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Article

The effect of digital leadership in nurturing teachers' innovation skills for sustainable technology integration mediated by professional learning communities

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Abstract: This study aimed to examine the impact of digital leadership among school principals and evaluate the mediating effect of Professional Learning Communities (PLCs) on enhancing teachers' innovation skills for sustainable technology integration, both in traditional classroom settings and e-learning environments. Employing a quantitative approach with a regression design model, Structural Equation Modelling (SEM) and Partial Least Squares (PLS-SEM) were utilized in this research. A total of 257 teachers from 7 excellent senior high schools in Makassar city participated in the study, responding to the questionnaires administered. The study findings indicate that while principal digital leadership does not directly influence teachers' innovation skills in technology integration, it directly impacts Professional Learning Communities (PLCs). Moreover, PLCs themselves have a significant influence on teachers' innovation skills in technology integration. The structural model presented in this study illustrates a noteworthy impact of principal digital leadership on teachers' innovation skills for technology integration through Professional Learning Communities (PLCs), with a coefficient value of 47.4%. Principal digital leadership is crucial in enhancing teachers' innovation skills for sustainable technology integration, primarily by leveraging Professional Learning Communities (PLCs). As a result, principals must prioritize the creation of supportive learning environments and implement programs to foster teachers' proficiency for sustainable technology integration. Additionally, teachers are encouraged to concentrate on communication, collaboration, and relationship-building with colleagues to exchange insights, address challenges, and devise solutions for integrating technology, thereby contributing to sustained school improvement efforts. Finally, this research provides insights for school leaders, policymakers, and educators, emphasizing the need to leverage PLCs to enhance teaching practices and student outcomes, particularly in sustainable technology integration.

Keywords: digital leadership; digital skills; digital innovation; PLCs; teachers' technology integration

1. Introduction

Teachers are essential for helping students learn about the environment and how to adapt to environmental changes. Education for Sustainable Development (ESD) involves teaching students in a way that helps them learn and grow in many different ways, like thinking, socializing, and behaving (Rauch and Steiner, 2013). In the 21st century, education, like other facets of human life, grapples with the transformative influence of rapid information and communication technology advancements. Indonesia's educational landscape, specifically cultivating individuals, notably teachers, lags in embracing digitalization. Consequently, there is a critical need for solutions centered around literacy, trust, safety, and policy considerations. Research indicates that a prevalent challenge in educating teachers lies in their perceived lack of optimal technological skills, particularly in Indonesia, where the incorporation of technology tools in learning activities, especially in rural areas, is infrequent (Adisel and Prananosa, 2020; Delia et al., 2018; Kuncoro et al., 2022; Latip, 2020; Subandiyo, 2016). Nurturing teachers' capacity and innovation skills for sustainable teaching involving technology is invariably linked to the effective leadership practices of school principals, especially in the era of Industry 4.0. Principal leadership plays a pivotal role in steering educational institutions through the challenges of digitalization and fostering change. Digital leadership emerges as a focal point for researchers exploring innovative approaches in teacher development. It is an effective model for principals to implement, ushering in transformative changes and fostering innovation within schools in the digital age (Domeny, 2017; Sheninger, 2014; Zhong, 2017). Numerous research studies on digital leadership exhibited by principals have demonstrated its positive impact on enhancing teachers' capabilities in general in integrating technology into the learning process (AlAjmi, 2022; Hafiza Hamzah et al., 2021; Karakose et al., 2021; Raman et al., 2019). The contextual exploration of principals' digital leadership, specifically its influence on teacher behavior and performance in the Indonesian educational setting, has also been examined (Prasojo and Yuliana, 2021; Timan et al., 2022).

Regrettably, deficiencies persist in earlier research efforts. Firstly, these studies gauged the integration of technology by teachers in a broad context (e.g., technology tools utilization), neglecting the need for quantitative research to address the specific skills (e.g., technological knowledge, teacher attitude and teacher practice in technology tool use) are essential for a comprehensive and sustained incorporation of technology into the learning process by teachers. (Skantz-Åberg et al., 2022). Secondly, they solely explored the direct correlation between digital leadership and teachers' integration of technology. Thirdly, a gap exists in research within the Indonesian school context, particularly in investigating how digital leadership influences teachers' innovation capabilities concerning sustainable technology integration. For instance, only Purnomo et al. (2023) and Sunu (2022) conducted quantitative research examining the impact of digital leadership on teachers' acceptance and utilization of digital technologies. Moreover, the development of teacher innovation skills is contingent on intricate thoughts, information diversity, collaboration, communication, and open discourse among teachers and colleagues in the workplace (Lee and Ip, 2023; Liu et al., 2022). These research inquiries delved into the professional development of teachers in innovation and the integration of technology in teaching, emphasizing its significance on Professional Learning Communities (PLCs) for future research. PLCs aim to enhance teacher skills and motivation through ongoing professional development. However, in Indonesia, PLCs face challenges like low participation and continuity (Sunaengsih et al., 2020), insufficient professionalism and collaboration (Napitupulu and Wibawanta, 2022), and issues within teacher working groups (Simanjuntak et al., 2020). In this context, the success of PLC activities relies heavily on principals who lead, motivate, and facilitate. A positive school culture that fosters commitment, responsibility, collaboration, and ongoing improvement is crucial. Therefore, our study exists trying to fill these gaps and aims to construct a structural model in which PLCs serve as a mediating variable for the impact of digital leadership on teachers' innovation abilities for technology integration. This endeavor addresses practical issues in the context of educational leadership in Indonesian high schools. PLCs are reflective, collaborative, critical, and learning-centred initiatives among educators to augment their professional knowledge and practices. These contribute to continual improvement in schools (Balyer et al., 2015; Harris and Jones, 2018), specifically regarding teachers' sustainable technology integration capabilities (Kaschuluk, 2019; Lai et al., 2022; Thyssen et al., 2023).

Hence, in this study, we develop a conceptual framework for digital leadership among principals, drawing from the contemporary International Society and Technology Education for Administrators (ISTE-A) standard. This framework includes visionary planners, equity and citizenship advocates, empowering leaders, system designers, and connected learners (ISTE-A, 2018). Our objective is to investigate its influence on teachers' ability to adopt innovative practices for sustainable technology integration, drawing from Rogers' (2003) theory of innovation diffusion integrated with the Technology Acceptance Model (TAM) (Davis, 1985), which delineates the necessary skills for technology integration among educators. We also examine the mediating role of Professional Learning Communities (PLCs) within the context of Indonesian high schools. Previous studies have frequently utilized the diffusion of innovation and TAM models to explore teachers' acceptance and utilization of technology (A'mar and Eleyan, 2022; AlAjmi, 2022; Ghavifekr and Rosdy, 2015; Ghavifekr and Wong, 2022; Gyeltshen, 2021; Leong et al., 2016; Purnomo et al., 2023; Sunu, 2022). Furthermore, research has investigated the impact of principals' digital leadership on overall professional development (Banoğlu et al., 2023; Dexter and Richardson, 2020; Thannimalai and Raman, 2018; Zhong, 2017). Conversely, Hero (2020) found a minimal direct effect of principals' digital leadership on teachers' technological proficiency, suggesting the need for a more nuanced model. Thus, further investigation is essential to explore principals' digital leadership variables mediated by PLCs and their effects on teachers' innovation skills in technology integration using comprehensive assessments. We aim to explore four potential relationships between the exogenous and endogenous variables, explicitly examining how digital leadership affects teacher innovation skills for sustainable technology integration and the extent to which professional learning communities mediate this relationship. Finally, this study has profound implications for practitioners, educational policymakers, and school principals in Indonesia, providing practical insights to enhance teacher professional development initiatives and foster improved technology integration in both traditional and e-learning settings. Additionally, the study contributes to advancing our theoretical comprehension of educational leadership and technology integration while indicating directions for future research to explore the dynamic nature of digital leadership and teachers' innovation in light of evolving educational landscapes and sustainable technological progress.

2. Theoretical framework and hypotheses development

Digital leadership is one of the effective strategies for utilizing technology in achieving school goals. Leadership with a digital-based model can help develop an ideal learning environment that supports communication and collaboration among teachers and stakeholders in policy-making by maximizing technology use in its process and creating a digitalization vision that impacts the innovation ability of teachers for sustainable technology integration (see **Figure 1**). Empirical research has been conducted to see how the principal's digital leadership contributes to improving the quality of learning in the 21st-century era through the ability of teachers to integrate technology in the learning process according to the demands of circumstances and student needs in the 21st-century age (Hafiza Hamzah et al., 2021; Karakose and Tülübaş, 2023; Purnomo et al., 2023; Timan et al., 2022).

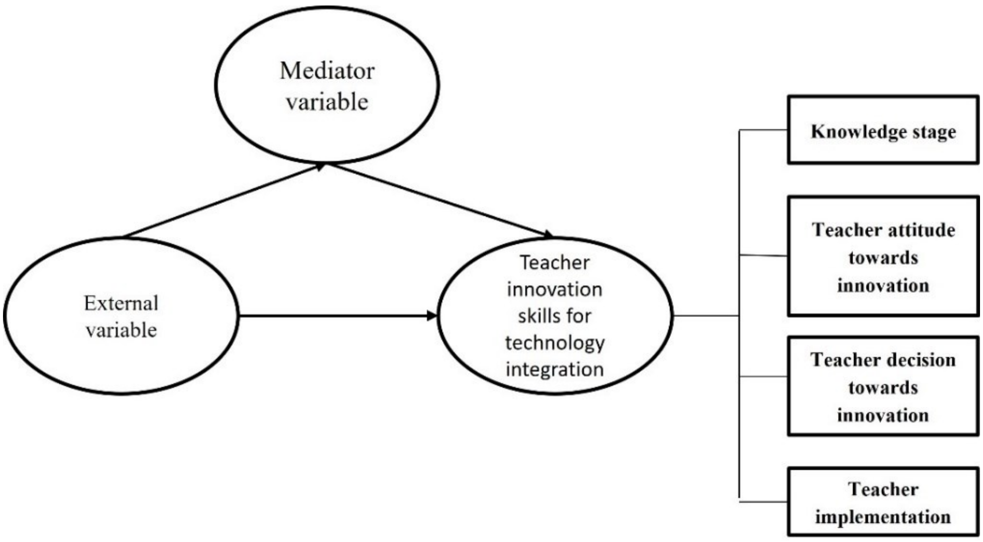

Figure 1. Theoretical framework of teacher innovation skills for technology integration.

Integrating information, communication, and technology (ICT) will help teachers change the conventional learning paradigm towards modern digital-based learning by utilizing the ease of technology tools (Ghavifekr and Rosdy, 2015; Hew and Brush, 2007; Instefjord and Munthe, 2017). Arkorful et al. (2021) emphasizes that diffusion theory is a model that can determine teachers' innovation in integrating technology into teaching and learning. Besides that, Ghavifekr and Rosdy (2015) also suggested that measuring the ability of innovation for teacher technology integration in the process is supported by teachers' basic knowledge of using technology, which aligns with the diffusion innovation theory. This framework is also aligned with the suggested theory by Davis (1985) on the Technology Acceptance Model (TAM). The two theories will lead to teachers' innovation capabilities in integrating technology. **Figure 1** represents the initial diffusion innovation by Roger (2003) combined with

TAM, suggested by Davis (1985).

2.1. Teacher innovation skills for sustainable technology integration (TIS)

Four steps must be passed in innovating, starting from the knowledge stage, persuasion stage, decision stage, and implementation stage (Rogers, 2003). In the first stage, knowledge is the initial stage that an individual must own to innovate, driven by awareness to create something new. Second, the persuasion stage is related to an individual's likes and dislikes (attitude) when making decisions in innovation. The third, the decision stage, concludes that individuals either adopt or refuse to innovate after going through the first and second stages. Finally, the implementation stage emphasizes behavior change shown in the form of individual actions or practices to carry out activities that produce innovation after deciding to commit to the process towards innovation.

Based on the steps towards innovation developed by Roger, it can be applied to the diffusion ability of teacher innovation. (Rogers, 2003) to the use of technology in teaching and learning integrated with the teacher acceptance model (TAM) (Davis, 1985) (see **Figure 2**).

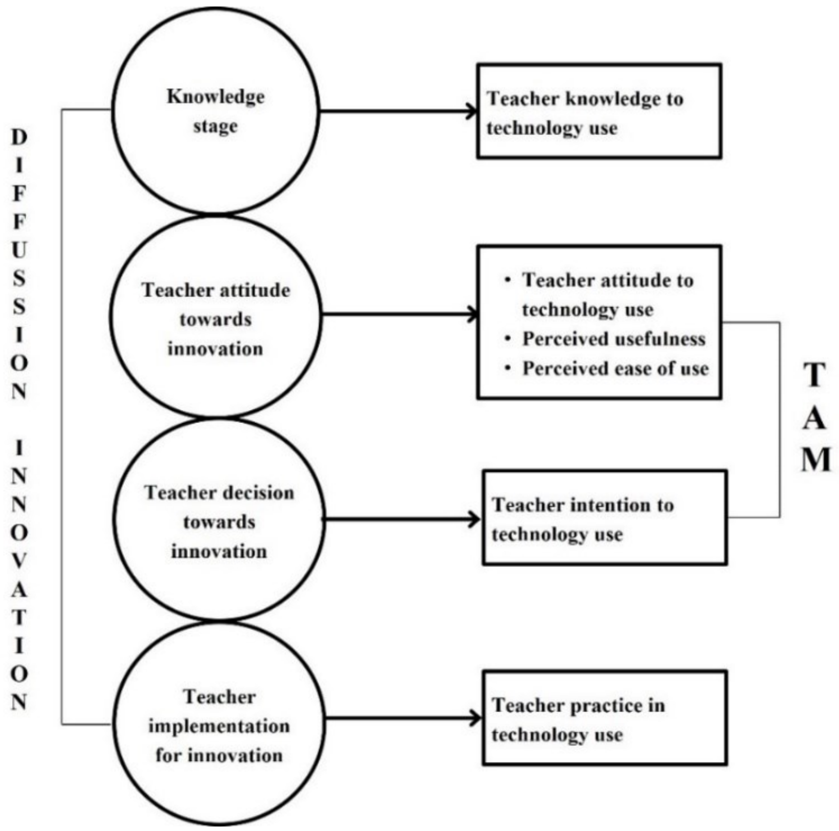

Figure 2. Theoretical and conceptual framework of teacher innovation skills using diffusion of innovation integrated with teacher technology acceptance model (TAM).

The first stage, knowledge, marks the initial step where individuals acquire the information necessary for innovation, driven by an awareness of the need to create something new. This stage is related to teacher technological knowledge in general

(Hämäläinen et al., 2021; Skantz-Åberg et al., 2022). The second stage, persuasion, is closely tied to an individual's preferences and attitudes, influencing the decision-making process in innovation. This stage is related to teachers' attitude to technology, use of their confidence, and perception of technology (Almås et al., 2021; Hämäläinen et al., 2021; Skantz-Åberg et al., 2022). Moving on to the third stage, the decision stage, individuals conclude whether to adopt or reject the innovation based on their experiences in the initial two stages. This stage is related to teachers' acceptance of technology utilization in the instruction (Sunu, 2022). Finally, the implementation stage underscores the need for behavioral change, manifested through individual actions or practices, as individuals commit to the innovation process and carry out activities that create something new. This stage is related to teacher practice on technology tools or strategy utilization in the teaching and learning process (Raman et al., 2019).

Empirical studies on teacher ICT integration have been conducted with digital leadership education and PLCs. First studies on the contribution of digital leadership principals (Hafiza Hamzah et al., 2021; Raman et al., 2019) and professional development described as PLCs (Cheng, 2017; Liu et al., 2022; Mei et al., 2019; Owen, 2015; Paulus et al., 2020; Thannimalai and Raman, 2018; Thoma et al., 2017) towards teacher ICT integration. In detail, Sangkawetai et al. (2020) found that teacher self-efficacy predicts teacher ability in ICT integration strategies in the classroom. Furthermore, Drossel et al. (2017) suggested that antecedents of school characteristics (ICT resources), teachers' attitudes (self-efficacy), teaching process (collaboration), and teacher background are predictors that influence teachers in the implementation of learning by integrating ICT in the process. In line with that, several studies have found explicitly that PLCs with the essence of collaboration have also been shown to have an impact on teachers' ability to use technology tools in the learning process (Cheng, 2017; Cifuentes et al., 2011; Paulus et al., 2020; Thoma et al., 2017; Vossen et al., 2020).

2.2. Principal digital leadership (DL)

The teachers' ability to integrate technology can be achieved through the role of the principal to make changes in several areas: infrastructure, structure, and policies in the organization, pedagogy and learning, and school culture (Edelberg, 2019; Sheninger, 2019). Based on these areas of change, the principal needs to have the relevant competencies represented in the latest ISTE-A (International Society for Technology in Education for Administrator) standard consisting of equity and citizenship advocate, visionary planner, empowering leader, system designer, and connected learner (ISTE-A, 2018). This standard is one of the effective benchmarks in measuring digital leadership in education that has been used globally. Previous studies have focused on how digital education leaders can build a vision for using technology in schools (Dexter and Barton, 2021). However, empirical research is still limited that measures the contribution of principals' digital leadership to teachers' innovation skills for technology integration in the learning process (Dexter and Richardson, 2020), specifically in the Indonesian context. Besides, principals' digital leadership is increasingly recognized as crucial in developing and succeeding professional learning communities (PLCs) in schools. Principal digital leadership plays a crucial role in PLCs by promoting visionary and inclusive leadership, encouraging collaboration and trust among staff (Antinluoma et al., 2021), and utilizing virtual platforms for ongoing professional development and innovation (Pashmforoosh et al., 2023).

The five ISTE-A standards can be used as a benchmark to measure the digital leadership competence of school principals as a predictor for PLCs and teacher innovation skills for technology integration in improving the quality of offline teaching and e-learning. First, visionary planners are defined as the ability of school principals to establish communication and involve school stakeholders in the development and determination of school vision with a combination of digitalization under the product and demands of the 21st-century era (Chua and Chua, 2017; ISTE-A, 2018). This is supported by Dexter and Richardson (2020) that change in organization and improvement of education begins with a vision built and monitored by leaders, both formally and informally. This vision is divided into several steps, which are creating, articulating, modeling, communicating, monitoring, and accounting for outcomes (Dexter and Richardson, 2020). Second, equity and citizenship advocates are related to the role of principals as digital leaders in ensuring equality, inclusion, and digital practices for all school residents, including teachers, without ignoring the ethical and legal use of technology (Dexter and Richardson, 2020; ISTE-A, 2018; Yuting et al., 2022). Third, the empowering leader is identified as the role of the principal as a formal leader to empower other staff, especially teachers, through daily routines in the use of digital tools (Dexter and Richardson, 2020; Tondeur et al., 2015; Vanderlinde et al., 2009). Fourth, the system designer is concerned with the role of the principal in building a team and designing systems to implement, maintain, and continuously increase the use of technology in supporting learning (Dexter and Richardson, 2020; ISTE-A, 2018). Lastly, connected learners are concerned with the role of principals in promoting continuous professional learning in developing technology instruction innovations for teachers and themselves (Gerard et al., 2008; ISTE-A, 2018).

Overall, principals' digital leadership significantly improves teachers' ability to integrate technology into their classrooms, which leads to increased student engagement and better learning outcomes (Bity Salwana Alias, 2023; Ghavifekr and Wong, 2022; Omar and Ismail, 2020). Furthermore, it also helps to improve the effectiveness of PLCs by supporting digital transformation, fostering teacher collaboration, and driving teaching innovation (Karakose et al., 2021; Navaridas-Nalda et al., 2020) However, these existing studies have not been done in the Indonesian context regarding how principal digital leadership influences PLCs and teacher innovation skills for sustainable technology integration. Given these research inquiries, two hypotheses were examined:

H_1: DL significantly affects TIS

H_2: DL significantly affects PLCs

2.3. Mediation of teacher professional learning communities (PLCs)

Generally, Professional Learning Communities (PLCs) offer significant benefits for schools, teachers, and students by fostering collaboration, professional development, and innovation, leading to improved teaching practices and student outcomes (Brown et al., 2018; Doğan and Adams, 2018; Liu et al., 2022). Thus, it is crucial to conduct investigations on PLCs to improve teacher competencies, which impact innovation and teaching quality in the 21st century. This is related to constructivist learning theory as a key to the success of Professional Learning Communities (PLCs) and sustainable technology integration (Wilson, 1996). In the context of PLCs, teachers engage in collaborative activities, discussions, problem-solving, co-constructing knowledge, and sharing best practices that lead to innovative teaching strategies. This collaborative process is essential for effective and sustained use of technology in the classroom, as it allows teachers to adapt to new tools and methods continuously. Digital leadership enhances this process by creating a supportive environment that encourages continuous improvement and experimentation with new tools. Therefore, principals who lead with a digital focus provide the resources and vision needed for PLCs to thrive, ensuring that technology integration is effective and sustainable.

Furthermore, Vescio et al. (2008) state that changes to the school's professional culture demonstrate that PLCs contribute to teachers' habits and mindset on daily tasks in the classroom. The context of PLC's contribution to teachers' ability to integrate technology has also been discussed by Owen (2015) articulating the effectiveness of PLCs in supporting teacher innovation in information and communications technology literacy. Ultimately, it was asserted that Professional Learning Communities (PLCs) represent a pragmatic strategy for enhancing teachers' capacity to innovate in education by integrating technology into the learning process. Aligned with Ottenbreit-Leftwich et al. (2010), emphasizes professional development in the context of Teachers' perceived technology use.

The main characteristic of PLCs is to promote collaboration or work collectively day-to-day in the teacher's professional environment to enhance the quality of learning (Bolam et al., 2005; Owen, 2015). Newmann (1996) broadly describes the essential characteristics that are idealized images of PLCs, which we used as an instrument in our study. First, shared values (shared responsibility) are related to teachers' responsibility in their role to enhance the learning quality process by working collectively (Lee and Louis, 2019). Second, reflective dialogue related to reflection among teachers through ongoing discussions about curriculum, instruction, and student development. Third, deprivatization practice is described as the openness of teachers to colleagues related to learning in the classroom to share and share through observation, discussion, and collaboration (Lee and Louis, 2019; Newmann, 1996).

Several empirical studies have also been conducted to identify the contribution of PLCs to teachers' technology integration in schools (Paulus et al., 2020; Vossen et al., 2020). Additionally, principals' digital leadership is crucial in facilitating this integration, mainly through establishing and supporting professional learning communities (PLCs) for teachers. Aligned with previous studies showed that school leaders can promote teachers' involvement in professional learning communities (PLCs), whether online, in-person, or hybrid, to enhance their technology integration skills by facilitating the sharing of resources, experiences, and best practices (Bingham, 2021; Dexter and Richardson, 2020). Although research shows PLCs contribute to positive school reform, concerns about methodological limitations in current studies suggest a need for more rigorous research to validate these findings (Doğan and Adams, 2018). Specifically, research on PLCs as a bridge to teacher innovation skills for technology integration learning is limited, especially with the principal's digital leadership as a predictor variable. Given these research inquiries, two hypotheses were examined:

H_3: PLCs significantly affect TIS.

H_4: DL significantly affects TIS through PLCS.

3. Materials and methods

This section contains several explanations regarding the methodology guidance we used in conducting this research, including guidance on research design, participant and procedure, instrument, and analysis.

3.1. Research design

Here is a revised version of your paragraph:

This study employed a quantitative approach, utilizing a regression design within an explanatory causality framework. The reason for choosing this approach was to identify and explain the causal relationships between the structural variables under investigation. This method was particularly suitable because it allowed for exploring how one variable influences another within a structured theoretical model, offering insights into the underlying mechanisms at play. Surveys, specifically questionnaires, were used as instruments to assess the alignment between theoretical constructs and empirical data to enable the collection of quantitative data that can be statistically analyzed to identify patterns, correlations, and causal relationships (Cresswell and Clark, 2014). The primary goal was to examine the influence of structural variables associated with principals' digital leadership on Professional Learning Communities (PLCs) and teachers' innovation skills in incorporating technology into teaching, using PLS-SEM (Partial Least Squares Structural Equation Modeling). The decision to utilize PLS-SEM for data analysis was based on its robustness in handling complex models with multiple variables, particularly in addressing how principals' digital leadership affects teachers' innovation skills for sustainable technology integration, mediated by PLCs. Additionally, PLS-SEM's ability to provide reliable estimates, even with smaller sample sizes, further justified its selection (Hair et al., 2021; Johnson et al., 2004).

3.2. Research population and sample

Data gathering for this study occurred in seven prominent high schools, encompassing both public and private institutions, located in the capital city of South Sulawesi Province, Makassar. The overall teacher population in these schools amounted to 428 individuals, as visualized in **Table 1**.

Table 1 represents the population of this study consisting of all teachers in top-ranking high schools in Makassar, chosen because these schools are observed to have implemented 21st-century digital leadership, which will provide primary data through online (Google form) and offline questionnaires completed by actively teaching teachers with a minimum of two years of experience. The sampling strategy employed was random sampling, guided by Isaac and Michael's table, with a 1% margin of error to ensure optimal results in the analysis process (Isaac and Michael, 1971). According to the Isaac table, out of the total population of 428 teachers, 257 were chosen as samples and respondents to examine structural model variables, including principal digital leadership (DL), Professional Learning Communities (PLCs), and teachers' innovation skills for technology integration.

Table 1. Research population and sample.

No.	School Name	Total of Teachers/Population	Sample
1.	Athirah	44	29
2.	Zion	40	28
3.	SMA Negeri 1	62	35
4.	SMA Negeri 2	68	34
5.	SMA Negeri 5	80	50
6.	SMA Negeri 17	53	30
7.	SMA Negeri 21	81	51
	Total	428	257

Source: Sekolah (n.d).

3.3. Research measurement

In this section, we provide the instruments and questionnaire items for each latent variable: DL (Digital Leadership), PLCs (Professional Learning Communities), and TIS (Teacher Innovation Skills), utilized to gather data from participants (see the Appendix). Content validity was ensured by reviewing the theoretical framework using IBM SPSS 25 as a tool to analyze the validity and reliability. Empirical trials involving 44 teachers were conducted to assess item validity through item-total analysis (α = 0.50). The questionnaire's reliability was evaluated using Cronbach's alpha (α = 0.60) (Sugiyono, 2019). Items failing to meet the criteria are excluded.

The criteria for assessing digital leadership align with the internationally recognized standards for Administrators set by the International Society for Technology in Education (ISTE-A). These standards, globally acknowledged, encompass dimensions such as equity and citizenship advocate, visionary planner, empowering leader, systems designer, and connected learner (ISTE-A, 2018). Several studies using this standard as a benchmark for digital leadership have found significant effects on teacher ICT integration (Edelberg, 2020; Hafiza Hamzah et al., 2021; Karakose and Tülübaş, 2023; Raman et al., 2019). The questionnaire items developed will be responded to by teachers with an option ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability assessment produced a reliability estimate of 0.935 > 0.60. Additionally, validity ranged from r = 0.281 to 0.924. Invalid items (<0.50) are excluded in this phase. The final items analyzed further are ten items.

To obtain mediator variable data, we developed questionnaires by adopting the essential characteristics of PLCs with dimensions of shared responsibility, deprivatization of practice, and reflective dialogue (Lee and Louis, 2019; Newmann, 1996). In each item, we gave an option range from 1 (strongly disagree) to 5 (strongly agree) for the teacher to respond to. Several other studies using this measure have been shown to affect teacher ICT integration (Cheng, 2017; Cifuentes et al., 2011; Paul et al., 2020; Thoma et al., 2017; Vossen et al., 2020). The reliability analysis produced a reliability estimate of 0.878 > 0.60. Concurrently, validity ranged from r = 0.179 to 0.737. Invalid items (<0.50) are excluded in this phase. The final items analyzed further are six items.

Lastly, endogenous variables are measured using Roger's innovation diffusion theory (2003) and TAM models (Davis, 1985). This combination is divided into several stages, which are the teacher knowledge stage (teacher knowledge of technological use), the teacher persuasion stage (teacher attitude to technological use), the teacher decision stage (teacher intention to technological use), and the teacher implementation stage (teacher practice to technological use). Some empirical research has also been conducted on this topic (Drossel et al., 2017; Ghavifekr and Rosdy, 2015; Sangkawetai et al., 2020). Each stage is developed into questionnaire items with options ranging from 1 (strongly disagree) to 5 (strongly agree) for the teacher to respond to. The reliability assessment resulted in a reliability estimate of 0.921 > 0.60. Additionally, the validity ranged from r = 0.191 to 0.884. Invalid items (<0.50) are excluded in this phase. The final items analyzed further are five items.

3.4. Data collection

Data was collected by distributing questionnaires about principal digital leadership, Professional Learning Communities (PLCs), and teacher innovation skills for technology integration. These questionnaires were distributed online (via Google Forms) and offline, with the researcher visiting schools at the study sites after obtaining permission from the local provincial authorities. The data were specifically obtained from teachers at excellent senior high schools in Makassar, who have been actively involved in the teaching process over the past two years. The research was carried out from July to October 2023. Once the respondents completed the questionnaires, the final step involved analyzing the collected data to test the hypotheses and achieve the research objectives.

3.5. Statistical analysis

Initially, descriptive statistical analysis was performed using SPSS. Subsequently, a cross-sectional analysis was conducted utilizing Structural Equation Modeling with the Partial Least Squares (PLS-SEM) method, incorporating latent constructs to evaluate the fit indices of the entire model. This analysis included the assessment of latent variables such as principal digital leadership, Professional Learning Communities (PLCs), and teachers' innovation skills. Moreover, PLS-SEM comprises two distinct models: the measurement and structural analysis models (Hair et al., 2021). The outer measurement model involved estimating the Average Variance Extracted (AVE), assessing discriminant validity, and computing composite reliability (CR). According to established guidelines, the AVE value should exceed 0.5, while the CR value should be 0.7 or higher (Hair et al., 2021; Henseler et al., 2015; Sarstedt et al., 2021). Additionally, discriminant validity was evaluated using the Fornell and Larcker Criterion, which compares the square root of AVE values with correlations among latent variables. Per this criterion, the square root of AVE for each construct should surpass its highest correlation with any other construct (Fornell and Larcker, 1981).

To assess our hypotheses, we constructed two structural equation models: firstly, direct effect consists of examining the effect between the exogenous constructs (principal digital leadership and Professional Learning Communities (PLCs)) and the endogenous construct (teacher innovation skills), as well as a partial mediation model, where we introduced direct relationships from the exogenous constructs (Professional learning communities) to the endogenous constructs (teacher innovation skills). Secondly, evaluate the indirect effect of exogenous constructs (principal digital leadership) on the endogenous constructs (teacher innovation skills) mediated by PLCs. The structural model evaluation in SEM PLS 4 is conducted by analyzing coefficients of determination, chi-square results ($R2$), $Q2$, SRMR, NFI, d_G, and d_Uls (Hair et al., 2021). After conducting the structural model fit test, the next step involves bootstrapping analysis, which is a process for assessing significance to measure (1) direct effects, (2) indirect effects, (3) overall effects (Hair et al., 2021). The significance levels are indicated through values such as $R2$, adjusted $R2$, outer loading, and cross-loading. The bootstrapping procedure generates *t* statistics to determine the influence of exogenous variables on endogenous variables. The *P* value, serving as an indicator of significance, is also obtained through the bootstrapping procedure. The original research sample is used as regression coefficients to complete the structural equation modeling (Henseler and Sarstedt, 2013).

4. Results

In analyzing this study, partial least squares (PLS) were used to answer the research hypothesis that had been established based on the model we built (Hair et al., 2021; Sarstedt et al., 2021). Two stages of analysis were performed: the measurement model and the structural model assessment.

4.1. Descriptive statistics

Table 2 shows that the skewness and excess kurtosis values for the three EC indicators are near zero, ranging from −0.578 to −0.317 and −0.256 to 0.194, respectively. Each indicator exhibits a nearly normal distribution (Kock, 2016). The normality of the indicators also ensures that any potential biases due to extreme values are minimized, allowing for a more accurate estimation of the relationships between digital leadership, teacher innovation skills, and the mediating effect of PLCs. Therefore, this analysis supports the robustness of the findings and the validity of the conclusions drawn from the research model.

Table 2. Descriptive Statistic of latent variables.

Variables	*N*	Min	Max	Mean	Std. Dev.	Skew		Kurtosis	
						Stat.	Std. Error	Stat.	Std. Error
PDL	257	19	50	41.64	6.195	−0.578	0.152	0.066	0.303
PLCs	257	12	30	24.20	3.856	−0.317	0.152	−0.256	0.303
TIS	257	9	25	20.00	3.601	−0.578	0.152	0.194	0.303

Note: $N = 257$.

4.2. Measurement model

4.2.1. Measurement model of convergent validity and composite reliability

Referring to **Table 3** allows us to scrutinize convergent validity and composite reliability values. Initially, the assessment of convergent validity for each variable involves checking the outer loading value, which is expected to exceed 0.7, and the average variance extracted (AVE) value, which should surpass 0.5 (Henseler et al., 2015; Sarstedt et al., 2021). Failure to meet these criteria suggests that the developed item inadequately represents construct variants and should be excluded. Subsequently, the evaluation of composite reliability aims to measure the consistency of internal indicators in construct measurement. The CR value is appraised with consideration given to Cronbach's alpha, and a satisfactory compromise is achieved by utilizing a composite reliability metric with a coefficient value of 0.7 and above (Hair et al., 2021).

Table 3. Measurement of convergent validity and composite reliability.

Construct	Item Code	β	α	C.R	AVE
DL	DL1	0.82	0.94	0.949	0.653
	DL2	0.813			
	DL3	0.871			
	DL4	0.841			
	DL5	0.826			
	DL6	0.811			
	DL7	0.782			
	DL8	0.837			
	DL9	0.721			
	DL10	0.744			
PLCs	PLC1	0.783	0.902	0.925	0.719
	PLC2	0.804			
	PLC3	0.863			
	PLC4	0.833			
	PLC5	0.846			
	PLC6	0.786			
TIS	TIS1	0.829	0.902	0.927	0.672
	TIS2	0.806			
	TIS3	0.878			
	TIS4	0.867			
	TIS5	0.857			

Table 3 illustrates that the outer loading values for each item fulfill the criteria by exceeding 0.7 for items within the DL, PLCs, and TIS variables. Furthermore, the average variance extracted (AVE) value surpasses 0.5, consistent with the specified standard. Similarly, the composite reliability (CR) registers a value greater than 0.7. Consequently, this study's convergent validity and composite reliability evaluations are considered satisfactory.

4.2.2. Measurement model of discriminant validities

The subsequent evaluation underscores the importance of discriminant validity, which aims to ascertain the uniqueness of each variable in capturing empirical phenomena distinct from other constructs (Hair et al., 2021). Discriminant validity is assessed using the Fornell and Larcker Criterion, where the square root of Average Variance Extracted (AVE) values is compared with the correlations between latent variables. According to the established criterion, the square root of AVE for each construct should surpass its highest correlation with any other construct (Fornell and Larcker, 1981). The discriminant validity assessment based on Fornell and Larcker's Criterion is elaborated in **Table 3**.

The Fornell and Larcker Criterion presented in **Table 4** indicates that the value of the reflective measurement model, in correlation with other constructs, is lower than the square root coefficient. This signifies that the constructs of DL (*X*), PLCs (*Z*), and TIS (*Y*) exhibit distinctions and uniqueness.

Table 4. Measurement of discriminant validity: Fornell and Larcker Criterion.

	X	***Y***	***Z***
X	0.808		
Y	0.576	0.848	
Z	0.641	0.805	0.82

4.2.3. Measurement model of goodness of fit

This evaluation is performed to analyze the coefficient of determination values for chi-square, *R* Square (*R*2), SRMR, and d_ULS, as well as D_G and NFI (Henseler and Sarstedt, 2013).

Table 5 indicates that the model's outcomes (saturated model) satisfy the criteria (estimated model), signifying that the model in this study aligns with the available data in the field. Consequently, a further bootstrapping analysis can be conducted to examine the influence between variables.

Table 5. Criteria model goodness of fit SmartPLS4.

	Saturated Model	**Estimated Model**	**Decision**
SRMR	0.055	<0.10	Good fit
d_ULS	0.692	>0.05	Good fit
d_G	0.427	>0.06	Good fit
Chi-Square	609.939	<3.00	Marginal Fit
NFI	0.858	>0.80	Good fit

4.3. Structural model assessment

In the structural model test stage, bootstrapping is carried out to assess the significance and relevance of each construct in the study. Based on Hair et al. (2021), an adequate and recommended bootstrapping setting to maintain stability is to use 10,000 bootstrap samples. Thus, this study used the bootstrap setting, with the results and visualization of **Figure 3** and **Table 6**.

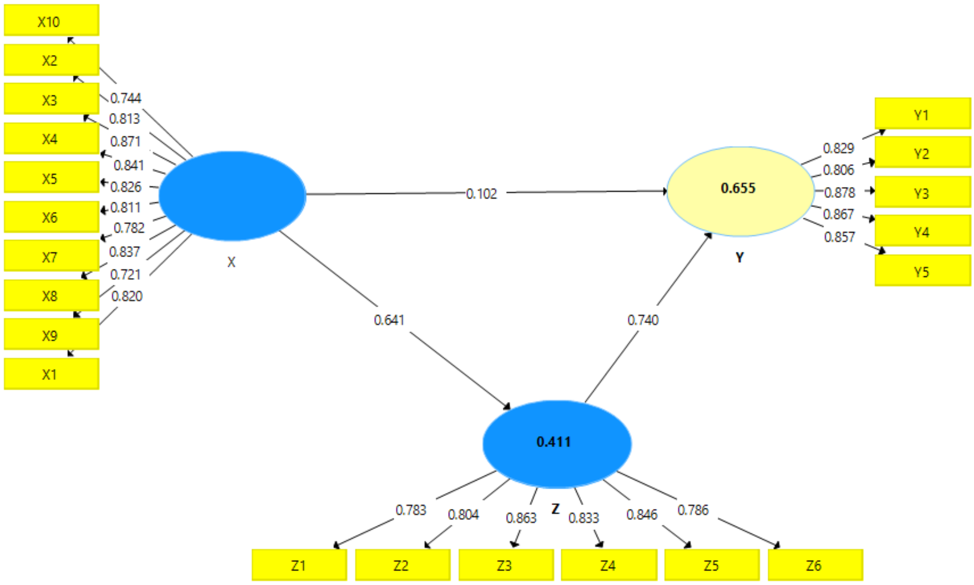

Figure 3. Result of structural model assessment.

Note: (P Value < 0.05, two-tailed test). X = Principal Digital Leadership. Y = Techer Innovation Skills for Technology Integration. Z = Professional Learning Communities (PLCs).

Table 6. Summary of hypotheses assessment.

Path	Direct and Indirect Effect	Orig. Sample (O)	Sample Mean (M)	Std. Dev. (STDEV)	T Stat. (|O/STDEV|)	*P.* Value	Confident Interval		
							5%	95%	Sig
$X \rightarrow Y$	0.652	0.102	0.103	0.061	1.679	0.093	0.001	0.221	No
$X \rightarrow Z$	0.408	0.641	0.643	0.040	15.881	0.000	0.002	0.771	Yes
$Z \rightarrow Y$	0.740	0.740	0.741	0.052	14.141	0.000	0.001	0.836	Yes
$X \rightarrow Z \rightarrow Y$	0.474	0.474	0.476	0.048	9.852	0.000	0.380	0.569	Yes

$P < 0.05$ (two-tailed).

Table 6 proves that three out of the four research hypotheses, representing H0, were rejected. Principal digital leadership (DL) does not exert a direct influence on teacher innovation in technology information (p-value 0.093 > 0.05). However, it does have a direct impact on professional learning communities (PLCs) (p-value 0.000 < 0.05), with a coefficient of determination of 0.408. Professional learning communities (PLCs) directly influence teacher innovation skills for technology integration (p-value 0.000 < 0.05), with a coefficient of 0.740. Lastly, principal digital leadership affects teacher innovation in technology information when mediated by professional learning communities (PLCs) (p-value 0.000 < 0.05), with a total effect of 0.474. The research findings provide valuable insights for both academics and practitioners. **Table 6** indicates that three out of the four research hypotheses were rejected, highlighting nuanced effects in the study. Specifically, principal digital leadership (DL) does not directly influence teacher innovation in technology integration (p-value 0.093 > 0.05). However, it significantly impacts Professional Learning Communities (PLCs) (p-value 0.000 < 0.05), with a notable coefficient of determination of 0.408. PLCs, in turn, have a substantial direct effect on teacher innovation skills for technology integration (p-value 0.000 < 0.05), with a coefficient of 0.740. Furthermore, the study reveals that principal digital leadership indirectly affects teacher innovation through

PLCs (p-value 0.000 < 0.05), with a substantial total effect of 0.474.

4. Discussion

The findings indicate that three out of four research hypotheses were rejected, representing H null (H0). Contrary to expectations, principal digital leadership does not directly impact teacher innovation for sustainable technology integration. This outcome is consistent with Lander (2020), who also found no significant influence between principal digital leadership and the category of teacher technology use. Hero (2020) reported similar findings and observed no significant effect between principals' technology leadership and teacher technological proficiency. These results diverge from previous research, introducing a notable discrepancy that warrants consideration when examining the direct relationship between principal technology leadership and teacher innovation skills for technology integration (AlAjmi, 2022; Hafiza Hamzah et al., 2021; Raman et al., 2019; Thannimalai and Raman, 2018). This evaluation extends to factors such as teacher technology acceptance, attitude, and intention to use technology, which align with the Technology Acceptance Model (TAM) framework (A'mar and Eleyan, 2022; Ghavifekr and Wong, 2022; Purnomo et al., 2023; Sunu, 2022). The incapacity of digital leadership to directly influence teachers' innovation capabilities for technology integration may be attributed to the principal digital leadership indicators concentrating solely on mindset and behavioral changes in teachers, neglecting the inclusion of training programs and learning communities that could aid teachers in comprehending and applying technological competencies. Within this context, indicators such as visionary planners, empowering leaders, and system designers might contribute primarily to modifying teachers' mindsets and behaviors toward innovation. Additionally, indicators like equity and citizenship advocates may support teachers in utilizing technology resources. Still, they may not sufficiently address proficiency areas, including teacher knowledge, content, attitude, critical approach, and pedagogical competence within the technological context. Regarding teacher innovation skills, evaluated through digital professional abilities essential for innovating technology-based learning and e-learning, principals are advised to adopt alternative strategies. This might involve implementing teacher professional development programs, including technology instruction training, or establishing communities where principals empower specific teachers possessing technology instruction expertise to aid and collaborate with their peers.

The initial interpretation of this outcome aligns with and substantiates the second result, demonstrating that principal digital leadership significantly influences professional learning communities (PLCs). As previously highlighted, the indicator of principal digital leadership addresses behavioral change and shifts in teachers' mindsets to foster innovation and alter the school's organizational environment. This finding is in harmony with the work of Banoğlu et al. (2023), which underscores the contribution of principal digital leadership to cultivating professional learning within the school. Additionally, Dexter and Richardson (2020) emphasize the pivotal role of leadership practices in constructing professional capacity, providing learning opportunities, and supporting teachers in enhancing technology teaching skills. Moving on to the third outcome, indicates that professional learning communities significantly influence teacher innovation skills for sustainable technology integration. This result consistently aligns with prior studies (Liu et al., 2022; Meier, 2019; Nolin, 2014; Ohayon and Albulescu, 2023). Furthermore, it corresponds to earlier research suggesting that schools with sufficient infrastructure and ICT resources, effective communication and collaboration, and teachers with a solid educational background will impact teacher self-efficacy in utilizing technology for teaching innovation (Cheng, 2017; Cifuentes et al., 2011; Drossel et al., 2017; Sangkawetai et al., 2020; Vossen et al., 2020). Furthermore, Vescio et al. (2008) found that PLCs contribute to teaching practice and student achievement through shared values, discussion, collaboration, and reflection in the school environment. This is supported by Owen (2015), who emphasizes that PLCs contribute to teacher innovation skills for technology integration, characterized by new teaching practices. Implementing practical PLCs implies that teachers lacking innovation skills for technology integration can learn from proficient colleagues through shared values, discussions, and collaborations. Teachers, in turn, feel accountable for the quality of teaching by continually enhancing their technological instructional abilities. Recognizing the significance of discussions and collaborations with more skilled colleagues, teachers become aware of the importance of addressing challenges encountered in learning. The feedback obtained by teachers serves as input for designing professional development programs, aiding teachers in advancing their technological skills in education.

The study findings suggest that professional learning communities (PLCs) are a significant intermediary between principal digital leadership and teacher innovation skills for sustainable technology integration. This indicates that regardless of the level of proficiency, teachers' ability to integrate technology into both offline and e-learning settings is shaped by the effectiveness of the principal's digital leadership in fostering a supportive learning community environment. This result aligns with previous research highlighting the direct impact of teacher professional learning on innovation skills, particularly concerning digital competence. Moreover, this influence is indirect and originates from the leadership practices of principals (Piotrowsky, 2016; Saputra et al., 2021; Thannimalai and Raman, 2018; Tondeur et al., 2009). Additionally, aligning these findings with prior research underscores the robustness of the relationship between educational leadership, professional learning, and innovation skills. These insights have practical implications for educational leaders, highlighting the importance of investing in principals' digital leadership development and establishing collaborative learning communities for sustainable professional development. By fostering a culture of innovation and continuous improvement within schools, educational leaders can contribute to preparing students for success in an increasingly digital world. Overall, the study underscores the interconnectedness of various factors within educational ecosystems and emphasizes the pivotal role of leadership and collaboration in driving innovation and improvement in education.

5. Conclusion

The rapid advancement of technology has significantly impacted various aspects of society, including education. Teachers are now faced with the challenge of adapting their teaching methods to meet the ever-changing needs of their students. The findings indicate that one out of the four hypotheses were not supported. Principal digital leadership does not directly affect teachers' technology innovation. Instead, it significantly impacts Professional Learning Communities (PLCs). These PLCs, in turn, greatly enhance teachers' ability to innovate with technology. Additionally, the influence of principal digital leadership on teacher innovation is indirect, mediated through the effectiveness of PLCs. This underscores the crucial role of PLCs in linking leadership with successful technology integration in schools.

Therefore, the study findings emphasize the pivotal role of PLCs as mediators between principal digital leadership and teacher innovation skills, stressing the significance of creating collaborative learning environments where educators can exchange insights and best practices related to teachers' sustainable technology integration. Furthermore, the findings suggest that efforts to enhance teacher innovation should encompass technical training, opportunities for reflective practice, and continuous professional development. This underscores the multifaceted nature of teacher innovation skills, which extend beyond technical proficiency to encompass broader competencies such as pedagogical knowledge and critical thinking. Moreover, the study underscores the importance of digital leadership practices in shaping organizational culture and fostering an environment conducive to innovation, suggesting that principals should explore alternative strategies such as implementing tailored professional development programs or establishing communities of practice to support teachers. Overall, the study contributes to a deeper understanding of the interaction between leadership, collaboration, and innovation in educational settings, underscoring the significance of supportive organizational structures and collaborative learning environments in driving technological advancement and educational improvement.

6. Suggestion for educational policy

Based on findings and discussion, several areas for improvement regarding education policies are suggested. To strengthen principal digital leadership, comprehensive training programs should focus on skills such as visionary planning, empowering leadership, and system design. These programs should emphasize the importance of creating an environment that supports changes in teacher mindset and behavior toward innovation and technology integration. Additionally, establishing and supporting Professional Learning Communities (PLCs) within schools should be promoted to facilitate collaboration, discussion, and reflection among teachers. Therefore, it is essential to ensure that PLCs have sufficient infrastructure and ICT resources to support effective communication and collaboration. Furthermore, ongoing professional development programs should be implemented, including training on technology instruction and integration, and teachers should be encouraged to participate in PLCs where they can learn from and collaborate with colleagues with expertise in technology integration.

Additionally, identifying and empowering teachers with strong technology instruction skills to mentor and support their peers within PLCs is crucial, as well as recognizing and rewarding those who contribute significantly to their colleagues' professional development. In this context, regular assessments of the impact of PLCs on teacher innovation skills and technology integration practices should be conducted, and feedback from these assessments should be used to refine and improve professional development programs and PLC activities. Finally, fostering a school culture that values continuous improvement, innovation, and collaboration is vital, with principals leading by example, demonstrating a commitment to digital leadership, and supporting teacher innovation.

7. Implication for future research

Based on our findings, several implications for future research emerge. Firstly, there is a need to delve deeper into the nuanced dynamics of digital leadership and its impact on teacher innovation for sustainable technology integration, considering contextual factors and cultural variations. Comparative studies across diverse educational contexts could provide valuable insights into the generalizability of findings and inform culturally responsive leadership practices. Additionally, longitudinal studies tracking the long-term effects of leadership interventions and PLC initiatives on teacher innovation skills for sustainable technology integration could offer a more comprehensive understanding of causal relationships over time.

Furthermore, intervention studies evaluating the effectiveness of specific leadership strategies or PLC interventions in promoting teacher innovation skills are warranted. By implementing controlled interventions and rigorously assessing their impact, researchers can provide evidence-based recommendations for educational leaders seeking to enhance technology integration in schools. Mixed-methods approaches combining quantitative analyses with qualitative methods could also offer a more comprehensive understanding of the mechanisms underlying the relationship between leadership, collaboration, and innovation in educational settings. By addressing these research gaps, scholars can advance our understanding of the complex interplay between leadership, collaboration, and innovation in technology integration, ultimately contributing to developing effective strategies for enhancing sustainable teaching and learning outcomes in schools.

8. Limitation

This study has several limitations. The reliance on self-reported data may introduce bias, and the cross-sectional design limits the ability to establish causality between principal digital leadership, professional learning communities (PLCs), and teacher innovation skills. The findings are context-specific to Indonesia and may not be generalizable elsewhere. Additionally, variability in the effectiveness of PLCs across schools and the lack of exploration of other influencing factors, such as teacher characteristics and school climate, may affect the results. Future research should address these factors to understand teacher innovation in technology integration comprehensively.

9. Statement of novelty

The novelty of this research lies in its exploration of the nuanced relationships between principal digital leadership, Professional Learning Communities (PLCs), and teachers' innovation skills for sustainable technology integration. In the Indonesian context, this research introduces a novel perspective by showing that principal digital leadership does not directly influence teachers' technology innovation skills but significantly impacts Professional Learning Communities (PLCs), enhancing sustainable technology integration. This finding challenges the traditional view that digital leadership alone drives technological adoption and highlights the critical role of effective PLCs in bridging the gap. By focusing on strengthening PLCs, this research provides a strategic framework for addressing the unique challenges of technology integration in Indonesian schools, especially in areas with limited resources. This insight offers valuable implications for educational leaders and policymakers, emphasizing the need to develop digital leadership and enhance collaborative learning communities to foster sustainable technology integration.

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Appendix

Table A1. Development of variable indicators.

NO.	Statement Items	Item Coding
A.	Principal Digital Leadership (DL)	
1.	The principal involves teachers, school committees, parents, and local education offices in developing and setting the digital learning vision.	(DL1-visionary planner)
2.	The principal actively communicates with school stakeholders, including teachers, school committees, education offices, and parents, to discuss the digital learning strategic plan.	(DL2-visionary planner)
3.	The principal ensures the availability of digital tools and facilities to implement digital learning models in schools.	(DL3-equity and citizenship advocate)
4.	There are sanctions for violators of the free and irresponsible use of technology in the school environment.	(DL4- equity and citizenship advocate)
5.	The principal is not concerned about increasing teachers' confidence in integrating digital devices into learning.	(DL5- empowering leader)
6.	The principal involves teachers in the school's strategic process according to their skills and background.	(DL6-empowering leader)
7.	The principal forms and directs the team in the success of the school's strategic plan related to digital learning.	(DL7- system designer)
8.	The principal can organize a team to implement the digital learning strategic plan.	(DL8- system designer)
9.	The principal can obtain the latest information and knowledge on innovations in technology and digital learning media.	(DL9- connected learner)
10.	The principal is active in various online activities to improve skills in learning technology.	(DL10- connected learner)
B.	Professional Learning Communities (PLCs)	
11.	Teachers responsible for the continuity of well-executed jobs in media innovation and digital learning strategies	(PLC1-shared responsibility)
12.	Teachers show a strong sense of responsibility in their jobs, especially when introducing new ideas in digital learning.	(PLC2-shared responsibility)
13.	Teachers contribute and share with colleagues in discussing the improvement of student learning outcomes on an ongoing basis.	(PLC3-deprivatization of practice)
14.	Teachers are open to discussing and collaborating in school programs to enhance the quality of digital learning.	(PLC4-deprivatization of practice)
15.	Teachers sometimes visit other classes to gain new perspectives or knowledge using digital media or learning strategies.	(PLC5-reflective dialogue)
16.	Teachers collaboratively assess each other's performance in further performance improvement.	(PLC6-reflective dialogue)
C.	Teachers' Innovation Skills (TIS)	
17.	Teachers understand the basics of using digital applications, especially in learning, such as Zoom, Google Classroom, etc.	(TIS1-teacher knowledge of technological use)
18.	Teachers believe in their ability to demonstrate technology tools as a medium in the learning process.	(TIS2-teacher attitude to technological use)
19.	Teachers believe using technology in teaching will ease their jobs and be useful for students.	(TIS3-teacher attitude to technological use)
20.	Teachers conduct critical analysis first on learning technology media before use.	(TIS4-teacher intension to technological use)
21.	Teachers use various applications to help students in learning, such as Zoom, Google classroom, etc.	(TIS5-teacher practice to technological use)