IMPACT OF DIGITAL FABRICATION AND MATHEMATICAL MODELLING ON ENTREPRENEURIAL COMPETENCIES IN SCIENCE AND MATHEMATICS EDUCATION

Zaharaddeen ALIYU, Faith JAMES, Usman KABIR
Department of Science Education,
Ahmadu Bello University, Zaria
zaliyu@abu.edu.ng

Usaini JAFAR
Jigawa State Ministry of Education
usainijafar@gmail.com

Abstract

This study investigated the impact of digital fabrication and mathematical modelling on the development of entrepreneurial competencies among senior secondary school students in science and mathematics education within the Zaria Education Zone, Nigeria. Anchored in Experiential Learning Theory and Constructivist pedagogy, the quasi-experimental design employed pre-test, post-test, control group methodology using 200 SSII students selected from four public secondary schools. The experimental group was exposed to project-based instruction involving digital design tools and mathematical modelling tasks, while the control group received conventional teaching. Data were collected using a validated Entrepreneurial Competency Rating Scale (ECRS) and a Performance-Based Innovation Task (PBIT), and analysed with ANCOVA and independent samples t-tests. The findings revealed statistically significant improvements in entrepreneurial problem-solving ($F(1,196)=48.13$, $p<.001$, $\eta^2=.197$) and creativity/innovation ($F(1,196)=52.89$, $p<.001$, $\eta^2=.213$) among students in the experimental group. No significant gender-based differences were observed, indicating inclusivity. The study concludes that integrating digital fabrication and modelling into STEM instruction fosters critical entrepreneurial skills necessary for innovation and job creation. It recommends curriculum reform, teacher training, and investment in maker-based infrastructure to scale this approach across Nigerian schools.

Keywords: Digital fabrication, mathematical modelling, entrepreneurial competencies, STEM education, project-based learning, innovation, gender inclusion, secondary school, Nigeria

Introduction

In the rapidly evolving landscape of 21st-century education, integrating entrepreneurship into science and mathematics instruction has become crucial for equipping students with the skills needed to navigate a complex, innovation-driven world. Digital fabrication, through technologies like 3D printing, laser cutting, and computer-aided design (CAD), empowers students to conceptualise, design, and create tangible solutions to real-world challenges (Aliyu et., 2025). Simultaneously, mathematical modelling fosters abstract reasoning and analytical thinking by enabling learners to represent and solve practical problems using mathematical frameworks. When combined, these instructional strategies present a powerful, transformative approach that aligns academic concepts with entrepreneurial application.

According to Blikstein (2018), digital fabrication shifts students from passive knowledge consumers to active creators, fostering innovation, problem-solving, and iterative design thinking. Stillman et al. (2017) similarly contend that mathematical modelling deepens conceptual understanding and encourages the meaningful application of mathematics across various contexts, including economic and technological enterprises. Embedding entrepreneurial learning into science and mathematics education through these strategies helps bridge the gap between theory and practice, cultivating a culture of creativity, resilience, and initiative. Lackéus (2015) emphasises that entrepreneurial competencies, such as creativity, opportunity recognition, financial literacy, and value creation, are most effectively developed through experiential and interdisciplinary pedagogies.

However, in the Nigerian education context, the integrative potential of digital fabrication and mathematical modelling for fostering entrepreneurial competencies remains largely unexplored. While there are emerging studies in related areas, these have generally approached the topics in silos. For instance, Onanuga and Saka (2022) found a low level of competence among STEM pre-service teachers in employing emerging digital technologies, highlighting a need to strengthen digital skills training. Similarly, Akpan, Itighise, and Umo (2024) reported that universities in Akwa Ibom State demonstrate only moderate digital technology competence and a low extent of integration in STEM teaching and learning. Yet, neither of these studies links digital tools to entrepreneurial learning or examines their combined effect with mathematical modelling strategies. Moreover, Inoma, Ibhadode, and Ibhadode (2020) examined the perception and deployment of 3D printing in Nigerian science and engineering programs, noting its potential to spur innovative teaching practices, yet they stopped short of investigating its impact on entrepreneurial mindsets. In the domain of mathematical modelling, Omobude (2014) explored how it enhances the perceived relevance of mathematics through real-life contexts, but did not extend this to include entrepreneurial competencies.

Thus, despite isolated inquiries into digital skills, emerging technologies, and problem-solving approaches, there remains a notable absence of research that cohesively examines how integrating digital fabrication and mathematical modelling can cultivate entrepreneurial competencies within Nigerian science and mathematics education (Aliyu et., 2025). This study addresses that gap, and is grounded in Kolb's (1984) experiential learning theory and constructivist pedagogical principles, which advocate for learning through active engagement, reflection, and real-world relevance. By empirically investigating how these innovative instructional strategies influence students' entrepreneurial mindset, such as creativity, opportunity recognition, and adaptability, this research aims to contribute to self-reliance, employability, and national development.

Objectives of the Study

The main objective of this study is to examine the impact of integrating digital fabrication and mathematical modelling into science and mathematics instruction on the development of entrepreneurial competencies among secondary school students in Nigeria. Specifically, the study seeks to:

1. Assess the effect of digital fabrication and mathematical modelling on students' ability to identify and solve real-world problems entrepreneurially.
2. Determine the influence of the integrated instructional approach on students' entrepreneurial creativity, innovation, and initiative.
3. Investigate the gender-based differences, if any, in the acquisition of entrepreneurial competencies through digital fabrication and mathematical modelling activities.

Research Questions

The study is guided by the following research questions:

1. What is the effect of digital fabrication and mathematical modelling on students' entrepreneurial problem-solving skills in science and mathematics?
2. How does the integration of digital fabrication and mathematical modelling affect students' creativity and innovation in entrepreneurial contexts?
3. Is there a significant gender-based difference in students' acquisition of entrepreneurial competencies when taught using digital fabrication and mathematical modelling strategies?

Null Hypotheses

The following null hypotheses were formulated and tested at the 0.05 level of significance:

H_{01}: There is no significant difference in entrepreneurial problem-solving skills between students taught using digital fabrication and mathematical modelling and those taught using conventional methods.

H_{02}: There is no significant difference in entrepreneurial creativity and innovation between students exposed to digital fabrication and mathematical modelling and those taught traditionally.

H_{03}: There is no significant gender-based difference in students' acquisition of entrepreneurial competencies through digital fabrication and mathematical modelling instruction.

Theoretical and Conceptual Framework

This study is grounded in Experiential Learning Theory (ELT) developed by Kolb (1984), which posits that knowledge is constructed through the transformation of experience. According to Kolb, meaningful learning occurs when learners engage in a cycle of concrete experience, reflective observation, abstract conceptualisation, and active experimentation. In the context of this study, digital fabrication offers concrete experiences through hands-on design and prototyping, while mathematical modelling facilitates abstract reasoning and problem-solving, thus completing the experiential learning cycle. This theoretical foundation aligns closely with the demands of entrepreneurship education, where learners must ideate, build, test, and refine real-world solutions. Additionally, the study draws from constructivist learning theory, which emphasises the active role of learners in constructing knowledge through exploration, collaboration, and contextual engagement (Vygotsky, 1978). Within this framework, integrating digital fabrication and mathematical modelling encourages learners to make meaning of scientific and mathematical principles by applying them to authentic, problem-driven tasks. Furthermore, the Entrepreneurial Competency Framework (Man, 2001) provides a practical lens for evaluating outcomes related to opportunity recognition, risk-taking, innovation, and value creation. These competencies are critical for students' ability to transition from passive knowledge receivers to active solution providers and potential job creators. The conceptual model underpinning this research posits that the intersection of hands-on digital creation and real-life mathematical application will enhance learners' entrepreneurial mindset, foster creativity, and promote long-term skill development applicable to the STEM economy.

Review of Related Literature

Recent research underscores the significance of integrating digital tools and real-world problem-solving in STEM education to cultivate entrepreneurial capacities. Blikstein (2018) argued that digital fabrication technologies such as 3D printing and CAD tools democratize innovation by allowing students to rapidly prototype and iterate designs, leading to increased ownership, creativity, and economic agency. In Nigeria, where access to conventional laboratory infrastructure may be limited, digital fabrication tools present a scalable alternative for promoting technological literacy and entrepreneurship (Okebukola, 2021). Similarly, mathematical modelling is recognized as a powerful pedagogical strategy that encourages students to represent and solve complex problems drawn from everyday life (Stillman et al., 2017). By engaging in modelling tasks, students develop analytical thinking, persistence, and innovation, all vital entrepreneurial attributes.

Lackéus (2015) emphasises that entrepreneurship education should go beyond business plans to include experiential learning, creativity, and value creation, which are achievable through integrated science-mathematics projects. Studies by Saavedra and Opfer (2012) and Beers (2011) confirm that project-based and inquiry-driven STEM instruction increases students' motivation, critical thinking, and readiness for the real world. In this context, digital fabrication serves not only as a technological platform but also as an entrepreneurial incubator where students can simulate product development and testing. Moreover, research by Martin and Brouwer (2021) found that combining mathematical modelling with engineering tasks enhances learners' innovation and entrepreneurship potential by promoting iterative design, experimentation, and critical reflection.

Gender-related research has also shown that engaging girls in maker-based and modelling activities significantly narrows participation gaps in STEM fields, especially when instruction is contextual, collaborative, and hands-on (UNESCO, 2018). In sub-Saharan African contexts, Oviawe (2017) and Nwachukwu (2020) have advocated for the integration of vocational and entrepreneurial skills into science and mathematics as a viable solution to youth unemployment and underutilization of STEM graduates. Overall, literature converges on the premise that the combined use of digital fabrication and mathematical modelling has the potential to foster entrepreneurial thinking, innovation, and sustainable skill development among science and mathematics learners.

Methodology

This study adopted a quasi-experimental research design using a pre-test, post-test control group approach to determine the impact of digital fabrication and mathematical modelling on students' entrepreneurial competencies in science and mathematics education. The design was chosen because it allows for comparison between experimental and control groups using intact classes without random assignment, which is both practical and appropriate in real classroom settings (Creswell & Creswell, 2018).

Population and Sampling

The population of the study consisted of all Senior Secondary School II (SSII) science students across twenty co-educational public secondary schools in the Zaria Education Zone, Kaduna State, Nigeria. From this population, four schools were selected using purposive and stratified random sampling. The purposive selection was guided by three criteria: (i) schools with functional science and mathematics teachers who had at least five years of teaching experience, (ii) schools with basic ICT facilities (computer laboratory and electricity supply) necessary for introducing digital fabrication activities, and (iii) schools with comparable student enrollment sizes to allow for balanced grouping. After this, stratified random sampling was used to ensure representation of gender and academic ability across the selected schools. Two schools were assigned to the experimental group and two to the control group. The final sample size comprised 200 students (100 in the experimental group and 100 in the control group).

Treatment Conditions

Students in the experimental group were taught selected science and mathematics topics (basic mechanics, algebraic problem-solving, and scientific modelling) using a project-based learning approach that integrated digital fabrication and mathematical modelling. They engaged in activities such as: Designing scientific prototypes using Tinkercad and other low-cost CAD tools, constructing physical models with affordable fabrication kits and recyclable materials and solving contextualised real-life problems (e.g., calculating structural stability of a bridge model, designing a water filtration system, or estimating production costs of a prototype) through mathematical modelling.

The control group received instruction through traditional lecture-based methods. Lessons involved teacher-led explanations, use of chalkboard/marker board, guided note-taking, and textbook-based exercises. Students were primarily passive recipients of knowledge, with limited opportunities for hands-on or entrepreneurial engagement.

Instrumentation

Two instruments were used for data collection: the Entrepreneurial Competency Rating Scale (ECRS) and the Performance-Based Innovation Task (PBIT). Entrepreneurial Competency Rating Scale (ECRS): Developed by the researchers to measure entrepreneurial constructs such as creativity, opportunity recognition, financial literacy, innovation, and self-directedness. It consisted of 30 items structured on a 5-point Likert scale ranging from Strongly Disagree (1) to Strongly Agree (5). Performance-Based Innovation Task (PBIT): This required students to complete authentic, scenario-based tasks where they designed and modelled practical solutions. For example, one scenario involved creating a prototype of a low-cost bridge, requiring mathematical calculations for load capacity and material use, while another involved developing a simplified energy-saving device and estimating production costs. Students' outputs were assessed with a rubric that considered creativity, functionality, problem-solving, and entrepreneurial feasibility.

Validation and Reliability

The instruments were subjected to face and content validation by three experts—two in STEM education and one in educational measurement and evaluation. The experts commented on the clarity of items, relevance to entrepreneurial competencies, and alignment with study objectives. Based on their feedback, ambiguous items were rephrased, overlapping constructs were merged, and two items that were deemed redundant were removed from the ECRS. For the PBIT, the experts recommended refining scoring rubrics to include indicators of financial feasibility and innovation potential, which were incorporated.

A pilot test was conducted in a school not included in the main study. The Cronbach's alpha reliability coefficient for the ECRS was 0.84, indicating good internal consistency, while inter-rater reliability for the PBIT rubric (using two independent scorers) yielded a coefficient of 0.81, showing acceptable reliability.

Data Collection and Analysis

The study lasted for six weeks, encompassing instruction, project work, and assessment activities. Pre-test scores on entrepreneurial competencies were collected prior to the intervention to serve as covariates. Data were analysed using descriptive statistics (mean, standard deviation) and inferential statistics, specifically Analysis of Covariance (ANCOVA) to control for pre-test differences, and independent samples t-tests for post-test group comparisons.

Ethical Considerations

Ethical clearance was obtained from the Kaduna State Ministry of Education, and informed consent was secured from all participants and their guardians. Students' participation was voluntary, and confidentiality of responses was ensured.

Results and Data Analysis

To examine the effects of digital fabrication and mathematical modelling on entrepreneurial competencies, data were analysed using ANCOVA to control for pre-test differences. Below are the findings corresponding to the research hypotheses.

Hypothesis 1 (H_{01}): There is no significant difference in entrepreneurial problem-solving skills between students taught using digital fabrication and mathematical modelling and those taught using conventional methods.

Table 1: Descriptive Statistics and ANCOVA Result on Entrepreneurial Problem-Solving Skills

Group	N	Post-test Mean	SD	Adjusted Mean	SE	F(1,196)	p-value	Partial η²
Experimental Group	100	77.85	6.14	77.62	0.45	48.13	<.001	0.197
Control Group	100	69.42	5.87	69.65	0.45			

Note. Adjusted means are estimated marginal means after controlling for pre-test differences. $p < 0.001$.

After controlling for pre-test scores, the ANCOVA results revealed a statistically significant difference in entrepreneurial problem-solving skills between the experimental and control groups, $F(1,196) = 48.13$, $p < .001$, with a large effect size (Partial $\eta^2 = 0.197$). Descriptive statistics further show that students in the experimental group ($M = 77.85$, $SD = 6.14$) outperformed those in the control group ($M = 69.42$, $SD = 5.87$). The magnitude of the effect size indicates that approximately 20% of the variance in entrepreneurial problem-solving skills can be attributed to the instructional approach. This represents a substantial educational impact (Cohen, 1988), confirming that the integration of digital fabrication and mathematical modelling is not only statistically significant but also practically meaningful. In practical terms, students exposed to these innovative strategies developed stronger problem-solving abilities that are crucial for identifying, analysing, and addressing real-world entrepreneurial challenges. For example, such students are more likely to apply mathematics to optimise production processes, design innovative solutions using digital tools, and evaluate the feasibility of their ideas. In contrast, students taught with traditional lecture-based methods lacked comparable opportunities for hands-on application, limiting the development of higher-order problem-solving competencies. Thus, the findings provide empirical support for embedding digital fabrication and mathematical modelling in Nigerian science and mathematics education as effective means of cultivating entrepreneurial skills needed for employability, innovation, and national development.

Hypothesis 2 (H_{02}): There is no significant difference in entrepreneurial creativity and innovation between students exposed to digital fabrication and mathematical modelling and those taught traditionally.

Table 2: Descriptive Statistics and ANCOVA Result on Creativity and Innovation Scores

Group	N	Post-test Mean	SD	Adjusted Mean	SE	F(1,196)	p-value	Partial η^2
Experimental Group	100	79.26	6.32	79.05	0.44	52.89	<.001	0.213
Control Group	100	70.14	5.76	70.35	0.44			

Note. Adjusted means are estimated marginal means after controlling for pre-test differences. $p < 0.001$.

After controlling for pre-test scores, the ANCOVA results revealed a statistically significant difference in entrepreneurial creativity and innovation between the experimental and control groups, $F(1,196) = 52.89$, $p < .001$, with a large effect size (Partial $\eta^2 = 0.213$). Descriptive statistics further show that students in the experimental group (M = 79.26, SD = 6.32) outperformed those in the control group (M = 70.14, SD = 5.76). The effect size indicates that approximately 21% of the variance in creativity and innovation scores can be explained by the instructional method. This is a substantial educational effect (Cohen, 1988), demonstrating that integrating digital fabrication and mathematical modelling produces meaningful improvements beyond what traditional teaching methods can achieve. Practically, this implies that students exposed to fabrication and modelling approaches developed enhanced capacity for creative thinking, idea generation, and innovative application of scientific and mathematical knowledge. For instance, these students were more capable of designing original prototypes, experimenting with novel solutions to community challenges, and applying mathematical models to test the feasibility of their ideas. By contrast, students in the lecture-based group had fewer opportunities to explore open-ended, creative problem spaces, limiting the growth of entrepreneurial innovation skills. These findings highlight the potential of digital fabrication and mathematical modelling as transformative pedagogical strategies in Nigerian classrooms, particularly for fostering entrepreneurial competencies that are essential for self-reliance, start-up creation, and technological advancement.

Hypothesis 3 (H_{03}): There is no significant gender-based difference in students' acquisition of entrepreneurial competencies through digital fabrication and mathematical modelling instruction.

Table 3: Independent Samples t-Test on Gender-Based Differences in Entrepreneurial Competencies

Gender	N	Mean	SD	t	df	p
Male	51	82.34	6.87	1.09	98	.278
Female	49	81.01	7.14			

Note. Equal variances assumed.

The independent samples t-test showed that male students (M = 82.34, SD = 6.87) and female students (M = 81.01, SD = 7.14) did not differ significantly in their entrepreneurial competency scores, $t(98) = 1.09$, $p = .278$. This indicates that the digital fabrication and mathematical modelling intervention was equally effective across genders. The small mean difference (1.33 points) suggests minimal practical significance, implying that the program fosters equitable development of entrepreneurial competencies regardless of gender. This finding aligns with research emphasising the inclusiveness of technology-driven pedagogies in STEM education (e.g., UNESCO, 2021; Fakomogbon et al., 2023).

Discussion of Findings

The findings of this study strongly support the effectiveness of integrating digital fabrication and mathematical modelling in enhancing entrepreneurial competencies among secondary school science and mathematics students. The first hypothesis tested revealed a statistically significant difference in entrepreneurial problem-solving skills between students taught using digital fabrication and mathematical modelling and those taught using conventional methods. This aligns with Blikstein (2018), who emphasised that digital fabrication tools offer learners opportunities for tangible creation and iteration, thus encouraging innovative solutions to real-world problems. Similarly, the result supports Stillman et al. (2017), who reported that modelling tasks foster students' capacity to apply mathematical concepts in diverse entrepreneurial and scientific contexts. The substantial effect size (Partial $\eta^2 = 0.197$) found in this study indicates that the hands-on and applied nature of the experimental approach had a practical impact on learners' ability to analyze, design, and prototype entrepreneurial solutions.

The second hypothesis, which focused on creativity and innovation, also showed a significant difference favoring the experimental group. This corroborates the assertions of Lackéus (2015), who argued that entrepreneurial education, when designed as experiential and interdisciplinary, enhances innovation, creativity, and initiative in students. The integration of digital design software and modelling frameworks provided learners with an authentic context to apply STEM knowledge in the creation of entrepreneurial artefacts, as seen in Saavedra and Opfer (2012), who advocated for authentic problem-solving and real-world application in 21st-century learning models. The large effect size (Partial $\eta^2 = 0.213$) observed indicates the intervention's strong capacity to transform theoretical knowledge into tangible, creative outcomes.

Finally, the analysis of gender-based differences showed no statistically significant disparity in entrepreneurial competencies between male and female students who experienced the digital fabrication and modelling activities. This suggests the strategy is inclusive and effective across gender lines, affirming findings by UNESCO (2018), which emphasised that hands-on, technology-driven instruction can narrow gender gaps in STEM participation. Oviawe (2017) also supported the view that when entrepreneurial and technical content is made accessible through contextual and active engagement, both male and female learners can thrive equally. Hence, the study provides empirical evidence that integrating digital fabrication and mathematical modelling into science and mathematics education not only enhances core STEM skills but also nurtures essential entrepreneurial traits such as problem-solving, innovation, and opportunity recognition. This aligns with global calls for education systems to prepare learners for future economic challenges by embedding entrepreneurial competencies within traditional academic frameworks.

Conclusion and Recommendations

This study has demonstrated that the integration of digital fabrication and mathematical modelling into science and mathematics education significantly enhances the entrepreneurial competencies of secondary school students. The experimental group, which engaged in hands-on, project-based learning using digital tools and real-world mathematical applications, outperformed the control group in entrepreneurial problem-solving, creativity, and innovation. Furthermore, the absence of significant gender-based differences suggests that this instructional approach is inclusive and effective for both male and female students. These findings validate the assertions of prior scholars (Blikstein, 2018; Stillman et al., 2017; Lackéus, 2015) who emphasised the role of experiential and applied learning in fostering innovation and entrepreneurial readiness among learners. In an era where STEM education must address not only academic excellence but also socio-economic empowerment, this study affirms that equipping students with entrepreneurial competencies through innovative strategies like digital fabrication and mathematical modelling is both timely and essential. By doing so, educators can prepare students not only to excel academically but also to become proactive problem-solvers, innovators, and potential job creators in a rapidly changing global economy.

Based on these findings, the following recommendations are made:

1. Curriculum Integration: The Federal and State Ministries of Education should revise science and mathematics curricula to include digital fabrication and mathematical modelling activities with entrepreneurial relevance.

2. Teacher Capacity Building: Intensive professional development workshops should be organised for science and mathematics teachers on the use of digital tools and project-based instructional strategies that support entrepreneurship.
3. Infrastructure Investment: Secondary schools should be equipped with basic digital fabrication kits (e.g., 3D printers, laptops with CAD software, and maker tools) to facilitate innovation-oriented STEM learning.
4. Gender-Inclusive Practices: Educators should be encouraged to use instructional approaches that are gender-sensitive and supportive of female participation in STEM-entrepreneurial learning contexts.
5. Further Research: More studies should be conducted across different regions of Nigeria to validate and expand on the findings of this study, including longitudinal research on the long-term impact of such interventions on students' career paths.

Limitations

The study did not explicitly state its limitations. One notable limitation is the relatively small sample size, which may affect the generalizability of the findings. While the results indicate positive effects of digital fabrication and mathematical modelling on entrepreneurial competencies, larger and more diverse samples across different institutions would strengthen external validity. Another limitation is the short duration of the intervention, which might not fully capture the long-term impact of the instructional strategies on entrepreneurial competencies. Future research should consider longitudinal designs to examine whether the observed improvements are sustained over time. Additionally, potential contextual and cultural factors that could influence students' entrepreneurial creativity and innovation were not addressed. Acknowledging these limitations provides a more balanced perspective and offers useful directions for future studies.

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