study were prospective mathematics teacher candidates on the islands of Java and SumatraData were collected using a questionnaire (Google form) which was distributed to prospective mathematics teacher students in several regions in Indonesia, distributed in the period from September 2022 to July 2023. Study participants were anonymous, and they voluntarily filled out the questionnaire. using purposive sampling, a total of 266 respondent answers were received from state and private universities in the provinces of Riau, West Sumatra, Bengkulu, Banten, Jakarta, West Java, Yogyakarta, and East Java. After selecting the data, we discarded 50 incomplete data, and the remaining data of 216 respondents were suitable for analysis. The implementation of this research has received ethical permission from the Indonesian University of Education.

Measurement

For the Measurement questionnaire, we used the Likert scale (Abdullah et al., 2019), with a 5-point scale, ranging from 1 (strongly disagree) to 5 (strongly agree). This is used to evaluate each component to measure attitudes, opinions, and perceptions of a person or group of people about social phenomena. The instrument used to measure the Information Literacy variable refers to the Big 6 Skills concept model which was developed by Michael B. Eisenberg and Robert E. Berkowitz in 1987 (Iriani & Wicaksono, 2021), consisting of 6 items. The optimization of the Digital Learning Spaces variable was measured using an instrument adapted from Alduraywish (Alduraywish et al., 2022) consisting of 6 items. To TPACK skills, we adapted from Imania et al. (Imania et al., 2022), consisting of 7 items. Meanwhile, measuring Mathematical Digital Literacy was adapted from (Abel et al., 2018; Donaldson & Alker, 2019), consisting of 5 items. All indicators of each variables are presented in Table 1. Experts have tested all instruments to make sure they work well and give accurate results. The tests showed that the instruments are reliable and give good results.

Data analysis

The data consists of primary data and secondary data. Primary data was obtained through observation, questionnaires, and interviews, while secondary data was obtained through a literature study. Data analysis was carried out using descriptive analysis and model analysis using Partial Least Square – Structural Equation Modeling (PLS-SEM) developed by Herman Wold (Dijkstra, 2010). SEM is a combination of two separate statistical methods, namely factor analysis (factorial analysis) developed in psychology and psychometrics and simultaneous equation modeling developed

Table 1.
Indicator of each variables

Variable	No	Statement	Reference
Information Literacy	DL1	I am able to define what information I need before starting a task.	(Eisenberg & Dean, 2003)
	DL2	I can identify effective sources to find information.	
	DL3	I know how to use different tools (books, internet, databases) to access information.	
	DL4	I can evaluate the quality and reliability of the information I find.	
	DL5	I am able to use the information I find to complete academic tasks or solve problems.	
	DL6	I know how to properly present and cite the information I use.	
Digital Learning Spaces Optimization	LM1	I actively use the features of the LMS (e.g., quizzes, forums, resources) for learning.	(Alduraywish et al., 2022)
	LM2	The LMS helps me manage my learning activities more efficiently..	
	LM3	I find it easy to access and navigate content in the LMS.	
	LM4	I use LMS to collaborate and communicate with peers and instructors.	
	LM5	The LMS supports my ability to learn mathematics digitally.	
	LM6	I am confident in using the LMS independently for academic tasks.	
TPACK Skills	TP1	I understand the mathematical content that I need to teach.	(Koehler & Mishra, 2008)
	TP2	I can use appropriate teaching methods to help students understand mathematics.	
	TP3	I know how to use technology to support the teaching of mathematical concepts.	
	TP4	I can integrate technology into lesson planning effectively.	
	TP5	I choose technological tools that align with the mathematics content.	
	TP6	I understand how students learn mathematics using digital tools.	
	TP7	I can reflect on and improve my teaching using feedback from technology-based tools.	
Mathematical Digital Literacy	LD1	I am able to interpret and analyze mathematical data using digital tools.	(Abel et al., 2018; Donaldson & Alker, 2019)
	LD2	I can use digital platforms (e.g., GeoGebra, Desmos, Excel) to solve math problems.	
	LD3	I am confident in representing mathematical ideas through digital media.	
	LD4	I can critically evaluate mathematical information presented in digital formats.	
	LD5	I can communicate mathematical reasoning using digital tools effectively.	

econometrically. With the SEM method, the effect of exogenous variables on endogenous variables can be identified (Bluman, 2012)

Results of data analysis using SMART-PLS software. Smart PLS is data processing software for structural Equation Modeling (SEM) research that uses the Partial Least Squares (PLS) method. The Institute of Hamburg Germany created this software, and now it is famous and used by people all over the world. By going through the first stage, measuring the outer model. Outer model test results to test convergent validity (AVE more than 0.5), discriminant validity (diagonal variable must be more than 0.7), and composite reliability (CR more than 0.7). According to Hair et al (Hair et al., 2017), the construct score (factor loading) is higher than 0.7. All variables in this study have a Composite reliability score above 0.8, which means that all constructs meet the dependency requirements. According to Hair et al. (2019), the AVE metric assesses convergent validity. The AVE value is at least 0.5, which ensures adequate convergent validity (Ab Hamid et al., 2017). All research variables have AVE values above 0.5, which indicates sufficient convergent validity. For discriminant validity, we estimated using the Fornell-Larcker (Ab Hamid et al., 2017). The correlation between items of one construct and the square root of the AVE should be greater. Meanwhile, secondly, measuring the inner model and testing hypotheses. Testing the inner model using bootstrapping techniques to test the hypothesis. The suitability test between the theoretical model and empirical data can be seen in the goodness-of-fit test results. A model is said to be fit if the covariance matrix of a model is the same as the covariance matrix of the observed data (Meyers, Lawrence S, Gamst., 2005).

FINDINGS

Respondent profile

In this section, the results of the study are presented which include demographic data, and descriptive data regarding the distribution of area of origin of prospective mathematics teachers in respondents from a questionnaire distributed, which can be seen in Table 2. The table shows the distribution of data taken by researchers randomly. By coordinating with fellow lecturers at several universities in Indonesia, we obtained a distribution of student data from various provinces on the islands of Java and Sumatra with a distribution of West Java (15.7%), Jakarta (11.3%), Banten (16.9%), Yogyakarta (15.5%, Riau (16.9%), Bengkulu and West Sumatra (8.6%).

Measurement model assessment

Data analysis techniques in PLS with Smart PLS software version 3.0 with the following stages:

Outer model testing,

Outer Model Testing specifies the relationship between latent variables with their indicators, or so to say that the outer model defines how each indicator relates to variables latent. Test performed on the outer model are presented as follows.

Convergent validity

Convergent validity is a way to check if a measurement model is accurate. We use SmartPLS software to look at how well items or parts of the model are related to each other. The size for individual reflexive indicators and the results of processing using SmartPLS can be seen in Table 3. The score for each construct indicator has met the required convergent validity, which is higher than 0.7. Based on Table 3., During the first test, several indicators had an outer loading value of less than 0.7, namely: LT 5, SL1 and SL3, TK2, TK3, and TK4, therefore these items were excluded from the model and retested (Imania et al., 2022). Because all loading factors are more than 0.7, all the variables used have good validity. Based on the results of testing the value of factor loading, it can be concluded that all indicators are valid and able to explain latent variables.

Discriminant validity

Discriminant validity measures how far a construct differs from other constructs. The meaning of a high discriminant validity value is that it provides evidence that a construct is different and capable of capturing the phenomenon being measured. The way to test discriminant validity is to compare the square root value of AVE (√AVE) with the correlation value between constructs. With SmartPLS, discriminant validity is obtained by looking at the Cross-Factor Loadings values. Average Variance Extracted (AVE). Expected AVE value > 0.5. The results of the discriminant validity testing can be seen in Table 4.

According to Table 4, the numbers on the diagonal are the AVE roots and the other numbers are the correlation coefficients between constructs. The construct needs to be different from other things. To do this, the average value extracted (AVE) should be higher than the correlation coefficient.

Table 2
Profile of respondents based on province of origin

Area Code	Province	Number of Respondent	Percentage (%)
I	West Java	42	15,7 %
II	Jakarta	30	11,3 %
III	Banten	45	16,9 %
IV	Yogyakarta	41	15,5 %
V	Riau	45	16,9 %
VI	Bengkulu	40	15,0 %
VII	West Sumatera	23	8,6 %
Total		266	100,00%

Table 3
The convergent validity result

	Information Literacy	Mathematical Digital Literacy	Learning Space	TPACK Skills
MD1		0.712		
MD2		0.793		
MD3		0.814		
MD4		0.821		
MD5		0.806		
IL1	0.780			
IL2	0.743			
IL3	0.756			
IL4	0.802			
IL6	0.712			
SL2			0.786	
SL4			0.750	
SL5			0.815	
SL6			0.806	
TK1				0.802
TK5				0.833
TK6				0.780
TK7				0.815

Because all the correlation coefficient numbers are smaller than the AVE root value, it can be concluded that the constructs developed in measuring the variables information literacy, optimized learning space, TPACK skills, and mathematical digital literacy have good discriminant validity.

Methods for assessing reliability

Method for assessing reliability can be determined with a composite reliability value greater than 0.7. Nevertheless, according to Beghozzi and Yi (Bagozzi & Youjae Yi, 1988), a value of 0.6 for composite reliability in exploratory research is still acceptable. Besides that, construct reliability can also be seen from the results of Cronbach's Alpha test. These results can be seen in the following table. The following Table 5 shows the value of composite reliability and Cronbach's Alpha.

From the Table 5, all the indicators and variables in the study can be said to be good, because they have a composite reliability value and a Cronbach's Alpha value greater than 0.7 (≥ 0.7). All values or scores of each variable are above the value of 0.9, which is between 0.91-0.96. In short, the test shows that each variable is very reliable.

Table 4
Discriminant validity (Fornell-Larcker criterion)

	IL	MD	LS	TK
IL	0.759			
MD	0.597	0.790		
LS	0.715	0.737	0.790	
TK	0.637	0.657	0.666	0.807

Note. IL = Information Literacy; MD= Mathematical Digital Literacy; LS= Learning Spaces; TK= TPACK
Source: Authors own result, based on Smart PLS software

Table 5
Construct reliability and validity

	Cronbach's Alpha	rho_A	Composite Reliability	(AVE)
IL	0.817	0.826	0.872	0.576
MD	0.849	0.854	0.892	0.625
LS	0.798	0.799	0.869	0.624
TK	0.823	0.825	0.882	0.652

Source: Authors own result, based on Smart PLS software

Table 6
Relationship between variables

Code	Hypothesis	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
H1	IL → MD	0.597	0.604	0.044	13.727	0.000
H2	IL → LS	0.715	0.719	0.032	22.542	0.000
H3	IL → TK	0.637	0.642	0.042	15.110	0.000
H4	LS → MD	0.994	0.992	0.027	37.156	0.000
H5	TK → MD	0.113	0.116	0.030	3.738	0.000

Structural model analysis (inner model testing)

The second stage of analysis is to test or measure the structural model, or it is called the measurement of the inner model. After reliability and validity tests, the measurement model shows that the specified requirements are accomplished. the structural model was evaluated to evaluate the significance of the path coefficients in this study. A bootstrap resampling approach was used with 1000 replications. A test of the inner model or structural model is carried out to see the relationship between the constructs, the significance value, and the R-square of the research model. The model's structure was assessed by looking at how well the t-test matches up with the dependent construct, and by checking if the coefficients for the structural paths are significant.

The next analysis is to analyze the relationship between the expectation variable and the withdrawal behavior variable. With PLS-SEM, we measure the relationships between things by calculating the path coefficients for each relationship (path analysis). We studied this relationship by sampling the data and using the bootstrapping method. This bootstrapping is meant to reduce the issue of strange research data. Table 6 shows the results of the t-test, which shows the significance of the causal relationship if the test value is more than or equal to 1.96 and the p-value is less than 0.05.

According to Table 6, the results of measuring or testing the relationship between variables show that the relationship variables are information literacy, optimized learning space, and mathematical digital literacy. The results above reflect the Path coefficients which are the results of

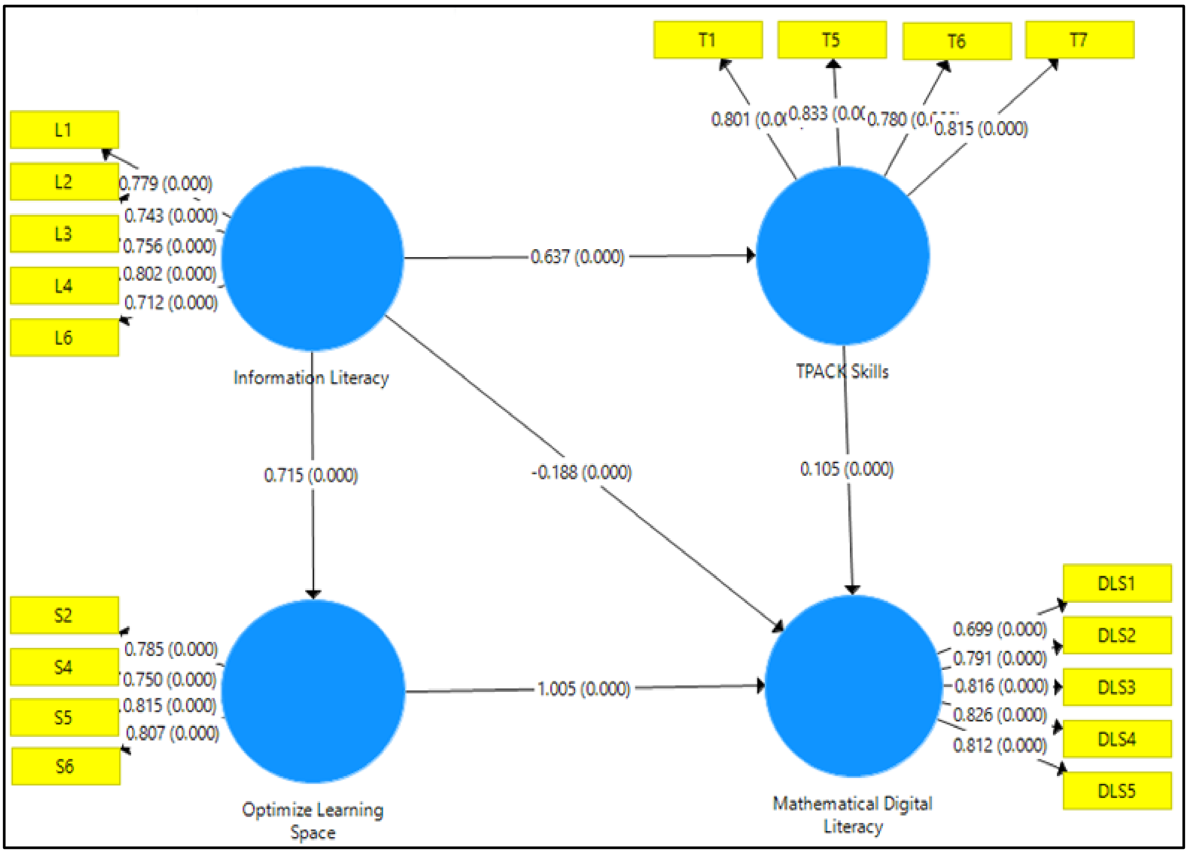

Figure 2. First Order design model of the influence of informational literacy, learning spaces, and TPACK on the mathematical digital literacy

testing the direct effect This value is greater than the t-table (1.36) with a significant level of 90% and an alpha of 10% so that it can be concluded as follows:

Relationship between information literacy and mathematical digital literacy

Information literacy has a positive effect on digital literacy mt statistic 13.727 ($p<0.05$). The total direct effect is 0.597; this shows that the effect of information literacy on mathematical digital literacy is positive, meaning that better information literacy will increase mathematical digital literacy. A p-value of 0.000 or lower than the significance level of 0.05 indicates that information literacy has a significant effect on the implementation of mathematical digital literacy.

Relationship between information literacy and optimizing learning spaces

Information literacy has a positive effect on optimizing learning spaces with a t statistic of 22.542 ($p<0.05$). The total direct effect is 0.715; this shows that the effect of information literacy on learning spaces is positive, meaning that better information literacy will increase optimized learning spaces. The p-value of 0.000 or lower than the significance level of 0.05 indicates that information literacy has a significant effect on the optimization of learning spaces.

The significant role of optimized learning spaces in shaping informational literacy among pre-service teachers can be interpreted through the lens of recent educational reforms in Indonesia. The *Merdeka Belajar* curriculum, which calls for more flexible, student-centered pedagogies, implicitly necessitates adaptive physical and digital learning environments. However, many Indonesian higher education institutions continue to face infrastructural and pedagogical limitations. Therefore, learning spaces that are intentionally designed to support autonomy, digital engagement, and collaboration become critical enablers of reform goals. These findings are also consistent with (Valentia, 2023), who highlight infrastructural disparities across regions, reinforcing that learning space design is not merely a logistical concern, but a strategic factor in equitable, quality education delivery.

Relationship between information literacy and TPACK skills

Information Literacy has a positive effect on TPACK Skills with t statistic 15.110 ($p<0.05$). The total direct effect is 0.637; this shows that the effect of information literacy on TPACK Skills is positive, meaning that better information literacy will increase TPACK Skills. The p-value of 0.000 or lower than the significance level of 0.05 indicates that information literacy has a significant effect on the optimization of learning spaces.

Relationship between optimized learning spaces and mathematical digital literacy

Information literacy has a positive effect on optimizing learning spaces with t-statistic 3.738 ($p<0.05$). The total direct effect is 0.715; this shows that the effect of optimized learning spaces on mathematical digital literacy is positive, meaning that better optimized learning spaces will increase mathematical digital literacy skills. The p-value of 0.000 or lower than the significance level of 0.05 indicates that information literacy has significant effect on the optimization of learning spaces.

The finding that *learning space* exerted the strongest direct effect on mathematical digital literacy ($\beta = 0.994$, $p < 0.05$) warrants deeper interpretation beyond statistical significance. This exceptionally high beta coefficient indicates a near-linear relationship, suggesting that the optimization of learning spaces—both physical and virtual—plays a pivotal role in fostering students' ability to engage with mathematical content using digital tools. In the Indonesian context, this may be explained by the increasing integration of technology in education through national policies such as the "Merdeka Belajar" curriculum and the push for hybrid learning post-COVID-19. Unlike more technologically saturated countries, where the TPACK framework often yields the highest influence (Koehler et al., 2013), Indonesian teacher candidates may be more affected by whether they have access to supportive digital environments, such as structured LMS platforms or school-based ICT labs, which are still unevenly distributed across regions (Haviz et al., 2020). This could explain why *learning space* outperforms TPACK in this model.

Relationship between TPACK skills and mathematical digital literacy

TPACK Skills has a positive effect on Mathematical Digital Literacy with t-statistic 15.110 ($p<0.05$). Total direct effect is 0.113; this shows that the effect of TPACK Skills on Mathematical Digital Literacy is positive, meaning that the better TPACK Skills will increase mathematical Digital Literacy. The p-value of 0.000 or lower than the significance level of 0.05 indicates that information literacy has a significant effect on the optimization of learning spaces. After revising the model through the modification indices technique, a new model was obtained. The resulting new model is presented in Figure 2.

The above research can be a basis for further theoretical development, where based on the SEM PLS test results it shows that there is a close relationship between information literacy, optimizing learning spaces, and TPACK skills with digital mathematics literacy skills, digital mathematics literacy skills are needed because of the need for competencies that cannot be achieved. completed using only mathematical literacy or digital literacy, but must collaborate on both competencies as a whole, namely digital mathematics literacy, so that digital mathematics literacy needs to be the focus of further research studies. Several studies on digital literacy and its relationship to mathematics learning are in line with several researchers including Machaba (Machaba, 2018) about the urgency of pedagogic skills needed in mathematical literacy, which include TPACK mastery skills in learning.

DISCUSSION

RQ1–RQ3: The effects of information literacy, learning spaces, and TPACK on digital mathematics literacy

The findings confirm that information literacy ($\beta = 0.328$, $p < .05$), learning spaces ($\beta = 0.994$, $p < .05$), and TPACK ($\beta = 0.221$, $p < .05$) each significantly affect digital mathematics literacy (DML) among prospective mathematics teachers. Among these, learning spaces exhibited the strongest influence, with a path coefficient nearing 1.0, indicating a nearly perfect positive linear relationship. This unexpectedly strong effect of learning spaces may be interpreted through both theoretical and contextual lenses. In the Indonesian context—particularly within public and private universities concentrated in Java and Sumatra—classroom and digital learning environments are increasingly being redesigned with government and institutional support, such as digital classrooms, Digital Learning Spaces platforms (e.g., SPADA Indonesia), and high-speed internet access. This structural development arguably provides the enabling environment that allows students to engage deeply with digital mathematical content (Zulkarnain et al., 2020). The dominance of this variable diverges from findings in Western contexts, where TPACK tends to be a stronger predictor (Angeli & Valanides, 2009; Zelkowski et al., 2013). This may reflect Indonesia's ongoing infrastructural digital transition, where physical and digital access remain primary conditions for effective learning, unlike in digitally mature systems where TPACK is more critical.

RQ4–RQ5: Mediating roles of Learning spaces and TPACK

The mediating role of learning spaces between information literacy and DML was statistically significant, suggesting that the effect of information literacy is amplified when embedded within supportive learning environments. This aligns with Vygotsky's sociocultural theory, where the zone of proximal development (ZPD) is optimized by contextual supports—such as spatial configurations and access to digital tools—that scaffold learning (Dofková, 2016).

Meanwhile, the mediating role of TPACK between information literacy and DML was also statistically supported, though with a smaller path coefficient. This suggests that while prospective teachers may possess the ability to search and evaluate information, their capacity to transform that information into pedagogically and technologically sound instructional strategies remains moderate. These results partly support (Koehler & Mishra, 2005) model but suggest contextual nuances: while TPACK is indeed essential, its development may be hindered by limited pedagogical training in digital integration during pre-service education in Indonesia (Yayuk et al., 2020).

The findings of this study are also in line with Zulkarnain (Zulkarnain et al., 2020) who found an increase in students' digital literacy skills in using e-learning in mathematics learning, then Pradana and Sholikhah (Pradana et al., 2020) connecting the Mathematics Kit virtual learning media with increasing mathematical literacy. Dofkova (2016) examined the positive relationship between mathematical digital literacy in the training of prospective teachers, then Abel et al. (Abel et al., 2018) reviewed literature studies regarding the characteristics of digital mathematics literacy, the results of the research emphasized the need for appropriate learning design studies that are useful or suitable for improving digital mathematics literacy skills. The following five items are stages of implementing digital technology in the next generation of mathematics classes, including: 1) Prepare digital-based mathematics learning activities to help students achieve learning goals. Most learning activities currently use ICT. Even teachers who are not supporters of the application of digital technology in teaching often look for new sources and inspiration on their computers, therefore a teacher needs to prepare digital-based learning activities so that students' access to knowledge becomes wider and increases. 2) Use computers and ICT to help teach mathematics. Nowadays, the use of ICT is nothing new. On the other hand, it is necessary to establish whether prospective mathematics teachers can use new digital technologies as a resource in teaching mathematics. Teachers can use computer-assisted learning models using mathematics learning software such as GeoGebra, Cabri-3D, and others to help students construct their understanding of concepts. 3) Creating an environment that supports the implementation of integrated mathematics learning using digital technology. 4) Incorporate effective classroom management strategies into your mathematics teaching, armed with teacher expertise in mastering TPACK. In next-generation classrooms/digital space learning, teachers must use effective strategies in teaching mathematics to develop the learning, problem-solving, social, personal, and civic competencies required under the Education Program Framework for Primary and Secondary Education. Mathematics teachers in the future must be aware of these competencies and must be ready to develop these TPACK skills in their work. 5) Future classroom learning must be able to provide a positive influence on students who have difficulty or are unmotivated in mathematics. The inclusion of digital technology in mathematics learning can have a positive influence on students who are less motivated or less involved in learning mathematics. The presence of digital technology is expected to be able to increase interactivity and connectivity in learning which may be able to attract their attention to mathematics so that learning goals can be achieved more optimally.

CONCLUSION

Based on the results of SEM testing through SMART PLS, all indicators meet the valid and reliable item criteria and can reflect latent variables. The R-Square value is 0. 901, which means that 90. 1% of the variability in mathematical digital literacy is due to the factors we studied, while 9. 9% is due to other factors we didn't study. Based on the results of the assumption test, validity test, and model fit test, it can be concluded that the SEM model in this study is suitable and feasible and can describe the theory and findings in the field. Based on the inner model test, it can be concluded that information literacy (LT), optimized learning spaces (LS), and TPACK skills (TK) have significant effects on mathematical digital literacy (DL) in terms of estimates and P <0.05. This states that the higher we increase information literacy, the TPACK skills of prospective teachers, and optimizing learning spaces, the more we will be able to increase the mathematical digital literacy of prospective mathematics teachers. The variable that has the highest influence is that optimizing learning spaces provides the greatest contribution to increasing digital mathematical literacy. prospective mathematics teacher.

This study supports the idea that the study of mathematical digital literacy is a strategic subject in the era of the Industrial Revolution 4.0 which demands mastery of technology in every area of life (Pratama & Hartini, 2019; Techataweewan & Prasertsin, 2018; Yuliardi et al., 2021). The recommendation from the initial literature study regarding the study of mathematical digital literacy is that there is an increasing need for the implementation of learning technology, especially in learning mathematics so that an increase in competence by teachers and students is needed in integrating technology in learning mathematics. Apart from that, it is also necessary to pay attention to the lowest indicators of each variable so that improvements and development plans are based on improving digital literacy skills, especially for student mathematics teacher candidates, Furthermore, we need to do more research on how well people understand and use math in digital formats. This includes understanding how well people understand math concepts and how good they are at using math in real life. We also need to study different ways of teaching and learning math digitally. In addition, support from policymakers is needed to support the integration of ICT in mathematics learning in Indonesia.

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AUTHOR'S DECLARATION

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Competing interests	The authors declare that the publishing of this paper does not involve any conflicts of interest. This work has never been published or offered for publication elsewhere, and it is completely original.

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