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Future-ready educators: assessing the effectiveness of technology-driven intervention in preparing pre-service teachers for 21st-century classrooms

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Background: The demands of 21st-century classrooms require pre-service teachers to develop digital competencies that enable effective instructional delivery and collaboration.

Objectives: This study evaluated the effectiveness of a digital-age teaching module in improving pre-service teachers' preparedness for future classrooms.

Methods: Using a quasi-experimental design, the study engaged first-year education students and assessed changes in four competency domains: digital literacy, instructional planning, collaborative learning, and technology integration for teaching and assessment. A structured, theory-driven methodology grounded in the Technological Pedagogical Content Knowledge (TPACK) framework guided the intervention and evaluation. Quantitative data were collected through validated instruments and analysed to determine the module's impact on participants' instructional competencies.

Results: The study found that the preservice teachers exposed to the digital-age teaching module demonstrated significantly greater instructional competency across all four dimensions of the study (digital literacy skills, instructional planning ability, collaborative learning ability and technology integration ability) compared to those in the control group.

Conclusion: The study concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' instructional competency and remain substantial aspect of the teacher-training's curriculum which prepared pre-service teachers for 21st-century classrooms and it recommended formal integration of the digital-age teaching module into pre-service teacher education programmes, structured monitoring and evaluation systems to assess the effectiveness of digital teaching modules, capacity building in technology and provision of adequate digital tools by the Government.

KEYWORDS

digital competence, digital pedagogy, future-ready educators, innovative teaching practices, teacher education

Introduction

Education systems around the world are evolving quickly. It is being driven by technological advancements, global interconnectedness, and the shifting expectations of today's job market. These changes require a paradigm shift in the preparation of future educators to ensure that they are well-versed in essential knowledge and skills required for effective teaching and learning in technologically integrated and competency-driven classrooms (Apata et al., 2025; Voogt et al., 2013). Teachers today are doing way more than just standing in front of a classroom and giving lectures as schools lean into technology and focus more on helping students build real-world skills. In addition to having subject-matter expertise, teachers are now required to support students' learning using digital resources, encourage critical thinking, creativity, teamwork, and problem-solving skills (Partnership for 21st Century Skills, 2019). There is a growing recognition that traditional teaching methods no longer adequately prepare pupils for the difficulties of today's rapidly evolving world, as more institutions shift to digital technologies and skill-focused learning. The fourth industrial revolution, characterized by the convergence of digital technologies and automation, has redefined the skills necessary for success (Schwab, 2016). In response, education systems must prioritize the development of future-ready competencies that are aligned with labour market needs and global trends. According to Redecker and Punie (2017), this transformation calls for a redefinition of the role of educators, emphasizing continuous professional development, technological fluency, and pedagogical innovation.

Within this context, teacher education institutions bear the primary responsibility of preparing pre-service teachers who can navigate and thrive in future-oriented educational landscapes. However, evidence suggests that many teacher preparation programs, particularly in developing countries, are lagging in the integration of digital competencies and innovative pedagogies into their curricula (Apata, 2021). Specifically, Demissie, et al., (2022) in their study found out that even among in-service teachers, digital skills are mainly possessed only by ICT teachers and a few private school teachers had basic computer skills. The capacity to use digital devices and technology with confidence and effectiveness is known as digital skills. These abilities include digital security, internet usage, online communication, information retrieval, and basic computer literacy (OECD, 2023). According to Helsper et al. (2020), digital skills refers to technical and operational abilities, communication and interaction skills, information navigation and processing skills, and content creation and production skills needed to navigate digital technologies. Digital skills and digital competencies are closely related, but digital competencies are broader and more holistic. They include not only technical skills but also the knowledge, attitudes, ethics, and critical thinking needed to use digital technologies effectively, responsibly, and creatively (Falloon, 2020).

However, Pre-service teachers often receive limited exposure to practical, technology-based teaching strategies and are inadequately trained to leverage digital tools for collaborative and personalized learning experiences (Anwar et al., 2025; Theodorio et al., 2024; Tondeur et al., 2018; Kafyulilo et al.,

2016). In Nigeria, the urgency of preparing teachers for 21st-century learning environments is accentuated by systemic challenges within the teacher education system. Although the Nigerian National Policy on Education (FRN, 2014) highlights the need to embed information and communication technology (ICT) into teacher preparation programs, its practical rollout has been uneven and largely inadequate. In many Colleges of Education and university Faculties of Education across Nigeria, instruction continues to lean heavily on theory, with limited opportunities for educators to engage in practical technology use or explore digital teaching methods (Adu and Olatundun, 2013). The teacher education programme in Nigeria is characterized by low adoption and application of IT in an age characterized by technological dominance (Yusuf, 2022). According to studies (Anwar et al., 2025; Theodorio et al., 2024; Tondeur et al., 2018), teacher education programs often prioritize theoretical knowledge over practical application, leaving gaps in student-centered, collaborative, and individualized learning techniques. These current situations can be attributed to external factors such as infrastructure deficits, lack of internet access, insufficient training for teacher educators, as well as internal factors related to teachers' general resistance to change, including their attitudes and beliefs, resistance toward technology in the classroom, and their knowledge and skills are challenges that can further exacerbate the situation.

In addition, many Nigerian pre-service teachers complete their training without gaining the practical skills needed to help students develop digital literacy, think critically, or approach problems with confidence and creativity. This gap between policy intentions and practical outcomes raises critical concerns about the efficacy of teacher education in equipping future educators for the demands of the 21st-century classroom (Yusuf, 2022). This may imply that most Nigerian teacher training institutions do not sufficiently incorporate ICT-based pedagogies, leaving new teachers ill-prepared for technologically enhanced teaching environments. As such, Amanchukwu and Ololube (2015) opined that teachers should be abreast with the new technology so as to make positive impact on the learners.

The implications of this gap are far-reaching, as it hinders both teacher effectiveness and student readiness for the global knowledge economy. Even though these challenges are widely acknowledged, there's still a noticeable lack of research that evaluates how well current efforts are helping Nigerian pre-service teachers build digital skills. While some research has explored teachers' attitudes toward ICT integration (Olaore, 2014), few studies have employed robust experimental designs to evaluate the impact of structured digital pedagogical training on preservice teachers' preparedness. This presents a research gap, as understanding the outcomes of such interventions is crucial for informing policy and improving teacher education practices.

This study aims to close this gap by evaluating the influence of a carefully designed and implemented intervention (digital-age teaching module) on pre-service teachers' preparedness for 21st-century classrooms through a quasi-experimental design. Specifically, we assessed the effects of the digital-age teaching module on pre-service teachers' instructional competency across key competency domains: digital literacy, instructional planning,

collaborative learning, and technology integration for teaching/assessment.

To achieve these aims, we generated and tested the following research hypotheses:

1. H₀₁: The digital-age teaching module has no significant effect on pre-service teachers' digital literacy.
2. H₀₂: The digital-age teaching module has no significant effect on pre-service teachers' instructional planning skills.
3. H₀₃: The digital-age teaching module has no significant effect on pre-service teachers' ability to facilitate collaborative learning.
4. H₀₄: The digital-age teaching module has no significant effect on pre-service teachers' technology integration for teaching and assessment.
5. H₀₅ (overall): The digital-age teaching module has no significant effect on pre-service teachers' instructional competency across the four key domains.

The significance of this study lies in its contribution to evidence-based reform in teacher education. By empirically evaluating the impact of a structured digital intervention, the study offers insights that can inform curriculum development, instructional practices, and policy formulation within Nigerian teacher education systems. Furthermore, the findings will serve as a resource for educational planners, curriculum developers, and teacher educators seeking to align pre-service teacher training with the realities of 21st-century education. As nations strive to meet global education targets and Sustainable Development Goal 4, which emphasizes inclusive and quality education for all, the need for well-prepared, future-ready teachers becomes even more critical (UNESCO, 2016). Hence, the global momentum toward digital and competency-based education underscores the imperative for transformative changes in teacher preparation. This study responds to that imperative by investigating how digital-age training can enhance the future-readiness of pre-service teachers within a Nigerian university context. It closes an important gap in empirical literature and provide practical strategies for equipping tomorrow's teachers with the tools, mindsets, and skills necessary for success in 21st-century classrooms.

2 Literature review and theoretical framework defining future-ready teaching competencies

According to Voogt et al. (2013), "future-ready teaching competencies" are the integrated set of knowledge, skills, attitudes, and values that enable teachers to effectively facilitate learning in a technology-driven, interconnected, and dynamic world. These competencies include not only the basic pedagogical knowledge required for effective instruction but also the ability to integrate digital tools, foster student collaboration, stimulate creativity, and grow critical thinking in diverse learning environments which is on increase. Rapid technological, social, and economic changes in the twenty-first century have redesigned the abilities and proficiencies required of teachers and students. Future-ready teachers must be able to incorporate new technology into their lessons, modify their

teaching methods to meet changing needs, and assist students in acquiring the skills they will need for lifetime learning, according to the OECD (2018). According to the International Society for Technology in Education (ISTE, 2022), a teacher who uses technology to empower students, creates inclusive and customized learning environments, and pursues ongoing professional development to stay up to date with emerging trends is considered future-ready. These skills are dynamic; they change as educational technologies and the demands of a global workforce do.

In practical terms, future-ready teaching competencies involve not only digital fluency but also the pedagogical capacity to redesign learning experiences around student-centered methodologies. Teachers must demonstrate agility in adopting innovations and critically evaluating the appropriateness of various technologies for specific instructional contexts (Redecker and Punie, 2017). This is particularly relevant in the Global South, where digital divides and infrastructural limitations complicate the adoption of emerging educational technologies. As such, teacher education programs must intentionally cultivate these competencies in pre-service teachers to ensure they are adequately prepared to thrive in the 21st-century classroom.

2.1 Core 21st-century skills: digital literacy, collaboration, critical thinking, and creativity

At the heart of future-ready teaching competencies are four interrelated 21st-century skills: digital literacy, collaboration, critical thinking, and creativity. These skills form the foundation of effective teaching and learning in modern educational contexts and are widely acknowledged in educational policy documents, such as UNESCO's Education 2030 Agenda and the Framework for 21st Century Learning by the Partnership for 21st Century Skills (2019). Digital literacy refers to the capacity to locate, evaluate, and use digital tools and resources effectively and ethically (Ng, 2012). It includes basic operational skills (e.g., using hardware and software), as well as higher-order competencies such as digital content creation, data interpretation, online collaboration, and digital citizenship. For pre-service teachers, digital literacy is essential in planning technology-enhanced lessons, managing virtual classrooms, and assessing learners through online platforms. However, the current realities on the ground show a wide disparity between expected benefits and actual implementation (Zou et al., 2025).

Collaboration as a core competency emphasizes the ability to work effectively with others toward shared educational goals. In the context of 21st-century education, this includes not just in-person teamwork but also virtual collaboration using platforms such as Google Workspace, Padlet, or Microsoft Teams. In this digital age, the transformation of teaching and learning promotes greater educational equality by expanding access and fostering collaboration within the framework of lifelong learning (Altunay, 2017). Digital platforms and emerging technologies provide opportunities for students to engage in interactive and participatory forms of learning that transcend traditional classroom boundaries. As such, pre-service teachers must be adequately prepared to design collaborative learning

environments that encourage peer-to-peer interaction, shared knowledge construction, and inclusive group participation. Developing these competencies not only equips future teachers to leverage digital tools effectively but also ensures that they can cultivate classrooms where every learner actively contributes and benefits from collective knowledge exchange.

Critical thinking is the ability to analyze, evaluate, and synthesize information to solve problems or make informed decisions. It is central to inquiry-based learning, problem-solving, and reflective teaching practice. According to [Aptata \(2021\)](#), the development of critical literacy skills has become a foundational necessity for navigating the complex demands of education, the workplace, and everyday social interactions in the 21st century. For pre-service teachers, developing critical thinking means not only being able to reflect on their instructional strategies but also fostering critical thinking in their students by encouraging debate, questioning assumptions, and supporting evidence-based reasoning. This is because critical teaching requires sensitivity to context, recognition of individual learner differences, and a commitment to social transformation. With critical thinking, the pre-service teachers will be actively able to participate in the transformation of their society ([Taştı, and Yıldırım, 2022](#)).

In digitally enhanced classrooms, this skill is also vital for discerning credible information online and guiding learners through digital content. Creativity in teaching goes beyond aesthetic expression; it involves the capacity to generate novel ideas, approaches, or solutions to pedagogical challenges. Creative teachers design curricula, lesson plans, innovative instructional activities that engage learners meaningfully, provide students with the freedom they need to construct their own knowledge and adapt to diverse student needs ([Sawyer, 2019](#)). Furthermore, in the digital era, creativity often intersects with technological fluency, as teachers must curate and integrate multimedia resources, design interactive activities, and personalize learning using digital platforms. Digitally literate teachers who lack critical thinking or collaborative abilities may find it difficult to adjust to the changing needs of the classroom. On the other hand, collaborative design and digital tools frequently improve innovative teaching methods.

Therefore, integrating these competencies into pre-service training courses requires a comprehensive strategy from teacher preparation programs.

2.2 Overview of digital pedagogy in pre-service teacher training

The planned and skilled application of technology to enhance instruction is known as digital pedagogy. It calls for a rethinking of instructional practices based on the potential and constraints of digital environments, going beyond merely incorporating digital tools into conventional methods ([Blundell, 2025](#)). When applied effectively, digital pedagogy can support personalized learning, foster collaboration, and offer greater flexibility. However, its implementation often faces challenges such as unreliable internet access, gaps in computer literacy, difficulties with online engagement, inconsistent power supply, and limited availability of devices ([Zakariya et al., 2024](#)). Digital pedagogy

has two purposes in pre-service teacher education: it ought to demonstrate optimal practices for using technology and provide aspiring teachers with the knowledge and self-assurance to use these strategies in their own classrooms. The degree to which digital pedagogy is included into teacher preparation programs varies greatly depending on the context, despite the fact that its benefits are generally acknowledged.

Across the globe, efforts to include technology into pre-service teacher education continue to vary widely, with many programs offering only initial-level exposure. While countries like the United States and parts of South Africa have achieved significant progress, regions such as Latin America and Sub-Saharan Africa often provide limited or foundational training, leaving graduates ill-equipped for meaningful classroom integration of digital tools ([Burns, 2023](#); [Rodriguez-Segura, 2022](#)). In Nigeria, the COVID-19 pandemic prompted universities to begin incorporating various forms of educational technology into teaching and learning ([Zakariya et al., 2024](#)). Yet, the adoption of digital pedagogy remains uneven, hindered by challenges such as inadequate infrastructure, gaps in technical expertise, and inconsistent institutional support.

Research on teacher education in Nigeria has regularly pointed to several barriers affecting digital integration, including; limited access to devices, unreliable internet connectivity ([Zakariya et al., 2024](#)), and a general lack of foundational technological skills. In addition, many educators require substantial professional development to effectively incorporate ICT into their teaching practices ([Dlamini and Rekai, 2022](#); [Molotsi and van Wyk, 2024](#); [Ogunyinka et al., 2015](#)). As a result, a significant number of pre-service teachers complete their training with little exposure to realworld digital teaching. Where digital instruction is offered, it often remains theoretical and disconnected from practical classroom application, which undermines its impact ([Adeoye and Agoro, 2019](#)). Best practices in digital pedagogy advocate for a constructivist, learner-centered approach, where technology is not used as a substitute for traditional instruction but as a transformative tool for active learning. This includes the use of flipped classrooms, blended learning, simulation, gamification, and the design of multimedia learning artifacts ([Means et al., 2013](#)). Additionally, mentorship, collaborative projects, and field-based teaching practicum in digitally rich environments help bridge the theory-practice gap in digital pedagogy. Emerging frameworks such as the SAMR model (Substitution, Augmentation, Modification, Redefinition) and TPACK (Technological Pedagogical Content Knowledge) provide conceptual tools for teacher educators to scaffold pre-service teachers' digital integration skills ([Mishra and Koehler, 2006](#); [Puentedura, 2014](#)). These models emphasize the need for pedagogically sound and contextually relevant technology use rather than mere adoption for novelty's sake.

In response to the COVID-19 pandemic, many Nigerian universities, including Osun State University, were compelled to accelerate their digital transformation initiatives. This presented both opportunities and challenges for reimagining digital pedagogy in teacher education. Emergency remote teaching sparked creativity and forced institutions to re-evaluate their digital strategy and make investments in capacity building, even as it revealed systemic flaws ([Onyema et al., 2020](#)). Pre-service teachers should be prepared by their training institutions with

the information and abilities that will enable them to be effective and have a high degree of creativity. In order to integrate digital pedagogy into teacher education programs in Nigeria going forward, a systemic change is needed, involving curriculum redesign, digital infrastructure investment, lecturer professional development, and improved collaborations between ICT support units and education faculties. Only then will pre-service teachers be able to acquire the competences that will enable them to succeed in modern classrooms.

2.3 Theoretical framework: the TPACK framework

The incorporation of technology into teaching methods has emerged as a major concern for both educators and policymakers in the changing context of 21st-century education. Mishra and Koehler (2006) created the Technological Pedagogical Content Knowledge (TPACK) framework, which offers a thorough theoretical foundation for comprehending how educators may successfully integrate digital technologies into their teaching methods. To Shulman's initial concept of pedagogical content knowledge, this theoretical model adds a third essential area of technological knowledge. It explains that using technology to educate demand deeper comprehension of how these tools may be utilised to enhance learning in certain subject areas rather than just knowing how to use them.

According to TPACK, effective technology integration calls for the harmonization of seven interrelated categories of teacher expertise. Among these is pedagogical knowledge, which encompasses familiarity with learning theories and instructional practices; technological knowledge, which includes competence with digital platforms and tools; and content knowledge, which denotes mastery of the subject matter. The framework further examines the points where various domains converge, including Technological Material Knowledge, which examines how technology may creatively alter and portray material, and Pedagogical Content Knowledge, which concentrates on efficient methods for teaching certain subjects. Technological Pedagogical Content Knowledge, the framework's cornerstone, is the seamless integration of all three domains in a manner that is grounded in effective teaching practices and contextually aware. Technological Pedagogical Content Knowledge examines how the use of technology may alter how people learn and teach.

In Nigeria teachers' education, and particularly in pre-service training programmes, the TPACK framework provide a valuable perspective for analysing how well future teachers are being prepared to engage with 21st-century learning environments. This study adopts the TPACK framework to assess the effectiveness of a digital-age teaching module in equipping pre-service teachers with the competencies required for future-ready classrooms. Apata (2023) reveals the importance of the TPACK model in the Nigeria, arguing that English language teachers, and by extension all subject educators, must move beyond basic technological literacy to develop the subtle comprehension of how technology, pedagogy, and content interact. Apata (2023) contends that "an effective English language teacher in Nigeria today must not only possess content and pedagogical knowledge but must also demonstrate competence in integrating

appropriate technologies to enhance learners' engagement and comprehension" (p. 10). This perspective aligns closely with the goals of this study, which seeks to evaluate whether the intervention module significantly improves pre-service teachers' technological integration competencies.

The TPACK model is particularly relevant in Nigeria where educational institutions face challenges, such as limited infrastructure, inconsistent power supply, and inadequate digital training. Despite these constraints, applying TPACK principles can guide teachers to develop strategies that are contextually appropriate for incorporating digital tools into lesson planning, instructional delivery, assessment, and learner engagement. The study's quasi-experimental design which covers a 6-week intervention focused on digital lesson planning, online instruction, collaborative tools, and assessment technologies which were informed by the TPACK model's emphasis on knowledge domains interdependence. Moreover, TPACK encourages reflective practice, an essential component in pre-service teacher education. Through pre and postintervention assessments, and questionnaires, this study measures not just knowledge acquisition but also shifts in teachers' perceptions and confidence in integrating digital tools into their pedagogy. As noted by Chai et al. (2013), teachers' beliefs and attitudes toward technology integration are often shaped during pre-service training, and a systematic framework for building these experiences is offered by the TPACK model.

By situating the study within the TPACK framework, the research adds to the growing body of evidence on how to prepare teachers who are both digitally competent and pedagogically sound. It affirms that cultivating educators who are future-ready requires more than ordinary discrete technical training, but also an integrated approach that helps teachers navigate the complexities of content delivery, instructional design, and learner engagement in technologically mediated contexts.

2.4 Empirical reviews

Globally, teacher education programmes have increasingly integrated digital technologies to enhance delivery of instruction, student engagement, and professional competence. A prominent example is Estonia's "AI Leap" initiative, which aims to provide students and teachers with world-class artificial intelligence tools by 2027. The programme emphasizes digital ethics, independent learning, and equitable access to digital resources, establishing Estonia as a pioneer in education driven by AI (The Guardian, 2025). This national commitment emphasizes the potential of digital interventions to transform education when embedded within coherent policy frameworks and sustained professional development.

In the broader international landscape, digital pedagogy has shifted from being a supplementary tool to an essential component of teacher education. Research by Oubibi et al. (2024) thoroughly examined online teacher education across Africa from 2014 to 2024. The study revealed an upward trend in the use of interactive technologies for remote instruction, assessment, and teacher collaboration. However, It also pointed up notable variations in adoption rates due to inconsistent

policy support, inadequate infrastructure, and educators' lack of digital competency.

Digital interventions are making their way into teacher education have expanded, though the progress has been uneven throughout Sub-Saharan Africa. UNESCO (2023) noted that technology is being used more and more throughout the continent to support content distribution, improve teacher collaboration, and offer flexible learning settings. However, the implementation is still dispersed, differing according to the preparation of institutions, geographic region, and socioeconomic position. For example, while urban-based institutions may benefit from stable internet and digital infrastructure, rural or underfunded schools often struggle to implement even basic digital solutions.

In Nigeria, Interest in digital innovation is rising within teacher education, but serious obstacles remain. Umeji (2024), for instance, examined the digital assessment practices of lecturers in teacher training institutions in Anambra State. The findings revealed limited adoption of digital tools for assessment, primarily due to lack of access to devices, inconsistent internet connectivity, and insufficient training for educators. While awareness of these tools is improving, their actual use in classrooms is still quite limited.

Similarly, Schlebusch et al. (2024) examined how two Southern African colleges are working to integrate technology into their teacher education programs. Their findings showed that although lecturers acknowledged the value of integrating digital tools into their teaching, the level of integration varied significantly. These differences were largely influenced by the degree of institutional support available and disparities in access to technological resources. Although research on digital interventions in teacher education is growing across Nigeria and Sub-Saharan Africa, several critical gaps remain. Much of the existing literature focuses on access to digital tools and general ICT literacy, with limited emphasis on how these technologies are pedagogically integrated into pre-service teacher training.

Few studies adopt structured, theory-driven interventions, particularly those grounded in frameworks like TPACK to evaluate their impact on teacher preparedness. Additionally, there is inadequate assessment of digital competence across multiple instructional dimensions such as lesson planning, delivery, assessment, and student engagement. Most studies also overlook the contextual realities of resource-constrained environments, offering little guidance on how digital pedagogies can be adapted to such settings. Notably, empirical research using quasiexperimental designs to evaluate the effectiveness of digital modules within Nigerian teacher education programs remains sparse, thus highlighting the need for context-specific, evidencebased studies like the present one.

3 Methodology

This study adopted a structured and theory-driven methodological approach to evaluate the effectiveness of a digital-age teaching intervention in improving the future-readiness of preservice teachers. Grounded in the TPACK framework, the methodology was designed to capture quantitative changes in competencies related to digital literacy,

instructional delivery, and pedagogical integration among first-year education students. The subsections below detail the specific research design, study context, instruments, and data analysis techniques employed.

3.1 Research design

The study employed a quasi-experimental pre-test/post-test design with a control group. This design measures outcomes in both an experimental and a control group before and after the intervention. Causal inference is strengthened by comparing the magnitude of change over time between the intervention group and the non-exposed control group, offering greater internal validity than descriptive approaches (Cook and Campbell, 1979). This design enabled the assessment of pre-service teachers' baseline competencies and the measurement of any statistically significant gains following the intervention.

3.2 Study context and participants

The target population comprised all 470 first-year pre-service teachers enrolled in the compulsory ASE 102 course (Computer Instruction in Social Science and Arts Education) across five programs at Osun State University, College of Education, Ipetu-Ijesa Campus, during the 2024/2025 session. This institution was selected for its curriculum modernization efforts and integration of the ASE 102 course, providing a foundational digital pedagogy exposure relevant to the study. Also, the course was selected because it introduces pre-service teachers to the effective integration of computers and modern technologies into instructional practices. It equips them with foundational knowledge and practical skills for planning lessons, delivering engaging instruction, and evaluating learning using digital tools. The distribution of Study Population is as showed in Table 1.

An intact class enrolled in ASE 102 (264 students) was purposively selected as the experimental group to receive the digital-age intervention. The remaining 216 students formed the control group, though only 139 (64.35%) participated voluntarily. The sampling and group allocations are as shown in Table 2.

Participants were predominantly female (69.7%) and aged 16–21 years. This homogeneous academic background facilitated the comparison of learning outcomes. For intervention delivery and instructional efficiency, the experimental group was

TABLE 1 Distribution of study population.

Category	Frequency (n)	Percentage (%)
Total population	470	100
Economics education	67	14.2
English education	250	53.2
Political science education	93	19.7
Educational management	37	7.9
Guidance & counselling	23	5.1

TABLE 2 Sampling and group allocation.

Group	Description	Frequency	Percentage (%)
Experimental	Intact class receiving digital-age intervention	264	56.2
Control	Voluntary participants not receiving intervention	139	29.6
Non-participants	No participation recorded in control allocation	67	14.2

systematically organized into five managed groups (A–E) of approximately 50 students each (Group A: 46, Group B: 53, Group C: 50, Group D: 56, Group E: 49). However, one of the limitations to this methodology was the lack of random assignment.

3.3 Instruments and intervention

3.3.1 Instruments

Two primary quantitative instruments were used for data collection; a pre-test and a post-test structured questionnaire. The questionnaire was a researcher-developed rating scale titled: *Teaching in the Digital Era: Preparing Pre-Service Teachers for the Future of Work*. The questionnaire measured actual self-reported competence in using technology for teaching, using a 5-point performance continuum:

- Novice (1) – cannot use the tool
- Slightly Able (2)—can use with significant assistance
- Moderately Capable (3)—can use with little assistance
- Competent (4)—can use independently
- Very Competent (5)—can use expertly

Given that this study adopted the TPACK framework, the instrument was structured into four (4) domains comprising a total of 28 items. In this study, the Digital Literacy domain aligns with Technological Knowledge (TK), while Instructional Planning reflects Technological Pedagogical Knowledge (TPK) and Pedagogical Content Knowledge (PCK). The Collaborative Learning domain corresponds to TPK, and Technology Integration for Teaching and Assessment reflects a combination of TPK and Technological Content Knowledge (TCK). As such, the Digital Literacy domain contained 6 items, which assessed pre-service teachers' problem-solving skills with technology, digital collaboration, information literacy, adaptability to new tools, and readiness to teach in technology-driven environments. The Instructional Planning domain consisted of 8 items, measuring competencies in technology-enhanced lesson planning, digital content creation, use of instructional tools, and design of engaging learning experiences. The Collaborative Learning domain included 5 items, focusing on the ability to use digital platforms for virtual classroom management,

teamwork, and collaborative instructional activities. Finally, the Technology Integration for Teaching and Assessment domain comprised 9 items, which assessed the use of digital tools for interactive teaching, assessment, gamification, feedback delivery, learning analytics, and data-driven instructional decision-making.

3.3.2 Intervention

The experimental group received a seven-week intervention designed to develop digital-age teaching competencies. Structured around the TPACK (Technological Pedagogical Content Knowledge) framework, the intervention comprised six interconnected modules carried out in seven weeks simulating authentic tasks for technology integration in 21st-century classrooms:

1. Technology Adoption: Foundational skills (e.g., using projectors, email setup).
2. Digital Lesson Planning: Utilizing tools like Google Docs and Planbook.
3. Multimedia Instruction: Delivering lessons via PowerPoint, Zoom, and Google Meet.
4. Digital Engagement: Facilitating interaction using Kahoot, and Padlet.
5. Collaborative Learning: Implementing group work through WhatsApp, Google Workspace.
6. Technology-Enhanced Assessment: Creating evaluations with Google Forms.

To ensure instructional consistency and control for instructor-related variability, the same course instructor facilitated both the experimental and control groups throughout the duration of the study. This approach ensured uniformity in content delivery, instructional style, pacing, and assessment procedures across groups, thereby minimizing potential instructor bias. Also, the intervention was delivered using a blended learning approach, which combined face-to-face classroom instruction with structured digital learning activities. In the experimental group, face-to-face sessions were complemented with guided use of digital platforms and tools such as Google Classroom, Zoom, Kahoot, and Google form to support active engagement and skill development. The control group, however, received only traditional face-to-face instruction without structured integration of digital tools or online learning activities.

3.4 Validity and reliability

To ensure content validity, the instruments (pre-test/post-test and questionnaire) were reviewed by three subject-matter experts in educational technology and curriculum studies. Their feedback informed revisions to strengthen alignment between the measurement tools and research objectives.

Reliability was established through a pilot test involving 30 pre-service teachers. The participants in the pilot study were pre-service teachers drawn from a similar institution offering comparable teacher education programmes and were of similar demographic characteristics to the main study sample, particularly in terms of age range, academic level (first-year pre-

service teachers), and exposure to basic ICT instruction. Cronbach's Alpha analysis of the questionnaire yielded an internal consistency coefficient of $\alpha = 0.81$, exceeding the accepted threshold for educational research (Taber, 2018), confirming the instruments' reliability in measuring the target constructs.

3.5 Data collection procedure

The instrument was administered electronically using Google Forms and participation in completing the questionnaire was voluntary but all the participants filled the form after attesting to the informed consent was obtained from all participants. This Google Forms platform allowed participants to access the forms anytime, anywhere, using their preferred devices. Responses were collected and monitored in real-time via email distribution.

1. Pre-test: Administered *before* the intervention, this instrument established a baseline for participants' self-assessed competency in using digital tools for teaching. It utilized a structured self-developed questionnaire by the researchers featuring a five-point Likert scale (ranging from *Novice* to *Very Competent*) across key competency domains: digital literacy, instructional planning, collaborative learning, and technology integration for teaching/assessment.
2. Post-test: Conducted *after* the intervention, the same instrument was used to assess participants' self-assessed competency in using digital tools for teaching across key competency domains: digital literacy, instructional planning, collaborative learning, and technology integration for teaching/assessment.

In addition, the study is limited by selection bias arising from the use of intact classes and nonrandom assignment of participants to groups, which may affect baseline equivalence. The use of the same instrument for both pre-test and post-test also introduces a potential testing effect, as participants may perform better in the post-test due to familiarity with the instrument rather than solely due to the intervention. Furthermore, intervention awareness (Hawthorne effect) may have influenced participants' behaviour in the experimental group, as their knowledge of being part of an intervention could have enhanced motivation and performance independent of the actual treatment effect.

The data collection followed a structured timeline:

- Week 1: Students completed the pre-test and baseline questionnaire.
- Weeks 2–7: The students underwent the digital-age teaching intervention, while the control group continued with traditional lecture method instruction not related to digital pedagogy (placebo).
- Week 8: students completed the post-test and final questionnaire to assess changes in knowledge, skills, and perceptions.

Ethical approval was secured from the university's research ethics board, and informed consent was obtained from all participants. Anonymity and confidentiality were assured throughout the study.

3.6 Data analysis

The data collected in this study were analyzed using the IBM Statistical Package for the Social Sciences (SPSS), version 26.0. Descriptive and inferential statistical analyses were performed using this software at a 0.05 level of significance. Descriptive statistics, including means, standard deviations, and frequency distributions, were used to summarize participants' demographic characteristics and pre-/post post-intervention scores. Initially, the assumptions of normality and homogeneity of regression slopes before using Analysis of Covariance

(ANCOVA) for the inferential test to the formulated study's hypotheses. The use of ANCOVA is considered appropriate for this study because it allows for the comparison of post-test mean scores of the experimental and control groups while statistically controlling for pre-test differences. However, for *post-hoc* analysis, the use of the Least Significant Difference (LSD) *post hoc* test constitutes a methodological limitation because it does not adequately control for Type I error inflation when multiple pairwise comparisons are conducted. Consequently, there may be an increased risk of identifying statistically significant differences that may occur by chance.

4 Results

4.1 Preliminary analysis

The results in Table 3 shows mean scores across all domains. Specifically, the experimental group demonstrated substantial gains in Digital Literacy, Instructional Planning, Collaborative Learning, and Technology Integration for Teaching and Assessment, reflecting enhanced competencies after exposure to the intervention. Overall, the findings suggest that the treatment had a positive impact on pre-service teachers' digital literacy-related competencies compared to the control condition.

4.2 Hypotheses testing

4.2.1 H₀₁: the digital-age teaching module has no significant effect on pre-service teachers' digital literacy

The results presented in Table 4 revealed the effect of the digital-age teaching module on preservice teachers' digital literacy using ANCOVA. The corrected model was statistically significant, $F(2,395) = 134.160$, $p < .05$, with an R^2 value of 0.405 (Adjusted $R^2 = .401$). This indicates that approximately 40% of the variance in post-digital literacy scores was explained by the predictors included in the model. The covariate Pre Digital Literacy was significant, $F(1,395) = 106.668$, $p < .05$, with a partial eta squared of 0.213, showing that prior digital literacy had a meaningful effect on post-test scores. More importantly,

TABLE 3 Descriptive statistics (Pre- and post-test scores) for experimental and control groups.

Domain	Experimental (<i>n</i> = 264) Pre M ± SD	Post M ± SD	Control (<i>n</i> = 139) Pre M ± SD	Post M ± SD
Digital Literacy	13.47 ± 5.72	22.70 ± 4.68	16.32 ± 6.48	16.32 ± 6.48
Instructional Planning	16.58 ± 7.31	29.59 ± 5.86	20.36 ± 8.30	20.36 ± 8.30
Collaborative Learning	10.35 ± 4.66	19.44 ± 3.76	12.51 ± 5.38	12.51 ± 5.38
Technology Integration for Teaching and Assessment	17.28 ± 8.12	32.97 ± 7.34	21.22 ± 9.31	21.22 ± 9.31

TABLE 4 ANCOVA statistics of the effect of the digital-age teaching module on preservice teachers' digital literacy.

Source	Type III sum of square	df	Mean square	F-value	<i>p</i> -value	Partial eta squared
Corrected Model	6131.890 ^a	2	3065.945	134.160	<.001	.405
Intercept	9713.601	1	9713.601	425.049	<.001	.518
PreDigital_Literacy	2437.671	1	2437.671	106.668	<.001	.213
Group	4931.787	1	4931.787	215.806	<.001	.353
Error	9026.884	395	22.853			
Total	181722.000	398				
Corrected Total	15158.774	397				

^aR Squared = .405 (Adjusted R Squared = .401).

TABLE 5 Pairwise comparisons of the effect of the digital-age teaching module on pre-service teachers' digital literacy.

(I) Group	(J) Group	Mean difference (I–J)	Std. Error	<i>p</i> -value	95% confidence interval for difference ^a	
					Lower bound	Upper bound
Experimental	Control	7.561*	.515	<.001	6.549	8.572
Control	Experimental	–7.561*	.515	<.001	–8.572	–6.549

^aAdjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*The mean difference is significant at the .05 level.

the main effect of Group was highly significant, $F(1,395) = 215.806$, $p < 0.05$, with a partial eta squared of 0.353, indicating a strong effect of the digital-age teaching module on improving pre-service teachers' digital literacy. The intercept was also significant, $F(1,395) = 425.049$, $p < 0.05$, with a partial eta squared of 0.518, confirming the overall strength of the model. Therefore, it can be concluded that the digital-age teaching module had a statistically significant and substantial positive effect on pre-service teachers' digital literacy, even after controlling for their prior digital literacy levels. The result underscores the value of integrating digital-age pedagogies within teacher education curricula to better prepare future educators for technology-driven classrooms.

Furthermore, the LSD *post-hoc* Analysis approach was further explored to determine which of the groups accounts for this significant effect and the result of the pairwise comparisons of the group effect is presented in Table 4.

The results of the pairwise comparisons presented in Table 5 show a statistically significant difference in post-digital literacy scores between the experimental and control groups. Specifically,

the experimental group had a higher mean score than the control group by 7.561 points ($p < .005$). The 95% confidence interval for this difference ranged from 6.549 to 8.572, confirming the robustness of the effect. When the control group was compared to the experimental group, the mean difference was -7.561 ($p < .05$), with the confidence interval ranging from -8.572 to -6.549 , further reinforcing the significant advantage of the experimental group. These findings further indicate that pre-service teachers exposed to the digital-age teaching module demonstrated significantly greater digital literacy compared to those in the control group. Therefore, it can be concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' digital literacy skills.

4.2.2 H₀₂: the digital-age teaching module has no significant effect on pre-service teachers' instructional planning skills

The results presented in Table 6 revealed the effect of the digital-age teaching module on preservice teachers' instructional

planning using ANCOVA. The corrected model was statistically significant, $F(2,395) = 144.874$, $p < 0.05$, with an R^2 value of 0.423 (Adjusted $R^2 = 0.420$). This indicates that approximately 42% of the variance in post-instructional planning scores was explained by the predictors included in the model. The covariate Pre Instructional Planning was significant, $F(1,395) = 87.345$, $p < 0.05$, with a partial eta squared of 0.181, showing that prior instructional planning ability had a meaningful effect on post-test scores. More importantly, the main effect of Group was highly significant, $F(1,395) = 255.817$, $p < 0.05$, with a partial eta squared of 0.393, indicating a strong effect of the digital-age teaching module on improving preservice teachers' instructional planning skills. The intercept was also significant, $F(1,395) = 488.712$, $p < 0.05$, with a partial eta squared of 0.553, confirming the overall strength of the model. Hence, the study concluded that the digital-age teaching module had a statistically significant and substantial positive effect on pre-service teachers' instructional planning, even after controlling for their prior instructional planning levels. As such, this practically implies that exposure to structured digital-age instructional strategies enhances pre-service teachers' ability to design lesson plans that integrate technology meaningfully, create engaging learning materials, and align instructional activities with modern classroom demands. Moreover, to determine which of the group accounts for this significant effect, LSD *post-hoc* Analysis approach was explored and the result of the pairwise comparisons of the group effect is presented in Table 7.

Result in Table 7 shows that the experimental group had a higher mean score than the control group by 10.652 points ($p < 0.05$). The 95% confidence interval for this difference ranged from 9.342 to 11.961, confirming the robustness of the effect. When the control group was compared to the experimental group, the mean difference was -10.652 ($p < 0.05$). These findings further confirm that pre-service teachers exposed

to the digital-age teaching module demonstrated significantly greater instructional planning skills compared to those in the control group. Therefore, it can be concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' instructional planning ability.

4.2.3 H₀₃: the digital-age teaching module has no significant effect on pre-service teachers' ability to facilitate collaborative learning

From the presented results in Table 8, the effect of the digital-age teaching module on pre-service teachers' collaborative learning using ANCOVA. The corrected model was statistically significant, $F(2,395) = 185.264$, $p < 0.05$, with an R^2 value of 0.484 (Adjusted $R^2 = 0.481$). This indicates that approximately 48% of the variance in post-collaborative learning scores was explained by the predictors included in the model. The covariate Pre Collaborative Learning was significant, $F(1,395) = 93.106$, $p < 0.05$, with a partial eta squared of 0.191, showing that prior collaborative learning ability had a meaningful effect on post-test scores. More importantly, the main effect of Group was highly significant, $F(1,395) = 334.491$, $p < 0.05$, with a partial eta squared of 0.459, indicating a strong effect of the digital-age teaching module on improving pre-service teachers' collaborative learning skills. The intercept was also significant, $F(1,395) = 516.761$, $p < 0.05$, with a partial eta squared of 0.567, confirming the overall strength of the model.

As such, it can be concluded that the digital-age teaching module had a statistically significant and substantial positive effect on pre-service teachers' collaborative learning. To explore further, the LSD PostHoc Analysis approach was used for pairwise comparisons of the group effect is presented in Table 9.

The results of the pairwise comparisons presented in Table 9 revealed a statistically significant difference in post-collaborative

TABLE 6 ANCOVA analysis showing the effect of the digital-age teaching module on preservice teachers' instructional planning.

Source	Type III sum of square	df	Mean square	F-value	p-value	Partial eta squared
Corrected Model	11046.452 ^a	2	5523.226	144.874	<.001	.423
Intercept	18631.793	1	18631.793	488.712	<.001	.553
PreDigital_Literacy	3329.970	1	3329.970	87.345	<.001	.181
Group	9752.812	1	9752.812	255.817	<.001	.393
Error	15059.076	395	38.124			
Total	302272.000	398				
Corrected Total	26105.528	397				

TABLE 7 Pairwise comparisons of the effect of the digital-age teaching module on pre-service teachers' instructional planning.

(I) Group	(J) Group	Mean difference (I-J)	Std. Error	p-value	95% confidence interval for difference ^a	
					Lower bound	Upper bound
Experimental	Control	10.652*	.666	<.001	9.342	11.961
Control	Experimental	-10.652*	.666	<.001	-11.961	-9.342

^aAdjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*The mean difference is significant at the .05 level.

TABLE 8 ANCOVA analysis showing the effect of the digital-age teaching module on preservice teachers' collaborative learning.

Source	Type III sum of square	df	Mean square	F-value	p-value	Partial eta squared
Corrected Model	5810.611 ^a	2	2905.305	185.264	<.001	.484
Intercept	8103.847	1	8103.847	516.761	<.001	.567
PreCollaborative_Learning	1460.092	1	1460.092	93.106	<.001	.191
Group	5245.485	1	5245.485	334.491	<.001	.459
Error	6194.387	395	15.682			
Total	127061.000	398				
Corrected Total	12004.997	397				

^aR Squared = .484 (Adjusted R Squared = .481).

TABLE 9 Pairwise comparisons of the effect of the digital-age teaching module on pre-service teachers' collaborative learning.

(I) Group	(J) Group	Mean difference	Std. Error	p-value	95% confidence interval for difference ^a	
		(I-J)			Lower bound	Upper bound
Experimental	Control	7.770*	.425	<.001	6.935	8.605
Control	Experimental	-7.770*	.425	<.001	-8.605	-6.935

^aAdjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*The mean difference is significant at the .05 level.

TABLE 10 ANCOVA analysis showing the effect of the digital-age teaching module on preservice teachers' technology integration for teaching and assessment.

Source	Type III sum of square	df	Mean square	F-value	p-value	Partial eta squared
Corrected Model	16465.747 ^a	2	8232.874	148.312	<.001	.429
Intercept	25722.099	1	25722.099	463.374	<.001	.540
PreTechnology Integration for Teaching and Assessment	3941.250	1	3941.250	71.000	<.001	.152
Group	15084.509	1	15084.509	271.742	<.001	.408
Error	21926.637	395	55.510			
Total	369351.000	398				
Corrected Total	38392.384	397				

^aR Squared = .429 (Adjusted R Squared = .426).

learning scores between the experimental and control groups. Specifically, the experimental group had a higher mean score than the control group by 7.770 points ($p < 0.05$). The 95% confidence interval for this difference ranged from 6.935 to 8.605, confirming the robustness of the effect and when the control group was compared to the experimental group, the mean difference was -7.770 ($p < 0.05$), with the confidence interval ranging from -8.605 to -6.935 , further reinforcing the significant advantage of the experimental group.

These findings further indicate that pre-service teachers exposed to the digital-age teaching module demonstrated significantly greater collaborative learning skills compared to those in the control group. Therefore, it can be concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' collaborative learning ability.

4.2.4 H₀₄: the digital-age teaching module has no significant effect on pre-service teachers' technology integration for teaching and assessment

The results presented in Table 10 indicated that the effect of the digital-age teaching module on pre-service teachers' technology integration for teaching and assessment using ANCOVA. The corrected model was statistically significant, $F(2,395) = 148.312$, $p < 0.05$, with an R^2 value of 0.429 (Adjusted $R^2 = 0.426$). This indicates that approximately 43% of the variance in posttechnology integration scores was explained by the predictors included in the model. The covariate Pre Technology Integration for Teaching and Assessment was significant, $F(1,395) = 71.000$, $p < 0.05$, with a partial eta squared

of 0.152, showing that prior technology integration ability had a meaningful effect on post-test scores. More importantly, the main effect of Group was highly significant, $F(1,395) = 271.742$, $p < 0.05$, with a partial eta squared of 0.408, indicating a strong effect of the digital-age teaching module on improving pre-service teachers' technology integration for teaching and assessment. The intercept was also significant, $F(1,395) = 463.374$, $p < 0.05$, with a partial eta squared of 0.540, confirming the overall strength of the model.

Therefore, it can be concluded that the digital-age teaching module had a statistically significant and substantial positive effect on pre-service teachers' technology integration for teaching and assessment, even after controlling for their prior levels of technology integration. The LSD PostHoc Analysis approach was further explored, and the results are presented in Table 11.

The results of the pairwise comparisons presented in Table 11 specifically indicated that the experimental group had a higher mean score than the control group by 13.203 points ($p < 0.05$). The 95% confidence interval for this difference ranged from 11.628 to 14.778, confirming the robustness of the effect and when the control group was compared to the experimental group, the mean difference was -13.203 ($p < 0.05$), with the confidence interval ranging from -14.778 to -11.628 , further reinforcing the significant advantage of the experimental group. These findings further reinforce that pre-service teachers exposed to the digital-age teaching module demonstrated significantly greater technology integration skills for teaching and assessment compared to those in the control group. Therefore, it can be concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service

teachers' technology integration ability for teaching and assessment.

4.2.5 H₀₅: the digital-age teaching module has no significant effect on pre-service teachers' instructional competency across the four key domains

The results presented in Table 12 revealed the effect of the digital-age teaching module on preservice teachers' instructional competency using ANCOVA. The corrected model was statistically significant, $F(2,395) = 160.805$, $p < .001$, with an R^2 value of 0.449 (Adjusted $R^2 = 0.446$). This indicates that approximately 45% of the variance in post-instructional competency scores was explained by the predictors included in the model. The covariate Pre-Teachers Instructional Competency was significant, $F(1,395) = 86.247$, $p < 0.05$, with a partial eta squared of 0.179, showing that prior instructional competency had a meaningful effect on post-test scores. More importantly, the main effect of Group was highly significant, $F(1,395) = 291.125$, $p < 0.05$, with a partial eta squared of 0.424, indicating a strong effect of the digital-age teaching module on improving pre-service teachers' instructional competency. The intercept was also significant, $F(1,395) = 482.381$, $p < 0.05$, with a partial eta squared of 0.550, confirming the overall strength of the model.

Therefore, it can be concluded that the digital-age teaching module had a statistically significant and substantial positive effect on pre-service teachers' instructional competency, even after controlling for their prior competency levels. However, the

TABLE 11 Pairwise comparisons of the effect of the digital-age teaching module on pre-service teachers' technology integration for teaching and assessment.

(I) Group	(J) Group	Mean Difference (I–J)	Std. Error	p-value	95% confidence interval for difference ^a	
					Lower bound	Upper bound
Experimental	Control	13.203*	.801	<.001	11.628	14.778
Control	Experimental	–13.203*	.801	<.001	–14.778	–11.628

^aAdjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*The mean difference is significant at the .05 level.

TABLE 12 ANCOVA analysis showing the effect of the digital-age teaching module on preservice teachers' instructional competency.

Source	Type III sum of square	df	Mean square	F-value	p-value	Partial eta squared
Corrected Model	145661.291 ^a	2	72830.646	160.805	<.001	.449
Intercept	218476.759	1	218476.759	482.381	<.001	.550
Pre-Teachers Instructional Competency	39062.338	1	39062.338	86.247	<.001	.179
Group	131854.369	1	131854.369	291.125	<.001	.424
Error	178900.608	395	452.913			
Total	3740132.000	398				
Corrected Total	324561.899	397				

^aR Squared = .449 (Adjusted R Squared = .446).

TABLE 13 Pairwise comparisons of the effect of the digital-age teaching module on pre-service teachers' instructional competency.

(I) Group	(J) Group	Mean difference (I–J)	Std. Error	p-value	95% confidence interval for difference ^a	
					Lower bound	Upper bound
Experimental	Control	39.160*	2.295	<.001	34.648	43.672
Control	Experimental	–39.160*	2.295	<.001	–43.672	–34.648

^aAdjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*The mean difference is significant at the .05 level.

LSD PostHoc Analysis was adopted to test for pairwise comparisons of the group effect and results presented in Table 13.

The results of the pairwise comparisons presented in Table 13 revealed a statistically significant difference in post-instructional competency scores between the experimental and control groups. Specifically, the experimental group had a higher mean score than the control group by 39.160 points ($p < 0.05$). The 95% confidence interval for this difference ranged from 34.648 to 43.672, confirming the robustness of the effect and when the control group was compared to the experimental group, the mean difference was –39.160 ($p < 0.05$), with the confidence interval ranging from –43.672 to –34.648, further reinforcing the significant advantage of the experimental group. These findings ultimately indicate that pre-service teachers exposed to the digital-age teaching module demonstrated significantly greater instructional competency compared to those in the control group. Therefore, it can be concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' instructional competency.

5 Discussion of findings

The study assessed the effectiveness of technology-driven intervention in preparing pre-service teachers for 21st-century classrooms. The result of first null hypothesis revealed that the digitalage teaching module had a strong positive and significant effect in enhancing pre-service

teachers' digital literacy skills in Osun State with a significant positive large effect size in favour of the group exposed to digital modules. This outcome is consistent with the TPACK framework, particularly the Technological Knowledge (TK) component, which emphasizes the development of teachers' competence in using digital tools as a foundation for effective technology integration. This finding aligns Tondeur et al. (2018) who found out that ICT competency development in teacher education is strongly influenced by the quality of training and opportunities for practical application. Similarly, Admiraal et al. (2019) reported that experience and guided practice significantly predict teachers' ability to integrate technology effectively.

More recently, Ahmed, et al. (2025) that the four core digital competencies (Information & Data Literacy, Communication & Collaboration, Digital Content Creation, and Safety & Well Being) significantly predict the Pedagogical Digital Literacy among the prospective teachers in the universities of Sindh, Pakistan. Similarly, a study conducted by Sheikh and Nath (2026) also indicated a substantial improvement in participants'

ability to work with data compare to the traditional group with their result showing a large effect size suggesting a highly impactful intervention. In contrary, Dolezal et al. (2025) found that approximately half of pre-service teachers did not feel adequately trained to foster digital competence in authentic classroom settings, highlighting persistent gaps between training and real instructional application. Also, Tondeur et al. (2018) emphasized that many teacher education programmes still struggle to effectively translate digital training into sustained digital competence, as pre-service teachers often acquire surface-level skills without deep pedagogical integration of technology.

The result of the research hypothesis two also revealed that the digital-age teaching module had a strong positive and statistically significant effect in enhancing pre-service teachers' instructional planning ability. This is consistent with the findings of Kerimbayev et al.'s (2017) observations about technology-enhanced pedagogy in Kazakhstan's universities and Cabero-Almenara et al. (2025) whose findings confirm that improved digital competence directly enhances student engagement and instructional planning, with digitally competent students demonstrating more active preparation and participation in online discussions and enhanced peer collaboration. Also, Ramdana et al. (2026) reported that targeted pedagogical innovations and institutional support mechanisms significantly enhance digital literacy development in higher education contexts. Similarly, Salim, et al. (2025) in their qualitative indicate that pre-service teachers view teachers as proactive planners and creators who require not only technical skills but also pedagogical creativity, reflective practice, and institutional support. These connect digital planning and design, technology integration and professional collaboration as key components of teacher-led innovation in teaching.

The result of the findings of the research hypothesis three further indicated that the digital-age teaching module had a strong positive and statistically significant effect on enhancing pre-service teachers' collaborative learning ability. This corroborates the empirical findings of Ahmed et al. (2025) who in their study also found that the influence of Digital literacy varies and that the communication & collaboration strongly predict Pedagogical Digital Literacy (PDL) of the prospective teachers. Similarly, Bakirova et al. (2026) whose in their quasi experimental study revealed a significant improvements in digital competence across all dimensions of the study and a significant positive relationship between digital competency and student engagement. Their result show that master's students with higher digital competency scores

demonstrated more active participation in digital learning environments, with significantly higher contributions to online discussions, digital content creation and peer collaboration with their qualitative findings also corroborated these findings above. However, Barroso-Tristán et al. (2025) discovered that while instructors demonstrate good digital competency in creating gamified ICT-based learning, students' poor collaboration in these settings is highlighted by their low Collaborative Learning.

More so, the findings of the research hypothesis four revealed that the digital-age teaching module had a strong positive and significant effect on enhancing pre-service teachers' technology integration ability for teaching and assessment. This is in tandem with the position of by Sheikh and Nath, (2026) in their Indian study also revealed that experimental group shows a significant increase in technology efficacy indicating improved confidence in using technology and with large effect size substantially indicating a significant change in their post-intervention scores. This is also supported by Bakirova et al., (2026) whose study revealed that students with higher self-efficacy in digital competency from experimental group demonstrated more initiative in technology enhanced learning activities and persisted longer when facing technical challenges and get them resolved. From a theoretical perspective, this outcome aligns strongly with the TPACK framework, particularly the integration of Technological Pedagogical Knowledge (TPK) and Technological Content Knowledge (TCK). It suggests that when pre-service teachers are engaged in purposeful, practice-based digital learning experiences, they are better able to connect technology with pedagogical strategies and subject content in meaningful ways.

Finally, the result of the analysis of the research hypothesis five stating that digital-age teaching module had a positive and significant effect on pre-service teachers' instructional competency across the four key domains revealed that digital-age teaching module had a strong positive and statistically significant effect on enhancing pre-service teachers' instructional competency with larger positive effect size and highest mean difference in favour of experimental group. This is in agreement with Bakirova et al., (2026) whose in their quasi experimental study titled "Enhancing digital competence and learning motivation of master's students: a new educational model for Kazakhstan's higher education system" revealed a significant improvements in digital competence across all dimensions of the study with experimental group showcasing higher Digital Competency compare to their Control group. More so, their Qualitative data from interviews also corroborated these findings, with participants in the experimental group describing progressive skill development. This is also supported by Abdillah and Wahyuilahi (2025) who found that students who actively engaged with digital platforms demonstrated better learning outcomes than those who used resources more passively. Similarly align with studies of Basilotta-Gómez-Pablos et al.'s (2022) findings on the strategic integration of digital tools and Fernández-Batanero et al.'s (2021) position laying emphasis on pedagogical frameworks with a model incorporating diverse digital tools, micro learning, and gamification that effectively enhances the digital competence of Master's students and the service teachers.

6 Conclusion

This study concluded that the digital-age teaching module had a strong positive effect on enhancing pre-service teachers' instructional competency and remain substantial aspect of the teacher-training's curriculum which prepared pre-service teachers for 21st-century classrooms. However, for future studies, researchers should explore the long-term impact of digital-age teaching modules across different levels of teacher education, investigate how specific digital tools can influence distinct pedagogical outcomes and conduct comparative studies across institutions and different geographical locations to enhance generalizability.

This study contributes uniquely to existing knowledge by empirically integrating the TPACK framework with a structured digital-age teaching intervention and validating its effect on multiple dimensions of pre-service teachers' competencies, including digital literacy, instructional planning, collaborative learning, and technology integration for teaching and assessment. The study provides empirical evidence on how technology integration can enhance teaching readiness among pre-service teachers, the manuscript fits within the specialties of higher education, teacher education, and digital learning. It also provides a context-specific evidence base on Nigerian teacher education setting in tertiary institution in relation to digital pedagogy implementation.

5.1 Recommendations

Based on the findings of this study, it can be recommended that;

1. Curriculum planners should integrate digital-age teaching modules into teacher education programmes to enhance digital literacy and instructional competence.
2. Teacher training institutions should adopt monitoring and evaluation systems to improve digital teaching effectiveness.
3. Government should provide adequate ICT infrastructure (computers, internet, smart classrooms, and stable power supply) to support digital learning.
4. The Ministry of Education should organize regular ICT capacity-building programmes for teacher educators.
5. Teacher educators should promote collaborative learning strategies to strengthen digital teaching practice.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Osun State University College of Education, Ethical Committee Approval. The studies were conducted in accordance with the local legislation and institutional requirements. The

participants provided their written informed consent to participate in this study.

Author contributions

YS: Conceptualization, Data curation, Investigation, Project administration, Supervision, Writing – original draft, Writing – review & editing. RI: Data curation, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. OA: Data curation, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. YZ: Conceptualization, Formal analysis, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. SA: Conceptualization, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. AA: Data curation, Formal analysis, Investigation, Project administration, Validation, Writing – original draft, Writing – review & editing.

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