

Article

Elevating Teachers' Professional Digital Competence: Synergies of Principals' Instructional E-Supervision, Technology Leadership and Digital Culture for Educational Excellence in Digital-Savvy Era

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Abstract: The educational landscape has been significantly influenced by the rapid development of technology, especially in the instructional process. Examining teachers' professional digital competence (TPDC) in Indonesia, a developing country, is of utmost importance. It is vital to comprehend the extent of professional digital competence among teachers to identify potential gaps and areas for improvement through training programs. This investigation aims to shed light on disparities and formulate strategies to bridge the digital divide. In this context, the principal's instructional e-supervision (PIS) and technology leadership (PTL) play a pivotal role in nurturing a school's digital culture (SDC). This culture is crucial for ensuring the effectiveness of the collaborative learning process that meets the needs of students in this digital-savvy era. Therefore, this study delves into the structural impact of PIS and PTL on TPDC mediated by SDC. Quantitative methods were employed to address research hypotheses through structural equation modeling (SEM) analysis with AMOS, utilizing inner and outer model techniques. Carried out in seven senior high schools in Indonesia, the research involved 257 productive teachers randomly selected from a population of 450. The findings revealed that PIS directly influences TPDC, albeit with the most negligible coefficient (0.192). Simultaneously, PTL directly impacts SDC (0.663) and TPDC (0.229). Moreover, SDC significantly influences TPDC (0.816). However, the direct coefficient of PTL has a more substantial impact on SDC than on TPDC. Consequently, the structural model suggests that PTL will profoundly influence TPDC when mediated by SDC (0.541). In light of these results, this study recommends the application of principal technology leadership-based humbleness for future research.

Keywords: technology leadership; professional digital competence; school digital learning; technology integration; principal leadership

1. Introduction

Developing teachers' professional digital competence is a critical educational challenge, particularly in developing countries [1]. This competence is essential for promoting teaching innovation and effective use of digital technologies in the classroom [2]. It is essential to consider the social and cultural aspects of digital competence and the specific skills required to foster students' digital skills [3,4]. These studies collectively highlight the need for comprehensive and ongoing support for teachers to develop and maintain their digital competence in developing countries. The importance of teachers possessing professional digital competence in today's digital-savvy era cannot be emphasized enough. As technology advances and becomes increasingly integral to different facets of our lives, particularly in education, teachers must acquire the essential skills to adeptly

use and maximize digital tools. Likewise, to prepare students for the modern digitalized era, teachers should have digital competency, indicating their adeptness in using digital tools and incorporating them into their instruction with a clearly defined pedagogical purpose [5]. Previous studies have investigated the importance of principal leadership and instructional supervision technology on teachers' technology integration [6–10]. However, teacher technology integration in these prior studies is related to teachers' digital skills in using technology tools in general skills only [11]. In addition to these skills, being a teacher requires skill in using digital tools and a crucial capability in evaluating and customizing these tools for specific areas of knowledge [12–14]. Hence, teacher professional digital competence (TPDC) is a holistic perspective in assessing teacher digital skills for technology integration, which consists of technological competence (TC), content knowledge (CK), attitudes to technology use (ATU), pedagogical competence (PC), and critical approach (CA) [15].

The most recent research on assessing the effectiveness of global technology leadership, particularly in the integration of technology in schools, especially among teachers, relies on the ISTE-A (International Society for Technology in Education for Administrator) standards, which consist of equity and citizenship advocate (ECA), visionary planner (VP), empowering leader (EL), systems designer (SD), and connected learner (CL) [16]. Moreover, enhancing the efficiency of teachers in their instructional approaches involves using educational supervision—a vital element in effective educational administration. As school leaders, principals can augment this procedure by integrating digital-based instructional supervision, using technological tools for increased convenience [17,18]. This adaptation is a response to the dynamic changes in the educational environment of the digital era, with an emphasis on technology-driven advancements in instructional academic supervision. E-supervision for instruction is a supervisory framework that employs Information and Communication Technology (ICT) as a support tool across all stages—from planning and implementation to evaluation. The objective is to elevate teacher professionalism, ensuring the seamless and efficient progression of the learning process, especially in teacher digital skills in the digital-savvy era [19–22]. Hence, it is evident that the framework of instructional e-supervision can enhance TPDC.

Indonesia is one of developing countries that still struggles to advance its teachers' capacity in digital instruction. The challenges to teachers' professional digital competence in Indonesia, as one of the developing countries, are multifaceted. Factors such as the need for systematic training [23], the role of digital competence in pre-service teacher education [24], and the lack of teacher training and insufficient ICT training [1] all contribute to this issue. Additionally, the need for regular maintenance of teachers' performance after certification [25] is a crucial aspect that needs to be addressed. The role of the principal as a leader and technology-based supervisor in a digital-savvy era toward those issues is essential [10,26,27]. Studies on principal technology leadership in the Indonesian context have been investigated quantitatively and qualitatively [9,28–31]. However, they are still limited, especially regarding their influence on teachers' digital competence comprehensively at the senior high school level. Furthermore, Ari [32] discovered that the digital competence of Indonesian teachers is presently at an intermediate level. More precisely, 43% are classified as Integrators (B1), and 26.9% are identified as Experts (B2). This represents the importance of increasing professional digital competence among teachers in Indonesia. Despite this extensive exploration, there is currently a gap in research, as no studies have examined the structural modeling between principals' instructional e-supervision, technology leadership, and teachers' digital competence comprehensively using the TPDC framework to integrate technology into instructional processes, particularly in Indonesia. Second, as mentioned earlier, most of the prior studies only examined teachers digital skills in technology integration using a general measurement, such as digital skills without involving the aspect of macro-, meso-, and micro-levels [11,18,33,34].

Furthermore, previous studies over the past five years only measured the significance of teacher education (TE) in enhancing teachers' professional digital competencies. These

studies have employed both quantitative [35–37] and qualitative approaches [38–42]. In addition, multiple studies have also shown that the technology leadership practices of principals play a crucial role in improving the skills and effectiveness of teachers when it comes to integrating technology into the learning process [18,43–46]. Similarly, evidence demonstrates that the principal technology leadership notably influences fostering a digital learning culture [34,45,47,48]. Conversely, some studies found no overt relationship between principal technology leadership and teacher technology integration [49,50]. Therefore, it sheds light on the possible improvement of TPDC by considering the mediating role of SDC influenced by PIS and PTL. The study's findings have valuable implications for designing educational and training programs to enhance TPDC. The theoretical insights gleaned from this research are especially relevant in developing countries, such as Indonesia, where the advancement of TPDC is of growing importance.

In today's education landscape, exploring the role of principals in technology leadership is vital for creating a dynamic and innovative teaching environment. Recognizing the pivotal role of principals as leaders and technology supervisors is essential for establishing a school digital culture that nurtures teachers' professional digital competence. Consequently, this study aims to investigate the extensive impacts of school principals' technology leadership and instructional e-supervision on enhancing teachers' digital competence. Special attention is given to assessing the moderating influence of school digital culture on shaping technology integration within the instructional context.

2. Literature Review and Hypotheses Development

2.1. Conceptual Framework

The digitalization era has witnessed a notable shift, with digital systems becoming pervasive in various aspects of human life, particularly in digital learning. In this context, teachers are compelled to acquire competencies that are in demand. Consequently, teachers must adeptly navigate this evolving landscape by enhancing their digital competence to fulfill their professional responsibilities. Leadership that is rooted in technology is essential for the successful implementation of digital learning in schools. The technological leadership exhibited by school principals can yield positive outcomes on the digital professional capabilities of teachers. This is achieved by cultivating a digital culture among teachers through collaboration and communication, thereby enhancing their ability to implement digital learning methods that align with the evolving needs of students and the demands of the 21st century.

School culture is crucial in navigating uncertainty and globalization. It is a concern for researchers studying its impact on the school environment and individual behavior for school improvement, often influenced by the principal's leadership [51–55]. This concern is aligned with Piotrowsky [56] regarding the role of school leadership in enhancing student achievement through competent teachers within the framework of a positive school culture. Furthermore, Divaharan [57] emphasized the importance of school leadership support in addressing the critical functions of Organizational Learning (OL) and Professional Learning Communities (PLCs) for successful adaptation and integration of ICT. Therefore, we use school digital culture as a moderator variable to enhance TPDC predicted by PTL, as illustrated in Figure 1.

Numerous studies and investigations have explored the importance of principal technology leadership in developing a school's digital culture [29,58–60]. This, in turn, directly affects the teacher's digital skills in technology integration [61–66]. In this investigation, we employ the role of PIS and PTL to evaluate the Teacher Professional Digital Competence framework comprehensively [15] and we also evaluate school digital culture defined by organizational learning and professional learning communities (PLCs) [67] from a technology-based perspective [68–70]. Besides PTL, instructional supervision stands as a field to offer teachers incentives and direction to elevate classroom teaching and foster the professional aptitude of teachers [71–73], specifically when it comes to teachers' digital skills [20,22,74,75].

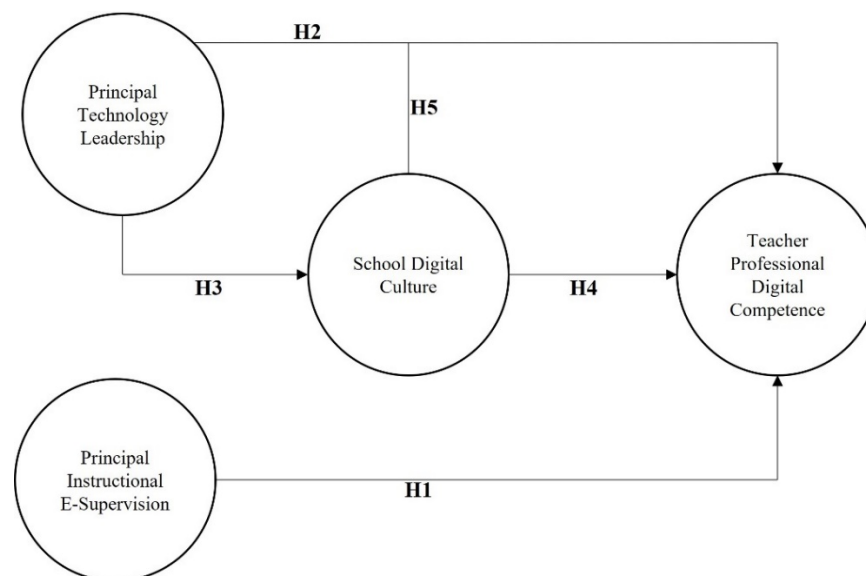


Figure 1. The proposed structural model.

2.2. Teacher Professional Digital Competence (TPDC)

The importance of teacher digital competence has been explored in several studies [5,76,77]. Examining through the lenses of PIAAC and TALIS, Hämäläinen et al. [78] uncovered insights into the TPDC, consisting of digital skills, knowledge about digital technologies, and attitude towards digital technologies. This is aligned to Skantz-Åberg et al. [15], who emphasized technology-related skills by highlighting discrepancies and confusion in the terminology of the teacher professional digital competence (TPDC) concept, influenced by Selwyn’s holistic approach addressing the school–society relationship and the implementation of technology in school operations in the scope of macro-, meso-, and micro-levels. Based on that, TPDC encompasses five key aspects: technological competence (TC) acquired individually, focusing on essential skills with digital tools; content knowledge (CK), central to teachers developing students’ subject understanding; attitudes toward technology use (ATU) influencing classroom application; pedagogical competence (PC), crucial for integrating technology to meet learning objectives and students’ needs; and critical approach (CA), related to teacher critical thinking before incorporating technology in their instruction.

In Indonesia’s context, to enhance teachers’ competency in information and communication technology (ICT) in line with the demands of the digital-savvy era, the Ministry of Education and Culture (Kemendikbud), through the Center for Data and Information Technology (Pusdatin), reintroduced the ICT-Based Learning Program (PembaTIK) in 2021 with the theme “Sharing and Collaborative Learning Together on the Rumah Belajar Portal”, which aims to attract 75 thousand teacher participants, building on the success of the previous year’s engagement with 70 thousand educators [79]. In addition, various factors influence teachers’ professional digital skills, such as teacher education (TE), including leaders’ role at the organizational level [38]. In this study, we examined the principal role of a school technology leader and instructional e-supervision to influence teachers’ professional digital competence by developing a school digital culture, as there is no quantitative study that has been conducted aligning this with TPDC.

2.3. School Digital Culture (SDC)

School culture relates to how individuals behave, dress, communicate, and seek assistance from colleagues, and teachers’ perspectives on students and their responsibilities. The principal’s leadership fosters a strong school culture by promoting positive relationships and collaboration among teachers, emphasizing mutual respect [80]. This involves fostering open discussions, respecting diverse opinions and ideas, sharing successes, and establishing

harmonious relationships with students. Lee [67] conceptualizes this positive relationship and collaboration as integral to professional learning communities, characterized by three indicators: shared responsibility, deprivatization of practice, and reflective dialogue. Furthermore, the role of organizational learning is essential for the sustainable development of a strong school culture [81–83]. Therefore, school culture comprises two interconnected dimensions: organizational learning and professional learning communities (PLCs). These dimensions are closely linked, as emphasized in various studies [67,84–86].

According to the literature, organizational learning is the teachers' capacity to consistently engage in activities to acquire relevant information from internal and external sources. Technology is a valuable tool in facilitating access to information sources supporting practical teacher professionals, encompassing research reports, books, newsletters, blogs, and podcasts, mainly focusing on the potential of learning technologies [69]. On the other hand, Professional Learning Communities (PLCs) encompass three key elements: shared responsibility, deprivatization of practice, and reflective dialogue [67]. Shared responsibility reflects teachers' commitment, translating into a sense of responsibility toward their roles and professions, aiming to enhance the quality of learning. The second element signifies teachers' openness to collaborative engagement with colleagues, continuously striving to improve learning quality. Finally, reflective dialogue pertains to teachers' attitudes and willingness to foster a culture of discussion, allowing them to analyze successes and failures in the learning process [67,87,88]. In integrating technology, Snyder [68] highlighted the significance of digital culture, where technology's presence can foster collaboration and communication within the organizational environment. McConnell et al. [70] also proposed videoconferencing as a practical tool to facilitate teachers in PLCs. Additionally, various studies indicate that the use of technology in PLCs positively influences teacher technology integration and efficacy in the teaching and learning process [89–91]. In summary, the amalgamation of organizational learning and professional learning communities (PLCs) within the school culture, facilitated by school principal leadership, along with the proficient use of digital tools, correlates with the advancement of TPDC.

2.4. Principal Technology Leadership (PTL)

The notion of principal technology leadership has been explored in various literature [8,92–94] or in alternative literature that refers to it as digital leadership [6,7]. Principal technology leadership encompasses guiding and directing organizations amid challenges and opportunities in the digital era. It requires a crucial set of skills, attitudes, and strategies for leaders to navigate the complexities of the digital landscape effectively. At its essence, principal technology leadership is focused on the capacity to leverage digital technologies to foster innovation, cultivate organizational flexibility, and accomplish strategic objectives. Technology leadership in education is the ability of an educational leader to lead educational organizations in achieving goals in the digital era that continues to change with the digitalization vision [6,7,95,96]. Furthermore, Garcia [97] suggests that the core of technology leadership for principals lies in their capability to understand technology tools and their effective use, communicate with stakeholders, and manage available resources. Additionally, Chang [98] articulates that the success indicators of technology leadership include the capacity to formulate a vision, provide professional development, support infrastructure, facilitate communication, and conduct evaluations. Nevertheless, the latest research inquiry concentrating on evaluating the impact of global digital leadership in improving technology integration in schools, specifically among teachers, is based on the ISTE-A (International Society for Technology in Education for Administrator) standards, highlighting its influence on enhancing digital learning culture and teachers' technology integration skills [18,33,44,60,99–101].

Specifically, research has been conducted exploring the connection between ISTE standards and teacher Technological Content Knowledge (TC), Content Knowledge (CK), and Pedagogical Content Knowledge (PC) within the Technological Pedagogical Content Knowledge (TPACK) framework [102]. Additionally, various studies have investigated the

roles of principals in technology leadership and their impact on teachers' technology integration in both K-12 schools [99,103–105] and higher education [100,106,107]. Nevertheless, these prior studies did not involve comprehensive aspects, such as digital skills, knowledge about digital technologies, and attitude towards digital technologies (macro-, meso-, and micro-levels) [15,78]. In light of the findings from prior research, it is important to investigate the role of principal technology leadership in encouraging teachers to enhance their professional digital competence (PDC) comprehensively, which will involve teachers' digital skills, knowledge of technologies, and attitude towards technologies (macro-, meso-, and micro-levels) using the TPDC framework.

2.5. Principal Instructional E-Supervision (PIS)

Instructional e-supervision is a coaching mechanism for educators to enhance their professionalism and address teaching challenges by utilizing technological platforms, including Google Meet, Google Forms, and Google Docs [20,21,108]. Aligning with this, in accordance with the school supervisor performance guidelines outlined by the Ministry of Education and Culture (Kemendikbud) in 2022, especially in the wake of the preceding pandemic, supervisors were expected to incorporate technology in providing individual coaching and support for school principals and teachers. This involved using various tools such as SMS, telephone, WhatsApp, Google Forms, Microsoft Teams, Zoom, Google Meet, Webex, and more. Additionally, video conferences with up to eight participants were employed for group coaching. Consequently, it can be affirmed that instructional e-supervision encompasses utilizing both hardware and software in diverse application forms throughout the instructional supervision process, enhancing teachers' digital professional competence.

Empirical studies focusing on instructional e-supervision have been undertaken, revealing that in the context of the Fourth Industrial Revolution, instructional e-supervision plays a substantial role in advancing teachers' professionalism. This is especially notable in their proficiency in utilizing Information and Communication Technology (ICT) and other pertinent administrative responsibilities during the learning process [10,19,21,74,75,109–113]. Furthermore, the findings of Wiyono et al. [114] emphasized that educational supervision based on technology significantly boosts teachers' academic competence, thereby contributing to enhancing education quality through integrating technology into the educational process. Hence, based on prior studies, we can refer to the role of instructional e-supervision in enhancing the TPDC framework.

Drawing on the examination of preceding research concepts and outcomes, this study endeavors to test the following research hypotheses:

H1: *PIS directly affects TPDC.*

H2: *PTL directly affects TPDC.*

H3: *PTL directly affects SDC.*

H4: *SDC directly affects TPDC.*

H5: *SDC is the significant mediator in measuring the effect of PTL on TPDC.*

3. Materials and Methods

3.1. Research Design

This study utilized a quantitative methodology, incorporating a causal regression design and employing survey instruments and questionnaires [115]. The main goal was to assess and confirm the alignment of theoretical models with empirical data gathered in the field. The primary focus of the research was to investigate the impact of structural variables linked to the principal's instructional e-supervision, principals' technology leadership on the school's digital culture, and the professional digital competencies of teachers [116].

3.2. Participant

This research was conducted in public and private senior high schools in Makassar, the capital city of South Sulawesi Province, Indonesia. Makassar has 24 public and 118 private high schools, with 2500 teachers distributed across 15 sub-districts (<https://dapo.kemdikbud.go.id>: 25 November 2023). The research focused on the productive teachers in schools categorized as excellent, comprising 7 schools with 428 teachers. The sample was selected using a random technique, following the Isaac and Michael tables with a 1% error rate to ensure optimal analysis results [117]. From the entire population of the seven schools, 257 samples were chosen as respondents for assessing the variables under study, which include the principal's instructional e-supervision (PIS), principals' technology leadership (PTL), school digital culture (SDC), and teacher professional digital competence (TPDC). Structural Equation Modeling (SEM) is typically categorized as a method suitable for large samples. Generally, the sample size of 200 respondents is considered large enough [118], precisely when using a Maximum Likelihood Estimator (MLE) like AMOS. Finally, the survey was distributed to each of the seven selected schools offline and online (utilizing Google Forms) and was conducted from 29 July to 30 November 2023.

3.3. Measures

In this section, we will present each latent variable's instrument and questionnaire items, including PIS, PTL, SDC, and TPDC, to gather data from respondents (see Appendix A). The content validity of the instrument was established through examination of the theoretical framework underlying the variables. Furthermore, empirical trials of the instrument were carried out on 44 teachers in the school which have the same characteristics as the whole population, focusing on item validity through item-total analysis ($\alpha = 0.50$). The questionnaire's reliability was assessed using the Cronbach's alpha ($\alpha = 0.60$) [119]. In this way, items that do not meet the criteria will be excluded.

3.3.1. Teacher Professional Digital Competence

In this study, the Teacher Professional Digital Competence (TPDC) assessment employed six indicators from an extensive literature review on teachers' digital competence in supporting their professional responsibilities [15]. Teachers' implementation of TPDC is gauged by their responses to statements related to technological competence (TC), content knowledge (CK), attitudes toward technology use (ATU), pedagogical competence (PC), and critical approach (CA), using a scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analysis yielded a reliability estimate for the instrument of 0.921. Meanwhile, the validity was $r = 0.191$ to 0.884 .

3.3.2. School Digital Culture

In evaluating school digital culture, we incorporated the concepts of organization learning (OL) and professional learning communities (PLCs) developed by Lee and Louis [67] as foundational elements of a robust school culture. These were further enriched by insights from Brandi and Iannone [69] regarding innovative organizational learning technologies (iOLTs) and digital professional learning communities [68,70] concerning digital learning culture and communication. These insights guided the development of items for each indicator, emphasizing the maximization of technology's presence. The dimensions encompass organizational learning, shared responsibility, deprivatization of practice, and reflective dialogue, using a scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analysis yielded a reliability estimate for the instrument of 0.878. Meanwhile, the validity was $r = 0.179$ to 0.737 .

3.3.3. Principal Technology Leadership

The evaluation of the principal's technology leadership in this study adhered to the five recent standards outlined by the International Society for Technology in Education for Administrators [16]. Widely employed in research studies, these standards have been used

to gauge their impact on teachers' ICT integration capabilities or, more broadly, teachers' digital competencies (as evident in prior studies [6,9,30,34,44,95,101] and in the context of learning organizations as integral to school culture [120]). To assess this, teachers were required to evaluate the extent to which the principal, as a technology leader, embodied the five dimensions of the ISTE-A standard: equity and citizenship advocate, visionary planner, empowering leader, systems designer, and connected learner. Each dimension in technology leadership is represented by an item elucidating its meaning, and teachers responded to these items on a scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analysis yielded a reliability estimate for the instrument of 0.935. Meanwhile, the validity was $r = 0.281$ to 0.924 .

3.3.4. Principal Instructional E-Supervision

For gathering data for instructional e-supervision purposes, we employed the supervision procedures that supervisors must oversee. These procedures encompass planning, implementation, and evaluation or feedback by maximizing the use of technology tools [20–22]. Within each step, there are two items to which teachers must respond on a scale ranging from 1 (strongly disagree) to 5 (strongly agree). The reliability analysis yielded a reliability estimate for the instrument of 0.861. Meanwhile, the validity was $r = 0.171$ to 0.858 .

3.4. Statistical Analysis

The data analysis employed in this study utilizes structural equation modeling to assess the proposed latent variable model, examining the impact of both exogenous variables on endogenous variables. The analytical process involves two distinct models: the measurement model and the structural analysis model [121]. First, the measurement model encompasses the outer model, which includes the loading factor values for each item, average variance extracted (AVE), construct reliability (CR), and model fit; the assessment relies on various criteria for goodness of fit, such as likelihood ratio chi-square value (χ^2), goodness-of-fit (GFI), Adjusted goodness-of-fit index (AGFI), comparative fit index (CFI), CMIN/DF, significance probability, and root mean square-error of approximation (RMSEA) [122]. Second, the structural analysis models (inner model) are executed to address hypotheses by scrutinizing the direct and indirect effects of exogenous and endogenous variables using bootstrapping [121,122].

4. Results

4.1. Respondent Profile

In this section, we present information about the backgrounds of respondents who participated in our research data collection, including (1) education level background and (2) length of respondents' work experience.

Figure 2 shows that the majority of respondents in this study come from a Bachelor's (S1) educational background (60.70%). This is in stark contrast to the Doctoral (S3) educational background, which has only (1.17%). As for teachers who pursued Master's level education, the number 38.13% is half of the Bachelor's background percentage.

Figure 3 shows that the majority of respondents have work experience in the range of 6–10 years, with a frequency of 37.35% respondents. This is followed by respondents with work experience in the ranges of 11–15 years and 0–5 years, accounting for 23.74% and 23.35%, respectively.

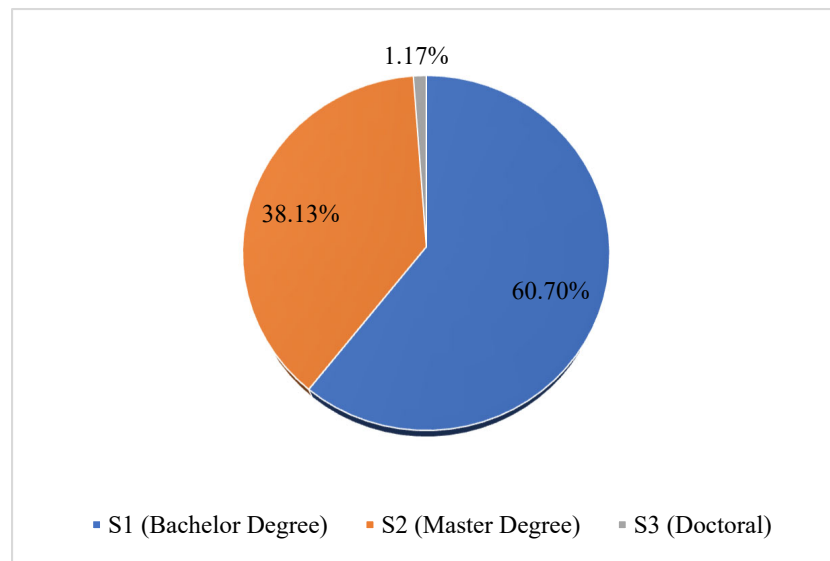


Figure 2. Education level background of respondent.

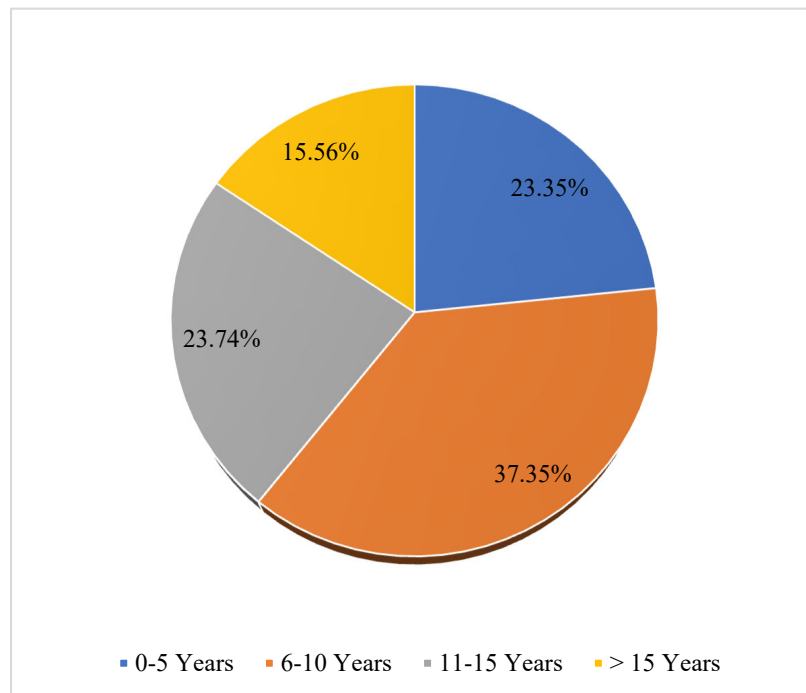


Figure 3. Length of respondents' work experience.

4.2. Descriptive Statistic

Table 1 below displays descriptive statistics for each survey item, including measures such as means, standard deviations, skewness, kurtosis, and critical ratio to assess the data normality.

The criteria for evaluating the normality of data include ensuring that the skewness value is equal to or less than 1, the c.r. must be less than 8, and the kurtosis falls within the range from -10 to 10 [121]. Table 2 indicates that the data for each observed variable follow a normal distribution.

Table 1. Variables descriptive statistics.

Observed Variables	N	Min	Max	Mean	Std. Deviation	Skew	c.r.	Kurtosis	c.r.
PIS6	257	1,000	5,000	3.4	0.795	0.221	1446	0.098	0.321
PIS5	257	2,000	5,000	3.35	0.742	0.365	2390	−0.080	−0.262
PIS4	257	1,000	5,000	3.38	0.792	0.312	2044	−0.053	−0.175
PIS3	257	2,000	5,000	3.34	0.706	0.551	3605	0.205	0.672
PIS2	257	2,000	5,000	3.3	0.714	0.713	4665	0.442	1446
PIS1	257	1,000	5,000	3.27	0.676	0.371	2428	1110	3632
SDC4	257	1,000	5,000	4.05	0.809	−0.706	−4624	0.663	2171
SDC3	257	1,000	5,000	3.96	0.797	−0.540	−3534	0.224	0.733
SDC2	257	2,000	5,000	4.13	0.698	−0.318	−2078	−0.445	−1455
SDC1	257	2,000	5,000	4.04	0.754	−0.447	−2927	−0.136	−0.444
TPDC5	257	1,000	5,000	3.93	0.905	−0.805	−5270	0.739	2417
TPDC4	257	2,000	5,000	4.07	0.77	−0.627	−4104	0.213	0.697
TPDC3	257	1,000	5,000	4.01	0.884	−0.933	−6109	1017	3327
TPDC2	257	1,000	5,000	3.96	0.835	−0.699	−4578	0.534	1749
TPDC1	257	1,000	5,000	4.14	0.793	−0.725	−4745	0.400	1307
PTL5	257	2,000	5,000	4.31	0.757	−0.738	−4827	−0.349	−1141
PTL4	257	1,000	5,000	4.06	0.899	−0.962	−6296	0.933	3052
PTL3	257	2,000	5,000	4.04	0.762	−0.337	−2208	−0.508	−1663
PTL2	257	2,000	5,000	4.2	0.759	−0.677	−4432	0.008	0.026
PTL1	257	2,000	5,000	4.26	0.706	−0.682	−4465	0.219	0.717
Multivariate								126,968	34,307

Table 2. Loading factor, AVE, CR, and collinearity measurement of latent variables.

Latent Variable	Observed Variable	λ (>0.50)	AVE (>0.50)	C.R (>0.50)	VIF (<5)	Validity and Reliability Conclusion	Fulfill the Collinearity Assessment
Principals' Instructional E-Supervision	PIS1	0.599	0.92	0.98	1.467	Valid	Yes
	PIS2	0.659			1.699	Valid	Yes
	PIS3	0.630			1.554	Valid	Yes
	PIS4	0.702			1.650	Valid	Yes
	PIS5	0.641			1.586	Valid	Yes
	PIS6	0.664			1.578	Valid	Yes
Principal Technology Leadership	PTL1	0.795	0.95	0.99	2.255	Valid	Yes
	PTL2	0.864			2.813	Valid	Yes
	PTL3	0.791			2.239	Valid	Yes
	PTL4	0.681			1.668	Valid	Yes
	PTL5	0.705			1.764	Valid	Yes
	SDC1	0.787			1.763	Valid	Yes
School digital culture	SDC2	0.830	0.96	0.99	2.169	Valid	Yes
	SDC3	0.826			2.462	Valid	Yes
	SDC4	0.736			2.416	Valid	Yes
	TPDC1	0.685			2.142	Valid	Yes
	TPDC2	0.718			2.532	Valid	Yes
Teacher Professional Digital Competence	TPDC3	0.784	0.95	0.99	2.505	Valid	Yes
	TPDC4	0.847			1.943	Valid	Yes
	TPDC5	0.834			1.701	Valid	Yes

4.3. Measurement Model Analysis (Outer Model)

The preliminary analysis model assessed the loading factor values for both exogenous and endogenous variables, with a target of values exceeding 0.7. Nevertheless, values above 0.5 were deemed acceptable in specific situations [121], as detailed in Table 2. Subsequently, AVE and CR values were employed to evaluate the validity and reliability of the instrument for each latent variable. AVE and CR values were calculated using Microsoft Excel (see Appendix B).

$$AVE = \frac{\sum Std.Loading^2}{\sum Std.Loading^2 + \sum \epsilon_j} \quad CR = \frac{(\sum Std.Loading)^2}{(\sum Std.Loading)^2 + \sum \epsilon_j}$$

The loading factor (λ) values for each observed variable in Table 2 meet the standards, as the outer loadings are greater than 0.5. The AVE values for PIS ($0.92 > 0.5$), PTL ($0.95 > 0.5$), SDC ($0.96 > 0.5$), and TPDC ($0.95 > 0.5$) are also within acceptable ranges. Additionally, the CR values for PIS ($0.98 > 0.7$), PTL ($0.99 > 0.7$), SDC ($0.99 > 0.7$), and TPDC ($0.99 > 0.7$) meet the criteria for reliability [121]. Furthermore, VIF (Variance Inflation Factor) values generated by each indicator of latent variables indicate low correlation or collinearity (<5) [123]. In addition, to measure the discriminant validity of latent variables in this study, the HTMT analysis was also conducted, and the results are summarized in the following Table 3.

Table 3. Heterotrait–monotrait ratio (HTMT) assessment of latent variables.

	PIS	PTL	SDC	TPDC
PIS				
PTL	0.162			
SDC	0.165	0.713		
TPDC	0.281	0.734	0.880	

Table 3 indicates that the correlation values between one latent variable and another are <0.90 , meaning that each variable has its own uniqueness [123]. This allows for the further estimation of effects in subsequent analyses. Therefore, the subsequent stage involves assessing the goodness-of-fit model to examine the congruence of the developed model with the available field data. The goodness-of-fit model results are presented in Table 4.

Table 4. Measurement of overall model goodness of fit.

Criteria	Cut of Value	Model Result	Conclusion
Chi-square	Expected to be small	223.438	Marginal Fit Model
p -value	≥ 0.05	0.002	Marginal Fit Model
GFI	≥ 0.90	0.920	Good Model
AGFI	≥ 0.90	0.899	Good Model
CFI	≥ 0.95	0.978	Good Model
CMIN/DF	≤ 2.00	1.354	Good Model
TLI	≥ 0.95	0.974	Good Model
RMSEA	≤ 0.08	0.037	Good Model

According to Table 4, it can be emphasized that the constructed hypothesis model aligns with the field data. Several criteria substantiate this alignment [118,121,122]. Consequently, a subsequent step involving the analysis of the structural model using bootstrapping is fulfilled.

4.4. Structural Model Analysis (Inner Model)

The following bootstrapping analysis was applied to assess the structural influence model of the direct and indirect effect of the variables examined and to determine the determinant factors (R^2) [121,122]. Therefore, four variables are tested: PIS, PTL, SDC, and TPDC. The model analysis results are presented in Figure 4 and Table 5.

As indicated in Table 5, it is noteworthy that the null hypotheses (H_0) are rejected based on the p -value (<0.05). In addition, T statistic values showed values > 1.96 [123]. The four measured variables exhibit a direct influence on each other. PIS demonstrates a noteworthy impact on TPDC, albeit the least pronounced compared to other observed effects. Meanwhile, PTL exerts a dominant impact on SDC, as well as on TPDC, but the latter impact is relatively lower. SDC significantly affects TPDC, with a higher contribution coefficient compared to the influence of other latent variables. Finally, the indirect effect of PTL on TPDC, mediated through SDC, demonstrates a higher coefficient than when not considering the mediation of SDC. These findings necessitate further discussion and exploration in future research endeavors.

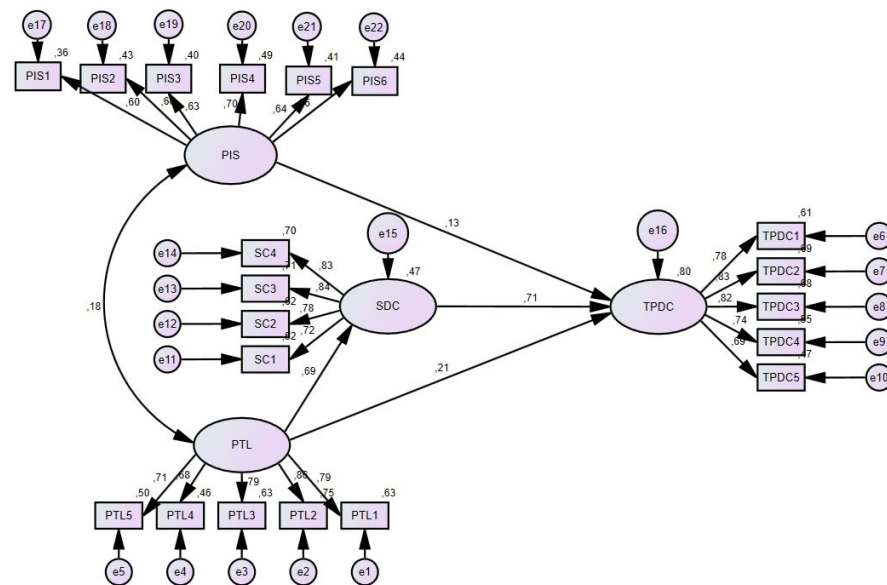


Figure 4. Structural effect model of technology leadership instructional e-supervision, school digital culture and teacher professional digital competence.

Table 5. Resulting structural coefficient (R2), T Statistic, and *p*-value of latent variables.

Path Analysis	T Statistics (>1.96)	<i>p</i> -Value (<0.05)	Direct Effects	Indirect Effects
PIS → TPDC	3.268	0.008	0.192	
PTL → TPDC	15.164	0.002	0.229	
PTL → SDC	4.585	0.000	0.663	
SDC → TPDC	11.333	0.000	0.816	
PTL → SDC → TPDC	8.883	0.001		0.541

5. Discussion

5.1. Direct Effect

The initial findings of this study revealed that PIS affects TPDC (H1). School principals' use of technological tools, such as WhatsApp, Zoom, spreadsheets, and others, in managing digital-based learning supervision has been proven to improve TPDC. This involves knowledge and concepts of device usage (TC), content knowledge (CK), attitudes toward technology use (ATU), pedagogical competence (PC), and critical approach (CA). However, the effect is lower. Positive effects are only likely to occur when school principals can offer programs and training recommendations to teachers in digital technology and media-based learning after evaluating the teacher's performance in the teaching process from the implementation phase. In this scenario, the principal as supervisor can identify teachers requiring training and suggest participation in government initiatives, such as the PembaTIK program by the Ministry of Education and Culture of the Republic of Indonesia, to enhance their technological teaching capabilities. Nevertheless, it continues to exert an influence. This discovery aligns consistently with Wiyono [22], indicating that communication techniques grounded in information and communication technology (ICT) during instructional supervision impact teachers' ability to discover practical techniques for enhancing instructional quality and optimizing digital media learning. In addition, several studies also indicate the importance of e-supervision in helping teachers utilize technological knowledge and skills to implement the effectiveness of instruction in the digital-savvy era [20,74,114,124–126].

The second finding of this study indicates that PTL significantly impacts TPDC (H2). This implies that implementing PTL impacts teachers' abilities to utilize technology for various learning models, encompassing technological skills, content knowledge, pedagog-

ical knowledge, attitudes toward technology use, and critical perspectives. Initially, as a visionary planner, the principal establishes clear objectives for incorporating technology into the educational environment. This provides teachers with a structured pathway to nurture and enhance their professional digital competence (e.g., TC, CK, PC, ATU, and CA), harmonizing with the school's overarching vision. Furthermore, engaging teachers in the development of the digital vision cultivates ownership and commitment (e.g., ATU), ensures relevance to classroom practices (e.g., PC and CK), aligns goals, fosters adaptability and innovation (e.g., TC and CA), and enables a sense of purpose toward its attainment. This is consistent with prior studies emphasizing that principals who are actively involved in helping teachers in strategically planning technology integration have a positive influence on enhancing teachers' digital competence. Key elements include establishing clear goals and envisioning technology-enhanced teaching [26,27,93,120]. Second, when the principal advocates for equity and citizenship, it assists teachers in acknowledging the significance of readying students for the digital challenges of global citizenship. This advocacy extends to teachers, motivating them to cultivate professional digital competence per the overarching objectives of promoting global awareness and competence. Additionally, the principal elevates teachers' professional digital competence by ensuring that every teacher enjoys equitable access to digital resources and tools regardless of their background or context. Third, as empowering leaders, principals provide teachers with the autonomy to experiment with and incorporate digital tools and strategies into their teaching practices, fostering attributes such as attitudes toward technology use (ATU), pedagogical competence (PC), and content knowledge (CK). Additionally, they nurture a growth mindset among teachers, encouraging them to welcome challenges and consistently seek learning opportunities, thereby influencing aspects like technological competence (TC) and critical approach (CA). This aligns with the findings of Aktaş and Karaca [127], who found that technology leadership influences the technological skills of school administrators, particularly their self-efficacy (defined as ATU) in using technology tools. Likewise, Purnomo et al. [9] discovered the influence of principals' technology leadership, such as empowering leaders, wherein it enhances teacher acceptance, self-efficacy, and attitude in incorporating technology into the learning environment. Furthermore, the existing studies consistently show how principal technology leadership contributes to teacher technology incorporation skills in the teaching process [11,18,44,120,128]. Another motor to enhance teacher technological competence is when the principal actively engages as a connected learner by leveraging technology. This role can comprehend and enhance their proficiency in technology education. This includes demonstrating effective use of technology, ultimately serving as a role model for teachers, who are more inclined to emulate such practices. Lastly, a principal who implements his role as a system designer will contribute to a workshop essential to enhancing proficiency in teaching with technology, including teachers' TPACK skills [99,104,107,120]. Hence, Hero [49] and Lander [50] assert that the negative impact of PTL on teachers' digital skills contrasts with this finding. However, this research marks the first instance of identifying the impact of PTL on TPDC, but the impact is lower. In this scenario, the principal, acting as a technology leader, furthers a collaborative culture to strengthen the impact delivered. This is aligned with the following finding, which will be discussed.

The third finding revealed that PTL directly affects the SDC (H3), encompassing dimensions such as OL and PLCs. This is consistent with prior studies regarding the significance of communication and collaboration among teachers within the school culture for effecting sustainable changes in educational organizations, where the principal's leadership plays a crucial role [54,58,67,97,129,130]. This implies that effectively implementing the principal's technology leadership in schools can foster an environment where teachers actively seek information, communicate, and collaborate, leveraging technology tools as facilitators. In addition, these findings align with previous studies highlighting the impact of principals' digital leadership on cultivating a digital learning culture and integrating technology into instruction [26,45,47,48,68,120].

Fourth, this study revealed a significant impact of SDC on TPDC (H4). First, innovative organizational learning technologies (iOLTs) facilitate both individual and collective learning among teachers, exposing them to various digital tools and sources tailored to specific educational objectives. Interacting with this diverse set of tools not only enhances teachers' familiarity with various technologies but also broadens their overall digital skill set (e.g., TC, CK, PC, ATU, and CA) [69]. Second, Professional Learning Communities (PLCs) are pivotal in promoting collaborative learning, peer support, mentoring, collective problem-solving, and access to diverse perspectives. Collaborative learning within PLCs enables teachers to share their experiences with digital tools and strategies, provide peer support and mentoring in digital skills, and engage in joint problem-solving when facing challenges. The diverse perspectives and experiences brought to the table in PLCs expose educators to a wide range of digital tools and strategies, enriching their understanding and application of digital skills across various contexts, including technological competence (TC), content knowledge (CK), pedagogical competence (PC), attitudes toward technology use (ATU), and critical approach (CA). This finding aligns with prior research, such as Lai et al. [61], highlighting the crucial role of school culture and professional development in predicting teacher knowledge, skills, and beliefs in using technology for teaching and learning. This includes dimensions like technology for content delivery, learning enrichment, and technology for transforming education towards self-directed learning. Similarly, McConnell et al. [70], observed that virtual Professional Learning Communities (PLCs) utilizing video-conferencing tools necessitated teacher technology skills, fostering relationships and collaboration among teachers to enhance the teaching and learning process in the 21st century. Furthermore, several studies consistently emphasized the impact of school culture, specifically in terms of organization learning, on teachers' technological, pedagogical, and content knowledge (TPACK), team communication, and support learning mediated by technology tools teachers' technology integration capabilities in the instruction [48,62–68,86,87,89–91].

5.2. Indirect Effect

Lastly, our findings reveal that the direct impact coefficient of PTL on SDC is higher than on TPDC. Meanwhile, the dominant coefficient is found in the influence of SDC on TPDC. This means the SDC is a significant mediator for PTL and TPDC (H5). This finding aligns with research models illustrating how practical leadership by principals influences teacher innovation through school culture [56,81,131]. In a more detailed context, Saputra [29] underscores that teachers' digital competence in implementing digitally-oriented learning is directly affected by digital collaboration and indirectly influenced by digital leadership. Similarly, Thannimalai and Raman [34] discovered that principals must foster school culture and teacher professional development to become influential technology leaders, motivating teachers to integrate technology in the classroom to advance students' skills in the digital-savvy era. Essentially, this implies that the principal's technology leadership can cultivate an optimal digital culture, enabling teachers to enhance their proficiency in using technology in the classroom by considering several specific competencies, including TC, CK, ATU, PC, and CA. Finally, teachers are urged to prioritize communication, collaboration, and the establishment of relationships with peers. This emphasis is essential for exchanging ideas, addressing challenges, and devising solutions to enhance skills required (TPDC) for effective technology integration, thereby contributing to ongoing school improvement.

5.3. A Brief Model for Future Research of Principal Technology Leadership (PTL-Based Humbleness Coaching)

The earlier discussion and research findings have revealed unique outcomes, notably where the exogenous variable, PTL, exhibits a coefficient value of 0.229 (22.9%). This starkly contrasts with other models in the research hypothesis. On a different note, the direct impact of SDC on TPDC is 0.816 (81.6%). The contribution from SDC diminishes when

PTL is positioned as an exogenous variable. The influence of PTL through SDC registers a value of 0.541 (54.1%). SDC is considered independent in shaping endogenous variables. Based on these observations, we propose a novel model of principal technology leadership, aiming to maximize the primary implications of this research in the long term, manifested in sustained professional skills for teachers.

Previous investigations have suggested that leadership constructs, while potentially enhancing specific employee competencies, often result in modest contributions. This is attributed to the requirement for effective leadership to bolster (1) work commitment, (2) work motivation, (3) employee self-efficacy, and (4) goal orientation in the workplace [132–134]. Despite the generally recognized importance of leadership, earlier research has not definitively established its substantial dominance in influencing TPDC. Thorough examinations of previous studies have highlighted instances where leadership constructs fell short in instilling superior competencies in employees. The identified causes for this shortfall encompass factors such as (1) a lack of emotional closeness, (2) setting overly ambitious achievement targets, (3) an inability to function as effective task coaches, and (4) a lack of humility [135,136].

The proposed novel model is grounded in the recognition that PTL can exert influence by (1) providing facilities, (2) empowering the school environment, and (3) displaying openness to technological adaptability in schools. However, the existing PTL framework falls short in translating these efforts into optimal competence improvement outcomes. Consequently, the core deficiency in PTL can be addressed by integrating it with coaching leadership characterized by humility. This integration forms a new dimension, representing the novelty in the recommendations and discussions of this study. Conceptually, these ideas are depicted in Figure 5.

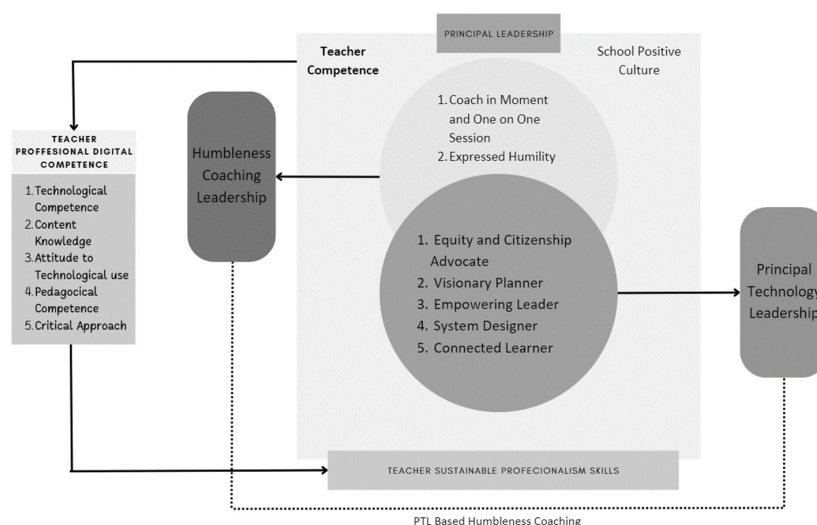


Figure 5. Proposed novel model of PTL-based humbleness coaching for future research.

The humbleness coaching leadership style comprises two essential components: (1) coaching leadership and (2) humble leadership. Coaching leadership involves a leader who can (1) incidentally provide training for employees, (2) offer one-on-one skill reinforcement, and (3) foster creativity among employees in their tasks [137,138]. The formulation of this novel model of principal leadership incorporates humble leadership, characterized by expressed humility: (1) modesty, (2) a low level of narcissism, (3) openness to learning, (4) honesty, (5) goal-oriented task approach, and (6) core self-evaluation [139]. Consequently, this proposed novel approach is anticipated to lead to a more comprehensive influence on TPDC for future research.

6. Conclusions

Based on the research findings, it is evident that there is a substantial influence among the four variables—instructional e-supervision, technology leadership, school digital culture, and teacher professional digital competence—although the impact is characterized by varying coefficients. Instructional e-supervision affects TPDC directly, but its coefficient effect is the lowest. Technology leadership directly affects both school culture and teachers' professional digital competence. School digital culture, in turn, significantly influences teachers' professional digital competence. While teacher professional digital competence exhibits a lower coefficient in response to technology leadership, it demonstrates a higher level of significance when traversing the school digital culture pathway. Therefore, the practice of the principal's technology leadership plays a crucial role in fostering collaboration and digital communication among teachers, colleagues, and relevant stakeholders, contributing significantly to the integration of technology in the learning process.

Although PTL has a notable impact on TPDC, its influence is relatively lower than its effect on SDC. The dimension of PTL does not directly address TPDC; rather, it underscores the principal's role as a leader in influencing and creating a conducive environment to support teachers' professional growth. In essence, the direct relationship with technology leadership primarily affects behavior, specifically the attitude of teachers toward technology, linked to their confidence in integrating technology into the learning process. This is evident from the high coefficient representing the influence of PTL on SDC, which subsequently contributes to the high coefficient on TPDC.

7. Limitation and Future Research

This study has some limitations in generalizing the findings. First, the sample used only represents some teachers in Indonesia, precisely in Makassar. Second, the context of school culture might be different in other places. However, the proposed model for future research has solidity with empirical evidence and previous studies. The proposed model of PTL based on humbleness coaching is put forward to enhance its contribution to TPDC. It is crucial to highlight that school principal leadership predominantly influences teacher behavior directly in TPDC. Meanwhile, humbleness coaching leadership focuses on training through teacher technology programs, and it might generate positive outcomes regarding digital technical skills and knowledge in teachers' professional digital competence. Additionally, humbleness coaching leadership might influence teachers' motivation to learn and develop their capabilities due to the openness and emotional connection established between leaders and subordinates (teachers). Moreover, the one-on-one training orientation of humbleness coaching leadership probably provides teachers with a comprehensive learning opportunity, fostering a serious commitment to developing their capacity for PDC. Therefore, the integration of principal technology leadership and humbleness coaching is suggested for future research.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest: We would like to confirm that we have no financial interests or affiliations with any organization that may have a direct or indirect interest in the subject matter discussed in the manuscript.

Appendix A

Table A1. Measurement of latent variables and indicators.

Latent Variables	Indicators	Items (Sub Indicators)
Principal Instructional E-Supervision (PIS)	Initial meeting (Planning)	The school principal uses spreadsheets/Google Docs to design digital-based teaching supervision programs or instruments (PIS1). The school principal discusses with teachers through WhatsApp/Zoom and similar platforms regarding the preparations and requirements for implementing a digital-based learning model (PIS2).
	Implementation	The school principal observes teachers' teaching activities through video, Zoom, and similar platforms (PIS3). The school principal provides direct feedback to teachers through WhatsApp, Zoom, and similar platforms (PIS4). The school principal conducts evaluations through WhatsApp/Zoom for teachers needing training in digital learning methods (PIS5).
	Evaluation (Feedback)	The school principal organizes an online training program to enhance teachers' abilities in implementing digital learning models (PIS6).
Principal Technology Leadership (PTL)	Equity and citizenship advocate	The school principal ensures the availability of facilities and digital tools for implementing digital learning models in schools by considering ethics (PTL1).
	Visionary planner	The principal involves the school stakeholders in determining and developing the school's digital vision (PTL2).
	Empowering leader	The school principal delegates teacher duties and responsibilities in the school's digitalization mission (PTL3).
	System designer	The school principal designs a team to make the school's strategic plan related to digital learning success by considering school data security (PTL4).
	Connected learner	The principal is active in various online activities to improve skills in learning technology (PTL5).
School Digital Culture (SDC)	Organizational Learning	Teachers actively seek information independently using Google, Ed.Podcast, etc to increase capacity in digital learning innovation (SDC1).
	Shared responsibility	Teachers have a high sense of responsibility in their professional duties, especially in digital learning innovation (SDC2).
	Deprivatization of practice	Teachers are open to discussing with colleagues using SMS, WhatsApp or Zoom regarding the success or obstacles faced in applying digital learning models in the classroom (SDC3).
	Reflective dialogue	Teachers assess each other's performance from discussion results using SMS, WhatsApp or Zoom to improve further performance in digital learning innovation.
Teachers' professional Digital Competence (TPDC)	Technological competence	Teachers can understand using technology tools as media in the learning process (TPDC1).
	Content knowledge	Teachers can apply relevant digital learning applications in the context of the subject being taught in the classroom (TPDC2).
	Attitude to technological use	The teacher has the self-belief to demonstrate digital media in the learning process (TPDC3).
	Pedagogical competence	Teachers can comprehensively understand integrating digital learning applications according to student needs (TPDC4).
	Critical approach	Teachers can conduct critical analysis before choosing any digital tools in the learning process (TPDC5).

Appendix B

Table A2. Formulation of AVE and CR using Microsoft Excel.

Latent Variables	PIS			PTL			TPDC			SDC		
Observed Variables	λ	Λ^2	S.E	λ	Λ^2	S.E	λ	Λ^2	S.E	λ	Λ^2	S.E
PIS1	0.599	0.358801	0.03									
PIS2	0.659	0.434281	0.032									
PIS3	0.63	0.3969	0.032									
PIS4	0.702	0.492804	0.037									
PIS5	0.641	0.410881	0.034									
PIS6	0.664	0.440896	0.038									
PTL1				0.795	0.632025	0.02						
PTL2				0.864	0.746496	0.019						
PTL3				0.791	0.625681	0.024						
PTL4				0.68	0.4624	0.042						
PTL5				0.705	0.497025	0.029						
TPDC1							0.783	0.613089	0.025			
TPDC2							0.829	0.687241	0.024			
TPDC3							0.823	0.677329	0.028			
TPDC4							0.739	0.546121	0.027			
TPDC5							0.686	0.470596	0.042			
SDC1										0.719	0.516961	0.027
SDC2										0.785	0.616225	0.02
SDC3										0.845	0.714025	0.022
SDC4										0.835	0.697225	0.023
Sum of Std Loading	3.895			3.835			3.86			3.184		
Sum of Std Loading ²		2.534563			2.963627			2.994376			2.544436	
Sum of Error			0.203			0.134			0.146			0.092
AVE	0.925846455			0.95674108			0.953508752			0.965104406		
CR	0.986795911			0.990971096			0.990296166			0.991006716		

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