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Transforming biology education: How DECODE cloud model and gender shape TPACK-21 and digital literacy

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Abstract: Digital transformation in education necessitates new competencies for biology teachers. This study examines the influence of the DECODE model integrated with Cloud Classroom and gender on TPACK-21 and digital literacy among biology education students. Using a quasi-experimental design with pretest-posttest nonequivalent control groups, 53 undergraduate students from Universitas Negeri Medan participated in the study. The experimental group (n=26) received the DECODE-Cloud Classroom intervention while the control group (n=27) followed a conventional case study approach. Data collection employed self-report questionnaires, teaching module evaluations, observation sheets, and learning product assessments. MANCOVA analysis revealed that the DECODE-Cloud Classroom model significantly enhanced both TPACK-21 and digital literacy with large effect sizes. Gender showed no significant effect on TPACK-21 but significantly influenced digital literacy development, with male students demonstrating greater improvement in digital security and content creation dimensions, while information and data literacy showed the smallest gap between genders. The interaction between the learning model and gender was not significant for either dependent variable, indicating consistent effectiveness across genders despite varying improvement rates. The findings support implementing the DECODE-Cloud Classroom model in biology teacher preparation programs while considering gender-responsive strategies to optimize digital competency development.

Keywords: Cloud classroom, gender differences, biology education

Abstrak: Transformasi digital dalam pendidikan menuntut kompetensi baru bagi guru biologi. Penelitian ini mengkaji pengaruh model DECODE terintegrasi *Cloud Classroom* dan gender terhadap TPACK-21 dan literasi digital mahasiswa pendidikan biologi. Menggunakan desain kuasi eksperimen dengan *pretest-posttest nonequivalent control group*, 53 mahasiswa Universitas Negeri Medan berpartisipasi dalam penelitian. Kelompok eksperimen (n=26) menerima intervensi DECODE-*Cloud Classroom* sementara kelompok kontrol (n=27) mengikuti pendekatan studi kasus konvensional. Pengumpulan data menggunakan kuesioner self-report, evaluasi modul ajar, lembar observasi, dan penilaian produk pembelajaran. Analisis MANCOVA menunjukkan bahwa model DECODE-*Cloud Classroom* secara signifikan meningkatkan TPACK-21 dan literasi digital dengan *effect size* besar. *Gender* tidak berpengaruh signifikan terhadap TPACK-21 tetapi signifikan terhadap perkembangan literasi digital, dengan mahasiswa laki-laki menunjukkan peningkatan lebih besar dalam dimensi keamanan digital dan pembuatan konten digital, sementara dimensi literasi informasi dan data menunjukkan kesenjangan terkecil antar gender. Interaksi antara model pembelajaran dan *gender* tidak signifikan untuk kedua variabel terikat, mengindikasikan efektivitas konsisten pada semua gender meskipun terdapat perbedaan tingkat peningkatan. Temuan mendukung implementasi model DECODE-*Cloud Classroom* dalam program persiapan guru biologi dengan mempertimbangkan strategi responsif *gender* untuk mengoptimalkan pengembangan kompetensi digital.

Kata kunci: Cloud classroom, perbedaan gender, pendidikan biologi

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INTRODUCTION

Contemporary educators recognize the urgent need for prospective teachers to master integrated competencies that align with 21st-century learning requirements. The

Technological Pedagogical And Content Knowledge (TPACK) framework has emerged as a comprehensive conceptual framework describing the synergistic relationship between three independent kn (Arifuddin et al., 2025; Madzamba & Matorevhu, 2024; Ning et al., 2024) owledge domains: technological knowledge (TK), pedagogical knowledge (PK), and content knowledge (CK), along with three integrated knowledge subsets (TPK, TCK, and PCK). Educational paradigms have evolved to adapt the TPACK framework for 21st-century educational demands, creating "TPACK for 21st-century skills" or "TPACK-21." Researchers characterize TPACK-21 by its specific measurement focus on pedagogical knowledge subdomains (PK, PCK, TPK, and TPACK) while integrating 21st-century skills components including reflective thinking, problem-solving, creative thinking, critical thinking, and mastery of information and communication technology (Valtonen et al., 2017).

Field realities reveal that many prospective teachers still demonstrate rigidity and hesitation in integrating ICT into learning processes despite the recognized importance of TPACK-21 (Tunjera & Chigona, 2020). Educational institutions observe that prospective teachers have not shown maximum readiness in appropriately utilizing technology in classroom learning contexts (Tondeur et al., 2017). Researchers identify this condition as ultimately impacting the effectiveness of technology integration in teaching strategies, both in face-to-face and online learning environments (Dita et al., 2023; Sánchez-Cruzado et al., 2021; Setyantoko et al., 2023).

Educational experts identify low digital literacy among prospective teachers as one of the main factors causing these integration problems (Nikat, 2020; Pratolo & Solikhati, 2020; Mawarni et al., 2021). Digital literacy researchers define this competency as encompassing four fundamental elements: appropriate perception, positive attitude, adaptive behavior, and competent ability to analyze information, operate technology, and interpret information within digital environments (Wu, 2024). Multiple studies reveal that digital literacy competencies of teachers and prospective teachers have not yet reached optimal levels in media literacy, information literacy, and ICT literacy aspects. Educational systems contribute to this condition by not providing adequate attention to developing digital competencies of teaching students (Lindfors et al., 2021; Gümüş, 2022).

Academic researchers categorize digital literacy levels among university students into several levels based on the Analysis of Common Digital Competences (ACDC) framework, ranging from basic level (Level 1) where users perform simple digital tasks, to advanced level (Level 4) where users demonstrate comprehensive digital competencies including content creation, digital citizenship, and complex problem-solving skills (Sánchez-Cruzado et al., 2021). Educational studies indicate that many university students, particularly in teacher education programs, still operate at Level 2 (intermediate), demonstrating basic digital skills but lacking advanced competencies required for effective technology integration in educational contexts (Zhao et al., 2021).

Empirical research establishes a strong correlation between digital literacy and TPACK-21 development among prospective teachers. Studies by Demeshkant et al. (2022) demonstrate that digital literacy positively impacts prospective teachers' TPACK-21 enhancement, where improvements in digital literacy correlate directly with TPACK-21 advancement (INTEF, 2022). Research findings align with Listiaji and Subhan (2021) who discovered positive effects of digital literacy on prospective teachers' technological competencies in several key aspects: understanding ICT in education, organization and administration of digital learning environments, and professional teacher development through digital media utilization.

Gender-based digital literacy gaps compound these challenges in Indonesian society. Survey data from Kominfo (2020) on Indonesia's digital literacy status reveals that 55% of male respondents scored above the national average in digital literacy, while only 45% of female respondents reached that level. Indonesian higher education contexts reflect similar patterns, with various studies showing significant differences in digital literacy levels between male and female students (Hartati et al., 2024; Putra et al., 2023; Ririen & Daryanes, 2022), though some contradictory findings exist (Hasibuan, 2021).

Biology education research reveals serious problems regarding TPACK competencies among prospective biology teachers. Studies by Malichatin (2019) specifically identify low TPACK among prospective biology teachers, particularly when measured through presentation activities, with three TPACK components categorized as low: content knowledge (CK), pedagogical knowledge (PK), and pedagogical content knowledge (PCK). Research by Hendra et al. (2022) reinforces these findings, revealing that TPACK among prospective biology teachers remains in the low category, specifically in three important subdomains: technological knowledge (TK), technological content knowledge (TCK), and technological pedagogical knowledge (TPK). More concerning research by Adipat et al. (2023), Lindfors et al. (2021), and Stockless et al. (2022) reveals that no prospective teachers optimally utilize technology in all aspects of teaching and learning activities. Contrasting research findings emerge from studies by Aumann et al. (2024), Wahab et al. (2023), and Hidayat et al. (2024) who demonstrate that TPACK profiles of prospective biology teachers actually fall in the good category, showing adequate ability to conduct biology learning by integrating information and computer technology. Research disparities reinforce Setiawan (2024) argument that TPACK among prospective biology teachers shows significant variation across different regions.

Educational researchers recommend the DECODE (DEmo-CO-DEsign/teach) learning model as an effective approach for enhancing prospective teachers' TPACK-21 (Cheng et al., 2022). The model comprises three essential components: "DE" representing teacher's demonstrations, "CO" referring to student collaboration, and "DE" pertaining to course design. Educational studies demonstrate that the DECODE model offers advantages over other approaches such as MAGDAIRE and Project-Based Learning (PjBL) by providing a comprehensive approach to integrating supportive factors for technology integration in learning practices aligned with students' 21st-century skills. Research shows that features within the DECODE model effectively support prospective teachers in constructing knowledge and using online classroom technology in Biology learning while enhancing students' content, pedagogical, and technological knowledge (Jin et al., 2023).

Educational technologists implement DECODE with Cloud ClassRoom (CCR), a web-based interactive response system that operates across various platforms (iOS, Android, and Windows), transforming smartphones into effective interactive learning tools in classrooms (Gao et al., 2021; Luo, 2021). Technology researchers design CCR as a web-based interactive response system to meet the needs of developing TPACK-21 and digital literacy for prospective teachers. System developers create CCR with the advantage of not requiring additional software or plug-in installations while operating on various platforms, enabling transformation of smartphone devices into effective interactive learning tools in classrooms. Educational research proves CCR effectiveness through various studies showing significant improvements in several aspects: learning outcomes (Wicaksono et al., 2022), 21st-century skills and digital literacy (Zan et al., 2021), TPACK-21 levels (Cheng et al., 2022), and communication skills and engagement in peer discussions (Malaningtyas et al., 2022).

Preliminary surveys at a state university's Biology Education Study Program in North Sumatra indicate suboptimal TPACK-21 and digital literacy among students. Researchers attribute this condition to the relatively new implementation of TPACK courses in biology education curricula. Initial analysis reveals suboptimal TPACK-21 and digital literacy through several critical findings: (1) students' TPACK-21 generally categorizes as moderate with an average score of 51, including component scores of TK (54), CK (65), PK (50), PCK (45), TCK (49), and TPK (50); (2) Analysis of Common Digital Competences (ACDC) assessment categorizes students' digital literacy as low at Level 2; (3) students perceive TPACK learning as only increasing understanding without significantly contributing to TPACK skill development; and (4) students demonstrate limitations in integrating digital technology when developing learning materials.

Educational analysis identifies additional problems including: (1) TPACK learning lacks comprehensive integration with 21st-century skills, (2) students experience difficulties in designing and implementing TPACK-based biology learning, (3) assessment and evaluation design of TPACK-based learning remains suboptimal, (4) students possess minimal experience using LMS for biology learning activities, and (5) teacher education TPACK learning environments have not integrated learning management systems (LMS) as supporting components for developing prospective teachers' TPACK competencies.

This research aims to implement the DECODE learning model integrated CCR as a strategic intervention to enhance TPACK-21 and digital literacy among biology education students while examining gender-based differences. Researchers expect this study to address various 21st-century educational demands and needs while serving as a guideline, reference, and evaluation instrument for biology education students in empowering TPACK-21 competencies and digital literacy. Educational leaders recognize that developing these competencies becomes crucial in preparing professional teacher candidates who can adapt to 21st-century learning demands, with particular attention to reducing potential gender gaps in digital competency development.

METHOD

Research design and participants

This quasi-experimental study employed a pre-respond—post-repond design with nonequivalent control groups to evaluate the effectiveness of the DECODE learning model integrated with Cloud Classroom (CCR) on TPACK-21 and digital literacy. The research was conducted from March to June 2024 at a public university in Medan, Indonesia, involving 53 biology education students from the 2022 cohort selected through cluster random sampling after confirming homogeneity via ANOVA and LSD tests. Biology Education Class E (n=26) served as the experimental group implementing the DECODE-CCR model, while Class A (n=27) served as the control group using conventional TPACK learning with case method.

DECODE-CCR model implementation

The DECODE-CCR model consists of four systematic phases designed to develop comprehensive TPACK competencies through collaborative technology integration as presented in Table 1.

Table 1. DECODE-CCR syntax and variable relationships

DECODE Phase (Cheng et al., 2022)	Procedure	TPACK Components (Valtonen et al., 2017)	Digital Literacy Domains (Redecker & Punie, 2017)
Demonstration	Educator demonstrates CCR functions in learning with interactive Q&A sessions	TK (Technological Knowledge)	Information and Media Literacy; Safety
Co-Training	Students in groups (2-3) rotate as teacher/student to practice CCR operations and features	TK, TPK	Communication and Collaboration
Co-Design	Groups develop ICT-based instructional courses using CCR, constructing subject-specific concepts through collaborative discussions	CK, PK, PCK, TPK, TCK	Digital Content Creation
Co-Teach	Groups demonstrate developed courses, reflect on CCR usage, explain materials/ methods, provide peer feedback	TPACK (integrated competency)	Digital Problem Solving

The Demonstration phase aims to enhance Technological Knowledge (TK) where educators systematically demonstrate Cloud Classroom implementation and functions in learning contexts, followed by interactive question-and-answer sessions to familiarize students with various CCR features. The Co-Training phase develops both TK and Technological Pedagogical Knowledge (TPK) through collaborative group work where students (2-3 members) rotate roles as teacher and student to practice CCR operations, functions, and features in authentic learning contexts. The Co-Design phase optimizes development of multiple TPACK components including Pedagogical Knowledge (PK), Content Knowledge (CK), Pedagogical Content Knowledge (PCK), TPK, and Technological Content Knowledge (TCK) as each group develops ICT-based instructional courses using CCR with emphasis on constructing subject-specific biology concepts through collaborative discussions. Finally, the Co-Teach phase integrates all TPACK components into comprehensive competency as groups alternately demonstrate their developed learning courses, reflect on ICT usage effectiveness, explain materials and teaching methods, and provide constructive peer feedback.

Research instruments

Multiple validated instruments were developed for this study, including Semester Learning Plans (RPS), Learning Session Units (SAP), and Student Worksheets (LKM). Additional instruments comprised student response questionnaires regarding the DECODE model integrated with CCR, TPACK-21 self-report questionnaires, analytical rubrics for

TPACK-21-based lesson plans, implementation observation sheets, holistic evaluation rubrics for learning products, and digital literacy self-report questionnaires.

The primary measurement instruments comprised TPACK-21 self-report questionnaires adapted from Valtonen et al. (2017) and digital literacy self-report questionnaires adapted from ACDC framework (Sánchez-Cruzado et al., 2021) and Digtal Competence of Educator (DigCompEdu) framework. The TPACK-21 instrument measures seven dimensions: Technological Knowledge (TK) with 4 indicators focusing on ICT problem-solving and new technology usage; Content Knowledge (CK) with 4 indicators covering foundational theories and disciplinary engagement; Pedagogical Knowledge (PK) with 7 indicators encompassing group guidance and critical thinking support; Technological Pedagogical Knowledge (TPK) with 6 indicators integrating ICT as educational tools; Pedagogical Content Knowledge (PCK) with 6 indicators combining subject-specific guidance approaches; Technological Content Knowledge (TCK) with 4 indicators identifying appropriate technologies for content delivery; and integrated TPACK with 7 indicators demonstrating comprehensive technology-pedagogy-content integration.

The digital literacy instrument measures four domains: Information and Media Literacy (ability to locate, evaluate, and use digital information), Communication and Collaboration (skills in digital platforms and collaborative technologies), Digital Content Creation (competency in creating and sharing digital materials), and Digital Problem Solving (creative and critical use of technologies for educational challenges), as referenced in DigCompEdu by Redecker & Punie (2017) and DigComp 2.2. by Vuorikari et al. (2022).

Variable categorization and scoring

TPACK-21 competencies were categorized using Niess (2011) model based on Rogers' innovation decision process with five progressive levels determined by percentage scores. Recognizing level (0-20%) represents knowledge stage where educators recognize ICT alignment with content but do not integrate ICT during learning. Accepting level (21-40%) represents persuasion stage where educators form favorable or unfavorable attitudes toward content learning with appropriate ICT. Adapting level (41-60%) represents decision stage where educators engage in activities leading to adoption or rejection choices for science learning with appropriate ICT. Exploring level (61-80%) represents implementation stage where educators actively integrate science learning with appropriate ICT. Advancing level (81-100%) represents confirmation stage where educators evaluate results of decision-making about integrating science learning with appropriate ICT.

TPACK-21 based lesson plan analysis, implementation analysis, and learning product evaluation were categorized using five progressive levels based on percentage achievement scores from analytical and holistic rubric assessments (scale 1-4). Very Poor level (0-20%) represents minimal integration and execution with inadequate alignment of components. Poor level (21-40%) represents limited integration with basic understanding but weak connections between elements. Moderate level (41-60%) represents adequate integration with reasonable alignment but inconsistent application. Good level (61-80%) represents strong integration with well-coordinated elements and effective implementation. Excellent level (81-100%) represents exceptional integration with seamless connection, innovative approaches, and comprehensive achievement of learning objectives.

Digital literacy levels were categorized according to DigCompEdu progression model (Redecker & Punie, 2017; INTEF, 2022) with six developmental stages based on mean scores ranging from 1 to 4. Newcomer (A1) level (scores 1.0-1.5) represents educators who are aware of digital technology potential but have minimal contact and use technologies mainly for lesson preparation, administration, or organizational communication, requiring guidance to expand their repertoire. Explorer (A2) level (scores >1.5-2.0) represents educators who are aware and interested in exploring digital technologies to enhance practice, beginning to use technologies in some areas but without comprehensive approach, needing encouragement and inspiration. Integrator (B1) level (scores >2.0-2.5) represents educators who experiment with digital technologies in various contexts and purposes, creatively using them to enhance professional engagement aspects while working to understand optimal tools for specific situations. Expert (B2) level (scores >2.5-3.0) represents educators who confidently, creatively, and critically use various digital technologies to enhance professional activities, deliberately selecting technologies for specific situations and understanding advantages and disadvantages of digital strategies. Leader (C1) level (scores >3.0-3.5) represents educators who have consistent and comprehensive approach to using digital technologies for enhancing pedagogical and professional practice, relying on wide repertoire of digital strategies while continuously reflecting and developing practices. Pioneer (C2) level (scores >3.5-4.0) represents educators who question adequacy of contemporary digital and pedagogical practices, concerned with practice constraints and driven to innovate education further by experimenting with highly innovative technologies and developing new pedagogical approaches.

Data analysis

Data analysis began with validity and reliability assessment of TPACK-21 and digital literacy self-report instruments through empirical validation. Student responses to the DECODE-CCR model were analyzed using questionnaire data comprising quantitative and qualitative feedback. TPACK-21 scores were converted to percentages and categorized into five levels: Recognizing (0-20%), Accepting (21-40%), Adapting (41-60%), Exploring (61-80%), and Advancing (81-100%) based on Niess (2011). Digital literacy scores were categorized into six levels: Newcomer/A1 (1.0-1.5), Explorer/A2 (>1.5-2.0), Integrator/B1 (>2.0-2.5), Expert/B2 (>2.5-3.0), Leader/C1 (>3.0-3.5), and Pioneer/C2 (>3.5-4.0) following INTEF (2022) and DigCompEdu framework (Redecker & Punie, 2017). TPACK-21 lesson plan analysis, implementation analysis, and learning product evaluation were categorized using five levels: Very Poor (0-20%), Poor (21-40%), Moderate (41-60%), Good (61-80%), and Excellent (81-100%) based on analytical and holistic rubric assessments.

Statistical analyses were conducted using IBM SPSS 29 for Mac with assumption testing including normality, homogeneity, linearity, and regression slopes homogeneity ($p > 0.05$). Multivariate Analysis of Covariance (MANCOVA) with pretests as covariates tested research hypotheses at 5% significance level. Effect sizes were calculated using Partial Eta Squared and learning gains analyzed using Normalized Gain Score with low gain ($g < 0.3$), moderate gain ($0.3 < g < 0.7$), and high gain ($g > 0.7$) criteria.

RESULTS AND DISCUSSION

Instrument validation and reliability analysis

The research instruments underwent comprehensive empirical validation and reliability testing to ensure measurement accuracy and consistency as presented in Table 2.

Table 2. Empirical validation and reliability results of research instruments

Instrument	Initial Items	Valid Items	Validity Coefficient Range	Category	Cronbach's Alpha	Reliability Category
TPACK-21	76	70	0.41 - 0.79	Moderate - High	0.87	Very High
Digital Literacy	58	50	0.38 - 0.76	Low - High	0.83	Very High

Empirical validation involved 30 randomly selected biology education students from the 2022 cohort. For practical implementation, we selected 38 representative items from the validated TPACK-21 questionnaire and 42 items from the Digital Literacy questionnaire. Both instruments demonstrated excellent internal consistency as shown by their high Cronbach's Alpha coefficients, ensuring reliable measurement of the studied variables.

Student response to DECODE-CCR model

Student responses to the DECODE-CCR learning model were measured using questionnaires consisting of quantitative Likert scale assessments and open-ended questions to provide comprehensive evaluation data (Table 3).

Table 3. Student response analysis results to DECODE-CCR model

No	Evaluated Aspect	Percentage	Criteria
1	Learning Design	86.25	Very Positive
2	TPACK-21 Development	84.75	Very Positive
3	Cloud Classroom Integration	82.50	Very Positive
4	Learning Product Development	85.00	Very Positive
5	Digital Literacy Development	84.75	Very Positive
	Mean	84.63	Very Positive

The quantitative analysis demonstrates consistently positive student responses across all evaluated aspects. Learning Design received the highest response at 86.25%, followed by Learning Product Development (85.00%), TPACK-21 Development (84.75%), Digital Literacy Development (84.75%), and Cloud Classroom Integration (82.50%). The overall mean score of 84.63% indicates a "Very Positive" response, suggesting that students found the DECODE-CCR model highly effective and beneficial for their learning experience.

Qualitative analysis from open-ended questions revealed that 88.5% of students appreciated the systematic learning structure as the primary advantage, while 92.3% positively responded to integrated technology-pedagogy-content skill development. However, implementation challenges included initial platform adaptation difficulties (46.1%), system bugs affecting learning efficiency (57.6%), and language interface issues

(53.8%). Students suggested more intensive initial training (42.3%) and additional time for collaborative stages (38.5%) for future improvements. The triangulation of quantitative and qualitative data showed consistency, indicating the DECODE-CCR model's effectiveness in facilitating TPACK-21 competency development among prospective biology teachers.

Effectiveness of DECODE-CCR model on TPACK-21 development

TPACK-21 pre and post intervention comparison

This study investigated the effectiveness of the DECODE model integrated with Cloud Classroom (DECODE-CCR) in enhancing TPACK-21 and digital literacy among biology education students. Analysis of the TPACK-21 self-report data showed significant differences between the experimental and control groups (Table 4).

The experimental group showed a notable improvement in TPACK-21 scores, progressing from the "Adapting" (50%) to "Exploring" (63%) category, with an N-Gain of 0.26. The control group showed minimal improvement, maintaining the "Adapting" category with only a 4% increase in scores and an N-Gain of 0.02. This finding demonstrates that although both groups had similar baseline TPACK-21 capabilities, the DECODE-CCR model facilitated more substantial growth in students' ability to integrate technology, pedagogy, and content knowledge in teaching biology with 21st-century skills.

Table 4. TPACK-21 development in experimental and control groups

Class	Measurement	N	Mean Score (%)	Category	N-Gain	N-Gain Category
Experimental	Pre-respond	26	50	Adapting	0.26	Low
	Post-respond	26	63	Exploring		
Control	Pre-respond	27	49	Adapting	0.02	Low
	Post-respond	27	53	Adapting		

Dimensional analysis of TPACK-21

Examining the seven dimensions of TPACK-21 revealed varied improvement patterns across different knowledge components (Table 5).

Table 5. Dimensional analysis of TPACK-21 development

Dimension	Experimental Class				Control Class			
	Pre-respond	Post-respond	N-Gain	Category	Pre-respond	Post-respond	N-Gain	Category
TK	49%	68%	0.37	Medium	52%	53%	0.02	Low
CK	54%	62%	0.17	Low	54%	55%	0.02	Low
PK	47%	60%	0.25	Low	44%	47%	0.05	Low
PCK	48%	60%	0.23	Low	45%	47%	0.04	Low
TPK	47%	61%	0.26	Low	49%	50%	0.02	Low
TCK	54%	64%	0.22	Low	54%	55%	0.02	Low
TPACK	48%	62%	0.27	Low	47%	48%	0.02	Low

Technological Knowledge (TK) showed the most significant improvement among experimental group students with an N-Gain of 0.37 (medium category), indicating that the

DECODE-CCR model particularly enhanced students' technological competencies. The TPACK dimension, representing integrated knowledge, showed the second-highest improvement (N-Gain = 0.27), followed by Technological Pedagogical Knowledge (TPK) with an N-Gain of 0.26. Content Knowledge (CK) displayed the smallest improvement with an N-Gain of 0.17, suggesting that the model had less impact on subject matter knowledge compared to technological integration skills.

Control group students showed minimal improvements across all dimensions, with N-Gain values ranging from 0.02 to 0.05. The largest gap between experimental and control groups appeared in the TK dimension (0.35 difference in N-Gain), highlighting the DECODE-CCR model's strength in developing technological capabilities.

Gender-based analysis of TPACK-21

The study also analyzed TPACK-21 development through a gender lens to identify potential differences in how male and female students responded to the intervention (Table 6).

Table 6. Gender-based analysis of TPACK-21 development

Gender	Class	N	Pre-respond		Post-respond		N-Gain	Category
			Mean	Category	Mean	Category		
Male	Experimental	6	53%	Adapting	66%	Exploring	0.28	Low
	Control	6	51%	Adapting	52%	Adapting	0.02	Low
Female	Experimental	20	48%	Adapting	61%	Exploring	0.25	Low
	Control	21	49%	Adapting	50%	Adapting	0.02	Low

Male students in the experimental group achieved slightly higher improvement (N-Gain = 0.28) compared to female students (N-Gain = 0.25), though both groups progressed from the "Adapting" to "Exploring" category. Both genders in the control group showed minimal improvement (N-Gain = 0.02). These findings suggest that while the DECODE-CCR model effectively benefited both genders, male students demonstrated marginally more responsiveness to the intervention, though the difference was not statistically significant.

TPACK-21 implementation in teaching materials and performance

The practical application of TPACK-21 was assessed through the quality of lesson plans/teaching modules, their implementation, and learning product evaluation (Table 7, Table 8, and Table 9).

Table 7. Analysis of TPACK-21-based lesson plans/teaching modules

Class	Gender	N	Mean Score	Percentage (%)	Category
Experimental	Male	6	3.19	80	Good
	Female	20	3.27	82	Good
	Mean	26	3.23	81	Good
Control	Male	6	2.55	64	Moderate
	Female	21	2.56	64	Moderate
	Mean	27	2.56	64	Moderate

Table 8. Analysis of lesson plan/teaching module implementation

Class	Gender	N	Mean Score	Percentage (%)	Category
Experimental	Male	6	3.27	81.75	Good
	Female	20	3.33	83.25	Good
	Mean	26	3.30	82.50	Good
Control	Male	6	2.72	68.00	Moderate
	Female	21	2.75	68.75	Moderate
	Mean	27	2.74	68.38	Moderate

Table 9. Learning product evaluation results

Class	Gender	N	Mean Score	Percentage (%)	Category
Experimental	Male	6	3.32	83.00	Good
	Female	20	3.18	79.50	Good
	Mean	26	3.25	81.25	Good
Control	Male	6	2.75	68.75	Moderate
	Female	21	2.70	67.50	Moderate
	Mean	26	2.72	68.00	Moderate

The experimental group consistently outperformed the control group across all three assessment areas, achieving "Good" category ratings compared to the control group's "Moderate" ratings. In lesson plan development, the experimental group achieved 81% versus 64% for the control group. Implementation scores showed similar patterns with 82.50% versus 68.38%. Learning product evaluation revealed the experimental group scoring 81.25% compared to 68.00% for the control group. Gender-based analysis showed that male students in the experimental group generally achieved higher scores in technology integration aspects, while female students demonstrated balanced performance across pedagogical components. These results confirm that the DECODE model integrated with cloud classroom effectively enhances students' ability to develop, implement, and evaluate technology-enhanced learning materials.

Impact of DECODE-CCR model on digital literacy

Digital literacy pre and post intervention comparison

Digital literacy assessments revealed substantial differences between the experimental and control groups (Table 10).

Table 10. Digital literacy development in experimental and control groups

Class	Measurement	N	Mean Score	Category	N-Gain	N-Gain Category
Experimental	Pre-respond	26	3.00	C1 (Leader)	0.57	Medium
	Post-respond	26	3.55	C2 (Pioneer)		
Control	Pre-respond	27	2.99	B2 (Expert)	0.04	Low
	Post-respond	27	3.03	C1 (Leader)		

Students in the experimental group demonstrated substantial growth in digital literacy, advancing from C1 (Leader) to C2 (Pioneer) category with an N-Gain of 0.57

(medium category). Control group students showed minimal improvement with an N-Gain of 0.04, advancing only slightly from B2 (Expert) to C1 (Leader). This significant difference indicates that the DECODE-CCR model effectively developed students' digital competencies.

Dimensional analysis of digital literacy

Examination of the five dimensions of digital literacy revealed varying patterns of improvement across different competencies (Table 11).

Table 11. Dimensional analysis of digital literacy

Dimension	Experimental Class				Control Class			
	Pre-respond	**Post-respond**	**N-Gain**	**Category**	**Pre-respond**	**Post-respond**	**N-Gain**	**Category**
Information and Media Literacy	3.40	3.75	0.35	Medium	3.38	3.39	0.01	Low
Communication and Collaboration	3.04	3.54	0.50	Medium	3.02	3.03	0.01	Low
Digital Content Creation	2.77	3.54	0.63	Medium	2.76	2.82	0.05	Low
Safety and Responsible Use	2.92	3.50	0.54	Medium	2.93	2.97	0.04	Low
Problem Solving	2.93	3.50	0.53	Medium	2.92	3.00	0.07	Low

Digital Content Creation showed the highest improvement among experimental group students with an N-Gain of 0.63, followed by Safety and Responsible Use (0.54) and Problem Solving (0.53). Communication and Collaboration improved with an N-Gain of 0.50, while Information and Media Literacy showed the lowest improvement (0.35), though still in the medium category. Control group students showed minimal improvements across all dimensions (N-Gain range: 0.01-0.07). The substantial improvement in Digital Content Creation aligns with the DECODE-CCR model's emphasis on creating digital learning materials. The model also significantly enhanced students' understanding of digital safety and ethical considerations, as well as their ability to solve technological problems creatively.

Gender-based analysis of digital literacy

Analysis of digital literacy development by gender revealed interesting patterns (Table 12). Male students in the experimental group achieved remarkably high improvement in digital literacy with an N-Gain of 0.73 (high category), advancing from C1 (Leader) to C2 (Pioneer). Female students demonstrated moderate improvement with an N-Gain of 0.48 (medium category), advancing from B2 (Expert) to C1 (Leader). Both genders in the control group showed minimal improvement (N-Gain = 0.04). Male students achieved the most substantial improvement in Digital Content Creation (N-Gain = 0.77) and Safety and Responsible Use (N-Gain = 0.70), while female students showed the highest improvement in Information and Media Literacy (N-Gain = 0.56). These findings suggest gender-specific strengths and learning patterns in digital competencies, with male students demonstrating greater confidence and skill development in technical aspects of digital literacy.

Table 12. Gender-based digital literacy development

Gender	Class	Dimension	Pre-respond		Post-respond		N-Gain	Category
			Mean	Category	Mean	Category		
Male	Experi-mental	1	3.53	C1 (Leader)	3.86	C2 (Pioneer)	0.52	Medium
		2	3.35	C1 (Leader)	3.86	C2 (Pioneer)	0.69	Medium
		3	3.00	C1 (Leader)	3.77	C2 (Pioneer)	0.77	High
		4	3.10	C1 (Leader)	3.73	C2 (Pioneer)	0.70	High
		5	3.04	C1 (Leader)	3.65	C2 (Pioneer)	0.64	Medium
		Average	3.20	C1 (Leader)	3.78	C2 (Pioneer)	0.73	High
	Control	1	3.42	C1 (Leader)	3.44	C1 (Leader)	0.03	Low
		2	3.26	C1 (Leader)	3.29	C1 (Leader)	0.04	Low
		3	3.00	C1 (Leader)	3.00	C1 (Leader)	0.00	Low
		4	3.06	C1 (Leader)	3.15	C1 (Leader)	0.09	Low
		5	3.04	C1 (Leader)	3.13	C1 (Leader)	0.09	Low
		Average	3.15	C1 (Leader)	3.20	C1 (Leader)	0.04	Low
Female	Experi-mental	1	3.36	C1 (Leader)	3.72	C2 (Pioneer)	0.56	Medium
		2	2.95	B2 (Expert)	3.44	C1 (Leader)	0.46	Medium
		3	2.70	B2 (Expert)	3.48	C1 (Leader)	0.60	Medium
		4	2.86	B2 (Expert)	3.43	C1 (Leader)	0.50	Medium
		5	2.89	B2 (Expert)	3.46	C1 (Leader)	0.51	Medium
		Average	2.93	B2 (Expert)	3.49	C1 (Leader)	0.48	Medium
	Control	1	3.37	C1 (Leader)	3.37	C1 (Leader)	0.00	Low
		2	2.95	B2 (Expert)	2.95	B2 (Expert)	0.00	Low
		3	2.70	B2 (Expert)	2.70	B2 (Expert)	0.00	Low
		4	2.89	B2 (Expert)	2.92	B2 (Expert)	0.03	Low
		5	2.89	B2 (Expert)	2.97	B2 (Expert)	0.07	Low
		Average	2.94	B2 (Expert)	2.98	B2 (Expert)	0.04	Low

* 1 (Information Media and Literacy); 2 (Communication and Collaboration); 3 (Digital Content Creation); 4 (Safety and Responsive Use); 5 (Problem Solving*)*

Prerequisite analysis for statistical testing

Normality test results

Normality testing determined whether the pre-intervention and post-intervention scores originated from normally distributed populations. Given our sample size (less than 50 participants), we employed the Shapiro-Wilk test with a 5% significance level. Table 13 presents the normality test results. All variables demonstrated significance values (Sig.) greater than 0.05, confirming that the data originated from normally distributed populations, thus satisfying the normality assumption for further analysis.

Table 13. Normality test results

Variable	Class	Shapiro-Wilk	
		Statistic	**df**
TPACK-21 Pre-respond	Experimental	0.959	26
	Control	0.967	27
TPACK-21 Post-respond	Experimental	0.962	26
	Control	0.976	27
Digital Literacy Pre-respond	Experimental	0.962	26
	Control	0.967	27
Digital Literacy Post-respond	Experimental	0.968	26
	Control	0.975	27

Homogeneity test results

Homogeneity testing was conducted to determine whether data group variations had equal variances. This study utilized Box's M Test with a 5% significance level, as presented in Table 14.

Table 14. Homogeneity test results

Box's M	F	df1	df2	Sig.
8.452	0.823	9	2044.885	0.19

The significance value (Sig.) of 0.19 > 0.05 indicates that the covariance matrices between groups are homogeneous, thus satisfying the homogeneity of covariance matrices assumption and allowing MANCOVA analysis to proceed.

Linearity test results

Linearity testing verified the linear relationship between covariates (pre-intervention scores) and dependent variables (post-intervention scores). We employed the Test for Linearity with a 5% significance level, as shown in Table 15.

Table 15. Linearity test results

Variable	Deviation from Linearity	Conclusion
	F	**Sig.**
TPACK-21 Pre-respond - Post-respond	0.541	0.916
Digital Literacy Pre-respond - Post-respond	0.231	0.999

The Deviation from Linearity significance values exceeded 0.05 for all variables, confirming the presence of linear relationships between covariates and dependent variables, thus satisfying the linearity assumption for MANCOVA analysis.

Homogeneity of regression slopes test

This test ensured no interaction between covariates (pre-intervention scores) and independent variables (learning model and gender). Table 16 presents these results.

Table 16. Homogeneity of regression slopes test results

Interaction Source	Dependent Variable	F	Sig.	Conclusion
Learning Model * TPACK-21 Pre-respond	TPACK-21 Post-respond	0.431	0.520	No interaction
Gender * TPACK-21 Pre-respond	TPACK-21 Post-respond	0.487	0.490	No interaction
Learning Model * Gender * TPACK-21 Pre-respond	TPACK-21 Post-respond	0.301	0.590	No interaction
Learning Model * Digital Literacy Pre-respond	Digital Literacy Post-respond	0.550	0.460	No interaction
Gender * Digital Literacy Pre-respond	Digital Literacy Post-respond	0.725	0.400	No interaction
Learning Model * Gender * Digital Literacy Pre-respond	Digital Literacy Post-respond	0.001	0.980	No interaction

All interaction significance values exceeded 0.05, confirming no interactions between covariates and independent variables, thereby satisfying the homogeneity of regression slopes assumption for MANCOVA analysis.

Hypothesis testing

MANCOVA analysis was conducted to test the study's hypotheses, with pre-intervention scores as covariates (Table 17).

Table 17. MANCOVA results for main and interaction effects

Source	Dependent Variable	df	Mean Square	F	Sig.
Learning Model	TPACK-21	1	6741.842	3868.679	<0.001
	Digital Literacy	1	4074.436	2845.667	<0.001
Gender	TPACK-21	1	3.221	1.849	0.180
	Digital Literacy	1	16.446	11.487	0.001
Learning Model * Gender	TPACK-21	1	2.274	1.305	0.259
	Digital Literacy	1	0.054	0.038	0.846

The results confirm that the DECODE-CCR model had a highly significant effect on both TPACK-21 and digital literacy ($p < 0.001$). Gender had a significant effect on digital literacy ($p = 0.001$) but not on TPACK-21 ($p = 0.180$). No significant interaction effect appeared between learning model and gender for either TPACK-21 ($p = 0.259$) or digital literacy ($p = 0.846$).

Effect size analysis

Effect size calculations provided further insights into the magnitude of the intervention's impact (Table 18).

Table 18. Effect size analysis results

Source of Variation	Dependent Variable	Partial Eta Squared	Category
Learning Model	TPACK-21	0.988	Large
	Digital Literacy	0.984	Large
Gender	TPACK-21	0.038	Small
	Digital Literacy	0.196	Medium
Learning Model * Gender	TPACK-21	0.027	Small
	Digital Literacy	0.001	Very Small

The learning model produced large effect sizes for both TPACK-21 (η^2 = 0.988) and digital literacy (η^2 = 0.984), confirming the substantial impact of the DECODE-CCR intervention. Gender showed a medium effect size for digital literacy (η^2 = 0.196) but only a small effect for TPACK-21 (η^2 = 0.038), aligning with the hypothesis testing results. The interaction effects were small or very small, confirming the independent contributions of the main variables.

The substantial effect sizes observed in this study (η^2 = 0.988 for TPACK-21; η^2 = 0.984 for digital literacy) reinforce the theoretical positioning of TPACK as a dynamic, integrated knowledge framework. These findings align with contemporary research emphasizing the critical importance of systematic technology-pedagogy-content integration in teacher education (Cheng et al., 2022; Lachner et al., 2021; Nithitakkharanon & Nuangchalerm, 2022). The progression from "Adapting" to "Exploring" categories demonstrates that meaningful competency development requires structured approaches that go beyond surface-level technological adoption. The four-phase DECODE-CCR progression strategically addresses different TPACK components while leveraging collaborative cloud environments. The demonstration phase's effectiveness in establishing Technological Knowledge foundation (N-Gain = 0.37) supports theoretical assertions that technological fluency must precede meaningful integration attempts (Cañavate et al., 2025). More significantly, the co-design phase's success in developing Digital Content Creation skills (N-Gain = 0.63) validates theoretical frameworks emphasizing creative aspects of TPACK development (Thyssen et al., 2023), extending recent research on cloud-based learning effectiveness (Kovalevskaia et al., 2021; Vakaliuk et al., 2021; Srikan et al., 2021).

The most theoretically intriguing finding involves differential gender effects on digital literacy (p = 0.001, η^2 = 0.196) versus TPACK-21 development (p = 0.180, η^2 = 0.038). While males demonstrated substantially higher digital literacy improvement (N-Gain = 0.73 vs. 0.48), both genders achieved equivalent TPACK-21 advancement. This pattern challenges conventional understanding of technology integration in educational contexts and suggests that pedagogical integration competencies may develop independently of technical digital competencies. This anomaly has significant theoretical implications for teacher education frameworks. The absence of gender effects on TPACK-21 suggests that well-structured collaborative approaches can overcome traditional gender disparities in educational technology adoption (Vijayatheepan, 2024), supporting recent research identifying gender-specific patterns in digital competency development (Wignall et al., 2024; Badjanova et al., 2021). However, the persistence of gender differences in digital literacy indicates that technical confidence and creative content creation skills may require differentiated instructional approaches.

The model's success in advancing students from C1 (Leader) to C2 (Pioneer) digital literacy levels contrasts sharply with typical teacher competency profiles where overall levels average only B2 level, with Digital Content Creation particularly weak (Dias-Trindade et al., 2023). This advancement suggests that collaborative learning environments naturally incorporate digital citizenship elements and creative problem-solving capabilities, extending theoretical understanding of how social constructivist approaches facilitate digital competency development. The lack of significant interaction effects between learning model and gender demonstrates that collaborative emphasis leverages diverse student strengths rather than creating competitive environments that highlight individual differences (Berezhna et al., 2025; Meyer & Baogui, 2025; Nasir et al., 2024). This finding supports contemporary understanding of effective collaborative learning in teacher education contexts (Lei & Medwell, 2021; Herrera-Pavo, 2021). Despite positive outcomes, implementation challenges reveal theoretical gaps in technology integration models. Platform adaptation difficulties (46.1%), system bugs (57.6%), and interface issues (53.8%) mirror broader concerns about the disconnect between theoretical frameworks and practical implementation realities. These challenges highlight that technological resources often remain underexploited due to preparation limitations rather than equipment constraints (Paran et al., 2024; Sucipto et al., 2024).

The model's effectiveness in bridging theoretical knowledge with practical application, evidenced by significantly higher product quality ratings (81% vs. 64%), validates theoretical frameworks emphasizing synthesized pedagogical knowledge where technology, pedagogy, and content merge into effective practice (Bwalya et al., 2023). The systematic framework offers a theoretically grounded, replicable approach that accommodates diverse learning styles while maintaining rigorous development standards. These findings contribute to evolving theoretical understanding of how integrated approaches can develop technological pedagogical competencies. The research confirms that well-designed collaborative models benefit diverse populations while maintaining pedagogical effectiveness, supporting more inclusive theoretical frameworks for educational technology integration in higher education contexts. The relatively small sample size, single-semester implementation, and context-specific nature within biology education limit theoretical generalizability. Future research should explore long-term retention effects and cross-disciplinary implementation to establish broader theoretical applicability of integrated technology-pedagogy-content development models.

CONCLUSION

This study investigated the effects of the DECODE model integrated with Cloud Classroom (DECODE-CCR) and gender on TPACK-21 and digital literacy of biology education students. The findings revealed that the DECODE-CCR learning model significantly enhanced students' TPACK-21 capabilities and digital literacy, with large effect sizes for both variables. Students in the experimental group demonstrated substantial improvement in TPACK-21 scores, advancing from "Adapting" to "Exploring" category, while also progressing from C1 (Leader) to C2 (Pioneer) level in digital literacy.

Additionally, these students produced higher quality TPACK-21-based lesson plans and teaching modules compared to the control group.

Gender showed no significant effect on TPACK-21 development but significantly influenced digital literacy improvement with a medium effect size. Male students exhibited higher improvement in digital literacy (high category) compared to females (medium category), particularly in Digital Content Creation and Safety domains, while both genders showed comparable TPACK-21 development patterns. No significant interaction effect was found between the learning model and gender for either dependent variable, indicating that the DECODE-CCR model effectively enhanced both competencies regardless of gender, despite varying improvement rates. The study suggests that institutions should integrate cloud-based learning environments into teacher education programs to develop both technological-pedagogical knowledge and digital competencies. Furthermore, gender-responsive approaches should be considered when designing digital literacy interventions, addressing specific needs of different gender groups while maintaining inclusive frameworks. Future research should explore the long-term impact of DECODE-CCR implementation on teaching performance and investigate the model's effectiveness across different subject areas and educational levels.

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