Journal of Innovation in Educational Assessment
Vol. 8 No. 1, May (2026)

DOI: https://doi.org/10.66545/770pt162

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

Received: 10th December 2025
Accepted: 24th April 2026

journal.iaiiea.org

GENDER DIMENSIONS OF TECHNOLOGY INTEGRATION AND FOUR C SKILLS (CRITICAL THINKING CREATIVITY, COMMUNICATION, AND COLLABORATION) IN STEAM EDUCATION

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Abstract

This study investigated the gender dimensions of technology integration in STEAM classrooms and its effect on fostering the Four Cs, critical thinking, creativity, communication, and collaboration. A quasi-experimental pretest–posttest control group design was adopted in Nigerian secondary schools. The population comprised Senior Secondary Two students, from which a stratified random sample of 200 students was selected. Data were collected using the Technology Integration Perception Questionnaire (TIPQ) and the STEAM Skills Performance Test (SSPT). Data were analysed using mean and standard deviation to answer research questions, independent t-tests, ANCOVA, and two-way ANOVA, alongside supplementary analyses to test the hypotheses. Results revealed that female students outperformed males with a small-to-moderate effect size. Teacher technology use significantly improved students' Four C skills, which partially mediated achievement. Prior achievement emerged as the strongest predictor, while class-level variance was negligible. The findings indicate that technology-enhanced pedagogy benefits both genders equitably and strengthens 21st-century skills. It is recommended that teachers adopt gender-responsive pedagogies and receive training in integrating creativity, collaboration, and critical thinking into digital learning environments.

Keywords: STEAM education, gender, Four C skills, technology integration, achievement

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To cite this article:

Uko, 1. P. J. U. and S. P. I., Empatuko, M., & Idiong, S. P. I. (2026). Gender Dimensions of Technology Integration and Four C Skills (Critical Thinking Creativity, Communication, and Collaboration) in STEAM Education. *Journal of Innovation in Educational Assessment, 8*(1), 204-220. https://doi.org/10.66545/770pt162

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Introduction

The increasing emphasis on Science, Technology, Engineering, Arts, and Mathematics (STEAM) education has positioned the "Four Cs" – critical thinking, creativity, communication, and collaboration – as essential skills for 21st-century learning. However, gender remains a persistent factor influencing students' access to and use of technology in STEAM contexts. The Fourth Industrial Revolution has redefined the competencies required of learners, emphasising adaptability, innovation, and problem-solving skills driven by technology (Schwab, 2017; Fullan, 2021). Within this paradigm, STEAM education integrating Science, Technology, Engineering, Arts and Mathematics has emerged as a multidisciplinary model fostering critical thinking, creativity, communication and collaboration (the Four Cs). These competencies are regarded as the bedrock of 21st-century learning and future workforce preparedness (Darling-Hammond & Oakes, 2021; Trilling & Fadel, 2019).

Despite global advances, gender disparities continue to shape participation in STEAM fields. UNESCO (2022) reports that while girls perform equally well as boys in early science and mathematics learning, gaps emerge in access to digital tools, representation in STEM careers, and engagement with technology-rich learning environments. Cultural expectations, teacher practices, and institutional biases often reinforce these inequities (Beede et al., 2017; Uko, 2022; Eyenaka, Uko & Eyenaka, 2017). In the Nigerian context, gender differences in learning experiences are further compounded by uneven access to digital resources, teacher preparedness, and socio-economic barriers (Uko & Uko, 2023).

Recent scholarship highlights that technology, when effectively integrated, enhances students' metacognitive awareness, engagement, and collaborative learning (Uko, Akanwa & Agbaegbu, 2025; Zhao et al., 2020). For example, Udofia and Uko (2018) demonstrated that digital tools such as Geogebra improved students' mathematics performance, while Eluwa & Uko (2019) emphasized adaptive pedagogic practices for sustainable mathematics education. However, the ways in which male and female learners leverage these opportunities differ. For instance, Uko, Eluwa & Uko (2024) demonstrated that adaptive testing platforms improved both achievement and self-efficacy, but female students reported higher gains in collaborative learning contexts. This aligns with research suggesting that teacher mediation and equitable pedagogical practices are critical for bridging gender gaps in STEAM (UNESCO, 2022; Wang & Degol, 2017).

The conceptual foundation of this study rests on three key constructs: STEAM education, the Four C competencies, and gender technology integration. STEAM education, as a multidisciplinary approach, emphasises the integration of science, technology, engineering, arts, and mathematics to build learners' capacity for problem-solving and innovation (Trilling & Fadel, 2019). Within this framework, the four Cs – critical thinking, creativity, communication

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

and collaboration – represent the essential skills for thriving in a knowledge-based economy. Teacher technology practices are conceptualised as mediating factors that can scaffold the development of these competencies. Gender is viewed as both a social and educational construct that shapes access, engagement, and outcomes in technology-enhanced learning environments (UNESCO, 2022).

Socio-Constructivism and Feminist Educational Theories

Theoretically, this study is anchored on socio-constructivist, feminist, and assessment-for-learning perspectives. Socio-constructivist theory, grounded in Vygotsky's work, underscores the role of social interaction and mediation in cognitive development. Technology tools, under this framework, serve as mediators that enable students to collaborate, communicate, and co-construct knowledge (Fullan, 2021). Feminist educational theory provides an equity lens, highlighting how systemic barriers and classroom practices can perpetuate or reduce gender disparities (Wang & Degol, 2017). It argues for the design of inclusive pedagogies that empower all learners. Assessment-for-learning (AfL) and mastery learning theories complement these perspectives by emphasising continuous feedback, formative assessment, and accountability systems that sustain long-term achievement gains (Udofia & Uko, 2016). Together, these frameworks provide a robust lens for interpreting the interplay between gender, teacher practices, technology use, and student achievement in STEAM contexts.

Empirical studies have shown mixed findings on gender outcomes in STEAM education. International research indicates that while female students often match or surpass males in performance, they remain under-represented in STEM careers (Beede et al., 2017; Wang & Degol, 2017). In Nigeria, evidence is accumulating on the role of digital pedagogy. For example, Udofia and Uko (2018) demonstrated that GeoGebra significantly enhanced mathematics achievement, while Eluwa and Uko (2019) identified adaptive pedagogic practices as vital for sustainable mathematics learning. Eyenaka, Uko, and Eyenaka (2017) found that gender shaped ICT-related pedagogical beliefs, and Uko, Uko, and Utibe (2024) highlighted the Dunning–Kruger effect among teachers as a barrier to effective instruction. Collectively, these studies confirm that teacher practices, gender, and technology are interlinked factors in determining learning outcomes, yet few have integrated these elements into a single framework.

STEAM education has been globally recognised as a transformative approach for preparing learners with the skills needed in the Fourth Industrial Revolution. Research emphasizes the importance of integrating critical thinking, creativity, communication and collaboration into classroom practices to build 21st-century competencies (Darling-Hammond & Oakes, 2021; Trilling & Fadel, 2019). However, gender disparities persist in many contexts, where female students encounter barriers to participation in technology-enhanced learning despite equal potential (UNESCO, 2022; Wang & Degol, 2017). In Nigeria, inequities in digital resource access, socio-economic conditions, and teacher readiness exacerbate these gaps (Uko & Uko, 2023). Teacher practices are also critical, as effective integration of ICT can foster engagement and enhance student achievement (Zhao et al., 2020). Studies such as Udofia & Uko (2018) and Eluwa & Uko (2019) provide evidence of digital tools improving mathematics outcomes, while Eyenaka, Uko, & Eyenaka (2017) revealed how gender influences ICT practices in science classrooms.

This study, therefore, interrogates the gender dimensions of technology integration in STEAM classrooms and examines how such practices foster the Four Cs. By situating the discussion within socio-constructivist and feminist educational frameworks, the research provides evidence-based insights for designing inclusive, technology-driven pedagogies. In addition to these focal objectives, the study also considered supplementary pathways that could provide a deeper understanding of how teacher practices and competencies relate to student outcomes. Specifically, exploratory analyses were conducted to examine whether the influence of teacher technology practices on achievement operates indirectly through four C skills, whether gender continues to matter after controlling for prior performance, and whether class-level variance meaningfully contributes to achievement outcomes (Udofia & Uko, 2016; Uko, Uko & Utibe, 2024). These additional variables were not hypothesised at the outset but emerged as important dimensions for extending the study's contributions. This gap justifies the present study's focus on technology-enhanced pedagogy, gender equity, and the Four C competencies in Nigerian secondary schools. Specifically, the study aimed to:

1. Determine the extent to which technology integration fosters the development of critical thinking, creativity, communication, and collaboration among students in STEAM education.
2. Examine whether gender differences exist in the development of these competencies within technology-supported learning environments.
3. Provide empirical evidence on the effectiveness of technology-enhanced instructional strategies in promoting 21st-century skills among secondary school students.

Research Questions

1. To what extent does technology integration in STEAM classrooms foster critical thinking among students?
2. How does technology use enhance students' creativity in STEAM learning?
3. In what ways does technology integration improve students' communication skills in STEAM education?
4. To what extent does technology foster collaboration among students in STEAM classrooms?
5. What are teachers' observed practices in facilitating the Four C's through technology integration

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

in STEAM lessons?

Hypotheses

HO1: There is no significant difference between male and female students' overall achievement in STEAM subjects when technology is integrated.

HO2: There is no significant relationship between teachers' use of technology and the development of the Four Cs among students.

HO3: There is no significant interaction effect of gender and teachers' technology integration practices on students' acquisition of the Four Cs.

Method

The study adopted a quasi-experimental design with a pretest-posttest control group structure. This design was considered appropriate because it allowed for the investigation of the causal influence of technology integration on the development of the Four Cs (critical thinking, creativity, communication, and collaboration) while accounting for baseline differences. The quasi-experimental approach was chosen since random assignment was not feasible in the school context, but intact classes were assigned to experimental and control conditions. The target population comprised all senior secondary school students in STEAM-related classes across selected schools in Akwa Ibom State, Nigeria. According to records from the State Ministry of Education (2024), the population of students in STEAM-related subjects (Science, Technology, Engineering, Arts, and Mathematics) was approximately 5,420 across 28 schools. These schools formed the population from which the sample was drawn.

A total sample of 200 students was selected through stratified random sampling. Stratification was based on co-educational schools for gender (male and female) and subject area (Science, Technology, Arts, and Mathematics) to ensure representativeness. The sample included 98 males and 102 females, respectively. This sample size was considered adequate for robust statistical analysis, consistent with the recommendations of Krejcie and Morgan (1970). Two main instruments were used in this study: a performance-based test and a supplementary questionnaire.

1. STEAM Skills Performance Test (SSPT): This test was developed by the researchers to objectively measure the four Cs. It comprised scenario-based problem-solving questions for critical thinking, open-ended project tasks for creativity, structured oral and written tasks for communication, and group activities assessed with a rubric for collaboration. The test was developed, validated, and administered. The content validity was established through expert review, and inter-rater reliability for creativity and collaboration scoring yielded coefficients above 0.82, indicating high reliability.

2. Technology Integration Perception Questionnaire (TIPQ): A structured Likert scale questionnaire was employed as a supplementary tool to gather students' perceptions of how

technology supported their development of the Four C's. This served as supportive evidence, complementing the performance test results.

Procedures for Implementing the Intervention

The intervention lasted for eight weeks. Students in the experimental group were exposed to structured technology-integrated lessons designed to foster the four Cs, while the control group received traditional lecture-based instruction.

1. Week 1 – Orientation and Pretest: Both groups were briefed on the study objectives. A pretest was administered to establish baseline performance in the four Cs.
2. Weeks 2–7 – Intervention: The experimental group engaged in activities integrating technology tools:

- Critical Thinking: problem-solving tasks using simulations and coding platforms.
- Creativity: digital storytelling, graphic design, and project-based STEAM challenges.
- Communication: presentations via PowerPoint, video-recorded discussions, and peer reviews.
- Collaboration: group projects using Google Docs, online brainstorming platforms, and peer-to-peer learning.

The control group continued with teacher-centred instruction without technology-enhanced strategies.

3. Week 8 – Posttest: Both groups were reassessed on the four Cs. The posttest results were compared to the pretest outcomes to evaluate the intervention effect.

Results

Research Questions

Table 1

Descriptive Statistics on Technology Integration and Development of the Four C's

Variable	N	Mean	SD	Interpretation
Critical Thinking	200	3.84	0.62	High extent
Creativity	200	3.67	0.71	Moderate extent
Communication	200	3.91	0.58	High extent
Collaboration	200	3.75	0.65	High extent

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 1 presents the descriptive statistics for achievement, FourC skills, and teacher technology use by gender. Female students (M = 71.56, SD = 7.45) outperformed male students (M = 68.24, SD = 8.12) in achievement. Four C scores were moderately high across both genders (M ≈ 3.8, SD ≈ 0.6), while teacher technology use also showed consistent means across groups (M ≈ 3.7). Female students demonstrated slightly higher achievement with less variability, while

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

Four C and teacher technology use reflected consistent, moderately high endorsement across the sample. Technology integration fosters critical thinking, communication, and collaboration to a high extent, while creativity is moderately enhanced.

RQ1: Critical Thinking and Technology Integration

The results (M = 3.84, SD = 0.62) indicate that technology integration significantly fosters students' critical thinking skills. The mean value lies within the 'high extent' range, suggesting that most students perceive technology-enabled tasks (e.g., simulations, coding exercises, and problem-solving apps) as enhancing their ability to analyse, evaluate, and justify solutions. The relatively low standard deviation indicates agreement among respondents, reflecting shared experiences across gender lines.

RQ2: Creativity and Technology Use

Creativity was rated moderately (M = 3.67, SD = 0.71), lower than other skills. The higher standard deviation suggests variability in experiences: while some students benefited from open-ended creative tasks (such as digital storytelling and design-based projects), others may not have had equal opportunities. The results suggest that technology's creative potential is underutilised, especially when teachers prioritise correctness over originality.

RQ3: Communication Skills

Communication scored the highest mean (M = 3.91, SD = 0.58), showing that technology strongly supports students' communication. The low standard deviation reflects widespread agreement. Digital platforms for presentations, peer discussions, and feedback appear to enhance students' confidence and multimodal expression. Bandura's social learning theory provides a basis for this finding, as students model and exchange ideas in tech-mediated environments. Thus, communication is the most consistently strengthened domain through technology use.

RQ4: Collaboration

Collaboration was fostered to a high extent (M = 3.75, SD = 0.65). The mean suggests strong collaborative benefits, but the standard deviation indicates some unevenness in experience. While tools like Google Docs and project-based platforms support teamwork, group dynamics and teacher practices likely explain the variability. Despite these challenges, results affirm that technology enhances collaborative learning, though its impact varies depending on context and teacher facilitation.

Table 2.

Teachers' Observed Practices in Using Technology

Practice	N	Mean	SD	Interpretation
Use of simulations & modeling	200	3.81	0.63	High
Digital collaborative tools	200	3.74	0.69	High
Creativity-centered apps/tools	200	3.55	0.72	Moderate
Communication platforms	200	3.88	0.60	High

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 2 shows teachers' observed practices in facilitating the four Cs through technology integration in STEAM lessons. The results indicate that communication platforms recorded the highest mean (M = 3.88, SD = 0.60), suggesting that teachers frequently use digital tools to support students' communication during instruction. The use of simulations and modelling (M = 3.81, SD = 0.63) and digital collaborative tools (M = 3.74, SD = 0.69) were also rated high, indicating that teachers often employ these technologies to promote critical thinking and collaboration in STEAM learning. However, creativity-centred applications recorded a moderate mean (M = 3.55, SD = 0.72), suggesting that tools specifically designed to enhance students' creativity are used less frequently. The relatively low standard deviations (0.60–0.72) indicate that respondents had similar views regarding teachers' technology practices. Overall, the findings suggest that teachers commonly use technology to support communication, collaboration, and critical thinking, while technology for creativity development is less emphasized.

Table 3.

Independent Samples t-Test on Gender and Students' Achievement

Gender	N	Mean	SD	T	df	P	Decision
Male	98	68.24	8.12				
Female	102	71.56	7.45	-2.91	198	.004	Reject H_0

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 3 shows the results of the independent samples t-test comparing male and female students' achievements. Female students scored significantly higher than males, $t(198) = -2.79$, $p = .006$, MD = 3.32, Cohen's d = 0.40. The gender gap was small-to-moderate, indicating meaningful but not large differences in performance.

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

Table 4.

Pearson Correlation between Teachers' Tech Use and Students' Four C's

Variable	R	P	Decision
Teachers' Tech Use ↔ Four C's	.482	.000	Reject H_0

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

There is a significant positive relationship between teachers' technology use and students' acquisition of the Four Cs ($r = .482$, $p < .01$).

Table 5.

Two-Way ANOVA on Gender × Teacher Tech Practice and Students' Four C's

Source	SS	Df	MS	F	P	Decision
Gender	112.43	1	112.43	4.21	.042	Reject H_0
Teacher Tech Practice	298.76	2	149.38	5.59	.005	Reject H_0
Gender × Practice	35.64	2	17.82	0.66	.516	Retain H_0
Error	5034.12		194	25.94		
Total	8284.95		199			

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Gender and teacher technology practice each had significant main effects on students' acquisition of the Four Cs. However, there was no significant interaction effect between gender and teacher practices ($p = .516$).

Beyond the primary hypotheses, further analyses were conducted to investigate additional relationships suggested by the data. These supplementary analyses examined whether gender and teacher practices predicted achievement after controlling for prior performance, whether teacher practices influenced achievement indirectly through the four C skills, and whether class-level clustering accounted for achievement variance.

Table 6

Descriptive Statistics of Key Variables by Gender

Gender	N	M (Achievement)	SD (Achievement)	M (FourC)	SD (FourC)	M (Teacher Tech)	SD (Teacher Tech)
Male	98	68.24	8.12	3.84	0.59	3.82	0.58
Female	102	71.56	7.45	3.72	0.62	3.69	0.69

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 6 presents the descriptive statistics for achievement of the four Cs skills and teacher technology use by gender. Female students (M = 71.56, SD = 7.45) outperformed male students (M = 68.24, SD = 8.12) in achievement. The SD values (7.45 and 8.12) indicate moderate spread; females were slightly more consistent. Four C scores were moderately high across both genders (M ≈ 3.8, SD ≈ 0.6), suggesting overall agreement, while teacher technology use also showed consistent means across groups (M ≈ 3.7). Female students demonstrated slightly higher achievement with less variability, while Four C and teacher technology use reflected consistent, moderately high endorsement across the sample.

Table 7

Independent Samples t-test for Achievement by Gender

Comparison	t(df)	P	Mean Diff	Cohen's d	Levene's p
Female – Male	-2.79 (198)	.006	3.32	0.40	.219

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 7 shows the results of the independent samples t-test comparing male and female students' achievements. Female students scored significantly higher than males, $t(198) = -2.79$, $p = .006$, MD = 3.32, Cohen's d = 0.40. The gender gap was small-to-moderate, indicating meaningful but not large differences in performance, suggesting the gender gap is meaningful but not large. Levene's test showed equal variances ($p = .219$).

Table 8

ANCOVA Results for Achievement Controlling for Prior Achievement

Source	SS	Df	F	P	Partial η^2	ω^2
Gender	84.78	1	2.77	.098	.014	.009
Teacher Tech	96.88	1	3.16	.078	.016	.011
Prior Achievement	7512.0	1	245.05	.000	.796	.793
Residual	6008.42		196			

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 8 reports the ANCOVA results for achievement with gender and teacher technology use as predictors, controlling for prior achievement. Prior achievement emerged as the strongest predictor ($F = 245.05$, $p < .001$, $\eta^2 = .80$). Gender and teacher technology use explained small additional variance ($\eta^2 \approx .01–.02$) but were not statistically significant after controlling for prior achievement. Achievement is primarily shaped by students' prior ability, though gender and teacher practices exert secondary effects. This shows prior ability dominates achievement outcomes, but gender and teacher practices still have minor influence.

Table 9

Two-Way ANOVA for Four C by Gender and Teacher Tech Group

Source	SS	Df	F	P	η^2
Gender	0.40	1	1.30	.255	.005
Teacher Tech Group	12.55	2	20.61	.000	.172
Gender × Tech Group	0.84	2	1.38	.253	.012
Residual	59.07	194			.811

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

*Significant at $p < 0.05$. Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 9 presents results for four C scores by gender and teacher technology group. Teacher technology group significantly influenced FourC ($\eta^2 = .17$, $p < .001$), while gender and the interaction were not significant. The teacher technology group had a large and significant effect on Four C scores ($F = 20.61$, $p < .001$, $\eta^2 = .17$), showing that students exposed to higher teacher tech use scored much higher on the Four Cs. Gender had no main effect, and the interaction was not significant, suggesting teacher practices benefit both genders equally.

Table 10

Bootstrapped Mediation Analysis of Teacher Tech on Achievement via Four C

Path	Estimate	95% CI Lower	95% CI Upper
a (Teacher Tech → Four C)	0.460	–	–
b (Four C → Achievement Teacher Tech)	5.820	–	–
Indirect (a × b)	2.680	1.320	4.410
Total Effect (Teacher Tech → Achieve)	4.320	–	–

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 10 shows the mediation results. Teacher technology use predicted the Four Cs ($a = 0.46$), and the Four Cs significantly predicted achievement, controlling for teacher technology ($b = 5.82$). The indirect effect was significant ($a \times b = 2.68$, 95% CI [1.32, 4.41]), indicating partial mediation. Teacher practices enhance achievement partly by strengthening students' Four C skills, confirming theoretical models of technology-enhanced learning. This shows teacher technology use improves achievement partly through enhancing the Four Cs skills. The direct effect remained positive, indicating partial mediation.

Table 11

ANCOVA Coefficients with Robust (HC3) SEs

Term	B	RobustSE	T	P
Intercept	10.320	3.120	3.31	.001
Gender (Female)	3.650	1.180	3.09	.002
Teacher Tech	2.420	0.920	2.63	.009
Prior Achievement	0.810	0.052	15.60	.000

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 11 shows ANCOVA coefficients with HC3 robust standard errors. Gender ($b = 3.65$, $p = .002$), teacher technology ($b = 2.42$, $p = .009$), and prior achievement ($b = 0.81$, $p < .001$) remained significant. Results are robust to heteroskedasticity, affirming the independent effects of gender and teacher practices alongside prior ability. This underscores that teacher practices and gender differences hold even when correcting for heteroskedasticity.

Table 12

Intraclass Correlation (ICC) for Class-Level Effects

Group Var	Residual Var	ICC
0.000	68.63	0.000

Source: Author's Fieldwork (2025), analyzed using SPSS Version 25

Table 12 reports the ICC for achievement at the class level. The ICC was negligible (≈0.00), indicating minimal variance attributable to class-level clustering. Achievement differences are primarily explained by individual-level factors and teacher practices, not class membership. This suggests individual student characteristics and teacher practices matter more than class-level clustering.

Discussion of Findings

Gender and Achievement

The study revealed a significant female advantage in achievement, consistent with recent shifts in gender dynamics within STEM-related contexts. Historically, male students have been positioned as outperforming females in mathematics and science, but emerging evidence points to narrowing or reversed gaps. In this study, female students achieved higher mean scores with slightly less variability, suggesting greater consistency in their performance. Although the effect size was modest, its educational implications are meaningful in contexts where equity remains a priority. These findings resonate with Eyenaka, Uko, and Eyenaka (2017), who reported that gender shapes ICT classroom practices and pedagogical beliefs. Similarly, Uko and Uko (2022) stressed that female learners, when provided with equitable opportunities, leverage technology effectively for problem-solving and collaboration. The observed higher standard deviation for creativity outcomes further implies differences in classroom opportunities; some learners had exposure to open-ended, project-based tasks that fostered innovation, while others remained confined to more teacher-directed approaches. Robinson (2020) underscores that creativity thrives in supportive environments that provide autonomy, time, and recognition of original contributions, aligning with the variability noted in this study.

Teacher Practices and Four C Skills

Teacher technology use significantly influenced the development of students' four Cs skills: critical thinking, creativity, communication and collaboration. This finding confirms socio-constructivist and socio-cultural perspectives, which view technology as a mediating tool for scaffolding learning (Fullan, 2021). Empirical support comes from Udofia and Uko (2018), who demonstrated that Geogebra integration improved mathematics achievement, highlighting how digital tools enhance problem-solving and conceptual understanding. Eluwa and Uko (2019) also emphasized that adaptive pedagogic practices foster sustainable mathematics and statistics education, reinforcing the role of teacher competence in leveraging technology

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

effectively. Johnson and Johnson (2019) further explained that cooperative learning structures, when supported by technology, amplify student collaboration through clearly defined roles and accountability mechanisms. This study's findings therefore extend prior evidence by showing that technology-mediated teacher practices not only promote subject mastery but also equip learners with transferable 21st-century competencies crucial for workforce readiness.

Mediation of Achievement Through Four C

The mediation analysis demonstrated that teacher technology use indirectly influenced achievement by first enhancing students' four Cs skills. This supports assessment-for-learning frameworks, which emphasise the formative role of teacher guidance and feedback in connecting classroom practices to learning outcomes (Udofia & Uko, 2016). By strengthening critical thinking, creativity, communication and collaboration, teachers indirectly raised student achievement, underscoring the interdependence of pedagogy and competencies. Uko, Uko and Utibe (2024) added that teacher overconfidence biases, as explained by the Dunning–Kruger effect, can undermine effective integration of technology. Professional development is thus crucial to ensure that teachers not only adopt digital tools but also apply them appropriately to foster both academic and affective gains.

Primacy of Prior Achievement

Prior achievement emerged as the most robust predictor of final performance, reflecting the cumulative and hierarchical nature of learning. Students who entered the study with stronger academic foundations consistently outperformed peers, even when exposed to similar teacher practices and technology integration. This aligns with mastery learning theory, which emphasises building sequential knowledge and skills for sustained success, and with assessment-for-learning approaches that prioritise continuous monitoring and scaffolding (Darling-Hammond & Oakes, 2021). While this finding underscores the importance of prior knowledge, it also raises equity concerns for struggling learners who risk falling further behind without targeted interventions. The results reinforce the necessity of formative assessments and remedial programmes to support weaker students and close persistent gaps.

Equity in the Impact of Technology

The absence of significant interaction between gender and teacher technology practices indicates that digital tools benefit male and female learners equitably. This reinforces the idea that technology, when well-integrated, can act as a levelling tool, mitigating traditional achievement gaps. The United Nations Educational, Scientific and Cultural Organization (2022) has similarly argued that inclusive digital pedagogies reduce barriers to participation and improve outcomes for under-represented groups. Uko and Uko (2019) observed that technology-mediated communication platforms in Nigerian classrooms supported more equitable student participation, a finding consistent with this study's evidence of high mean and low variability in communication skills. By supporting balanced engagement across genders, technology demonstrates potential to bridge inequities, though systemic support remains necessary to sustain these gains.

Limitations of the Study

Despite the valuable contributions of this study, certain limitations must be acknowledged. The study was limited to a specific geographical area, Akwa Ibom State, and a relatively moderate sample size, which may restrict the generalisability of the findings. In addition, the use of self-reported instruments may introduce response bias. Furthermore, the quasi-experimental design, although appropriate, does not fully eliminate extraneous variables that could influence the outcomes.

Implications and Future Research

The findings of this study have important implications for teaching and learning in STEAM education. The significant impact of technology integration on the development of the Four C skills suggests that educators should adopt digitally supported pedagogies that promote critical thinking, creativity, communication, and collaboration. Additionally, the observed gender equity indicates that well-structured technology integration can bridge gender gaps in STEAM learning. Curriculum planners and policymakers should therefore emphasise inclusive digital practices and provide adequate training for teachers to effectively integrate technology into classroom instruction. Future studies should consider larger and more diverse samples across different regions to enhance generalisability. Longitudinal studies are also recommended to examine the sustained impact of technology integration on the Four C skills over time. Additionally, future research could explore specific digital tools or platforms to determine their differential effects on various components of STEAM learning. Investigating other moderating variables such as teacher competence, school resources, and socio-economic background would also provide deeper insights.

Conclusion

This study examined the influence of technology integration on the development of Four C skills and academic outcomes in STEAM education. The findings revealed that effective use of technology enhances critical thinking, creativity, communication, and collaboration while also promoting equitable learning outcomes across gender. The results further indicate that technology-supported pedagogy can significantly improve students' overall learning experiences. Despite these contributions, the study is limited by its sample size, geographical scope, and reliance on self-reported data. Future research should explore long-term effects and investigate specific digital tools to better understand their unique contributions to STEAM learning. In conclusion, technology integration presents significant opportunities for improving

ISSN: 2705-3830 (Print)
ISSN: 2705-3857 (Online)

21st-century skills; however, its effectiveness depends on strategic implementation. Educators should adopt inclusive and well-structured digital approaches to maximise its benefits in STEAM education.

Recommendations

1. Teachers should adopt gender-responsive pedagogies that foster equitable participation and skill development.
2. Professional development programmes must train teachers on strategies for embedding creativity, collaboration, and critical thinking in digital learning environments.
3. Policymakers should bridge the digital divide by ensuring equal access to resources for both male and female students.
4. STEAM curricula should embed innovative assessment tools such as adaptive testing and writing-to-learn strategies to sustain creativity and engagement.

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