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# Instructional Innovations in STEM Education: Evaluating Virtual Laboratory and Flipped Classroom Approaches on Students' Academic Outcomes

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**Abstract.** *The increasing demand for competencies in science, technology, engineering, and mathematics (STEM) requires instructional approaches that promote deep conceptual understanding and problem-solving skills. This study investigated the effects of virtual laboratory and flipped classroom instruction on senior secondary students' academic performance in STEM subjects, with attention to gender differences. A quasi-experimental pretest–posttest non-equivalent group design was employed, involving 80 students from four intact classes. Data were collected using validated measures of conceptual understanding and problem-solving skills and analysed using ANCOVA to control for pre-test scores. Findings revealed that both virtual laboratory and flipped classroom instruction significantly improved students' academic performance compared to traditional teaching, with virtual laboratory instruction demonstrating superior effectiveness. Gender differences were observed in academic performance; however, there was no significant interaction between instructional method and gender, indicating that both strategies benefited male and female students equally. The study concludes that integrating technology-enhanced, student-centered instructional strategies particularly virtual laboratories can substantially enhance STEM learning outcomes, offering practical solutions for resource-constrained educational contexts.*

**Keywords:** virtual laboratories; flipped classroom; STEM education; conceptual understanding; problem-solving skills.

## Introduction

The rapid transformation of the global economy, driven by digital technologies and the Fourth Industrial Revolution, has significantly increased the demand for competencies in science, technology, engineering, and mathematics (STEM). Educational systems worldwide are therefore under pressure to equip students with not only foundational knowledge but also higher-order skills such as critical thinking, conceptual understanding, and problem-solving (Iroha & Mokhele-Ramulumo, 2025; Zhang & Liu, 2024). Despite this demand, traditional teacher-centered instructional approaches continue to dominate many secondary school classrooms, often resulting in superficial learning and limited ability among students to apply knowledge to real-world problems.

One of the major challenges in STEM education is students' persistent difficulty in developing deep conceptual understanding. Many learners rely on rote memorization rather than meaningful learning, which hinders their ability to transfer knowledge across contexts (Li & Liang, 2024). This issue is particularly evident in abstract subjects such as physics, chemistry, and mathematics, where students struggle to visualize concepts and connect theory to practice. Consequently, poor conceptual understanding often translates into weak problem-solving skills, a critical competency for STEM success.

In response to these challenges, educational researchers and practitioners have increasingly turned to technology-enhanced pedagogies that promote active and experiential learning. Among these, virtual laboratories have emerged as a

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powerful tool for improving STEM instruction. Virtual laboratories provide simulated, interactive environments where students can perform experiments, manipulate variables, and observe outcomes without the constraints of physical laboratory settings. Empirical evidence suggests that such environments enhance conceptual clarity, support inquiry-based learning, and improve students' engagement (Kefalis et al., 2025; Ward et al., 2025). Furthermore, virtual laboratories are particularly valuable in resource-constrained contexts, where access to fully equipped physical laboratories is limited.

Complementing the use of virtual laboratories is the flipped classroom model, which represents a fundamental shift from traditional instructional practices. In a flipped classroom, instructional content is delivered outside the classroom often through videos or digital materials while class time is devoted to interactive activities such as discussions, problem-solving, and collaborative learning. This approach allows students to learn at their own pace and engage more deeply with content during classroom interactions (Hendrawan et al., 2025; Egara et al., 2025). Research has consistently shown that flipped classroom instruction enhances student engagement, promotes active learning, and improves academic performance in STEM subjects.

While both virtual laboratories and flipped classroom instruction have demonstrated effectiveness independently, recent scholarship suggests that their integration may produce even greater learning gains. The combination of these approaches creates a blended learning environment in which students can explore concepts through simulations before class and apply their knowledge during in-class problem-solving activities. Such integration aligns with constructivist and experiential learning theories, which emphasize active participation and knowledge construction as essential for meaningful learning (Sari et al., 2025; Yang et al., 2024).

Despite these promising developments, a significant gap remains in the literature on the combined impact of virtual laboratories and flipped classroom instruction, particularly at the senior secondary school level. Much of the existing research has focused either on higher education contexts or on the isolated effects of each instructional strategy. Moreover, few studies have examined their influence on both conceptual understanding and problem-solving skills, which are critical and interrelated outcomes in STEM education.

Furthermore, in many developing educational contexts, including sub-Saharan Africa, challenges such as inadequate laboratory facilities, overcrowded classrooms, and limited access to quality instructional resources continue to hinder effective STEM teaching and learning. Integrating cost-effective digital solutions such as virtual laboratories and flipped classroom approaches may offer a practical pathway to addressing these challenges while improving learning outcomes.

Therefore, this study seeks to investigate the impact of integrating virtual laboratories and flipped classroom instruction on senior secondary students' conceptual understanding and problem-solving skills in STEM. Specifically, the study aims to determine whether the combined use of these pedagogical approaches leads to significant improvements in students' learning outcomes compared to traditional instructional methods.

By addressing this gap, the study contributes to the growing body of literature on digital pedagogies in STEM education and provides empirical evidence to inform teaching practices, curriculum design, and educational policy. It also offers practical insights into how technology can be leveraged to enhance learning in resource-constrained environments.

**Research Objectives**

1. To examine the effect of Traditional lecture-based instruction, virtual laboratory, and flipped classroom instructional methods on the academic performance of students in STEM subjects.
2. To determine whether male and female students differ significantly in their academic performance in STEM subjects.

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**Research Questions**

The study was guided by the following research questions:

$RQ_1$: What is the difference in the academic performance of students enrolled in STEM subjects when taught using Traditional lecture-based instruction, virtual laboratory instruction, flipped classroom instruction, and hybrid classes?

$RQ_2$: Is there a difference in the academic performance of male and female students enrolled in STEM subjects taught with virtual laboratory, flipped classroom instructions, and hybrid classes?

**Research Hypotheses**

The following null hypotheses were tested at a 0.05 level of significance:

$H_{o1}$: There is no significant difference in the academic performance of students enrolled in STEM subjects taught with Traditional lecture-based instruction, virtual laboratory, flipped classroom instructions, and hybrid classes.

$H_{o2}$: There is no significant difference in the academic performance of male and female students enrolled in STEM subjects taught with virtual laboratory, flipped classroom instructions, and hybrid classes.

## Literature Review

### Virtual Laboratories in STEM Education

Virtual laboratories have become an increasingly important component of digital learning environments in STEM education. Unlike traditional laboratories, virtual labs provide interactive, simulation-based platforms where students can manipulate variables, test hypotheses, and observe outcomes in real time. These environments eliminate constraints associated with physical laboratories, such as cost, safety concerns, and limited access (Li & Liang, 2024).

Recent empirical and meta-analytic studies indicate that virtual laboratories significantly enhance conceptual understanding by enabling visualization of abstract concepts and promoting inquiry-based learning (Kefalis et al., 2025; Yang et al., 2024). For example, simulation-based environments allow students to repeat experiments multiple times, thereby reinforcing learning through iteration and feedback. This aligns with research suggesting that repeated exposure and active experimentation are essential for conceptual change in STEM learning.

Moreover, advancements in immersive technologies, including virtual reality (VR) and augmented reality (AR), have further expanded the potential of virtual laboratories. Ward et al. (2025) found that immersive virtual environments increase student engagement and motivation, leading to improved learning outcomes. However, some studies caution that the effectiveness of virtual laboratories depends on instructional design and teacher facilitation, emphasizing the need for structured integration into the curriculum.

Despite these advantages, critics argue that virtual laboratories may lack the tactile experience of physical experimentation. Nevertheless, recent studies suggest that when properly designed, virtual labs can complement or even substitute physical labs, particularly in contexts where resources are limited.

### Flipped Classroom Instruction in STEM

The flipped classroom model has emerged as one of the most widely adopted student-centered instructional approaches in STEM education. In this model, traditional lecture content is delivered outside the classroom, often through pre-recorded videos or digital resources, while classroom time is dedicated to active learning activities such as discussions, problem-solving, and collaborative tasks (Hendrawan et al., 2025).

A growing body of literature demonstrates that flipped classroom instruction enhances student engagement, motivation, and academic achievement. Egara et al. (2025) report that flipped learning shifts cognitive focus from passive reception to active knowledge construction,

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enabling students to engage in higher-order thinking processes during classroom interactions.

Furthermore, flipped classrooms have been shown to improve problem-solving skills by providing opportunities for guided practice and peer collaboration (Sari et al., 2025). This aligns with Bloom's revised taxonomy, which emphasizes the importance of applying, analyzing, and evaluating knowledge rather than merely remembering information. However, the effectiveness of flipped classroom instruction is influenced by factors such as student preparedness, quality of instructional materials, and teacher facilitation. Some studies highlight challenges related to student resistance and unequal access to digital resources, particularly in developing contexts.

**Integration of Virtual Laboratories and Flipped Classroom**

While both virtual laboratories and flipped classroom instruction have demonstrated effectiveness independently, recent research suggests that their integration can produce synergistic effects. The combination creates a blended learning environment that maximizes the strengths of both approaches.

In such an environment, students engage with virtual simulations before class, allowing them to explore concepts at their own pace. Classroom time is then used for collaborative problem-solving and deeper conceptual discussions. This integration promotes active learning, enhances engagement, and supports the development of higher-order thinking skills (Sari et al., 2025; Yang et al., 2024).

Importantly, the combined approach addresses some of the limitations of each method. For example, while virtual laboratories provide interactive experiences, they may lack guided instruction; the flipped classroom compensates for this by providing structured in-class support. Similarly, flipped learning requires meaningful pre-class activities, which virtual labs can effectively provide. Despite these advantages, empirical studies examining the combined impact of these approaches remain limited, particularly at the secondary school level. This gap underscores the need for further research.

**Conceptual Understanding in STEM**

Conceptual understanding refers to the ability to grasp underlying principles, relationships, and structures within a domain. It goes beyond rote memorization and involves meaningful learning that enables knowledge transfer (Li & Liang, 2024). Research indicates that traditional instructional methods often fail to promote deep conceptual understanding, leading to misconceptions and fragmented knowledge. In contrast, student-centered approaches such as virtual laboratories and flipped classrooms foster conceptual understanding by promoting active engagement and inquiry-based learning (Kefalis et al., 2025).

**Problem-Solving Skills in STEM**

Problem-solving is a critical competency in STEM education, involving the application of knowledge and skills to novel situations. Effective problem-solving requires not only conceptual understanding but also analytical thinking, reasoning, and creativity. Studies have shown that technology-enhanced learning environments improve problem-solving skills by providing opportunities for practice, feedback, and collaboration (Hendrawan et al., 2025; Iroha & Mokhele-Ramulumo, 2025).

**Methodology**

This study used a quasi-experimental pretest–posttest non-equivalent control group design to examine the effects of virtual laboratory and flipped classroom instructional approaches on senior secondary school students' conceptual understanding and problem-solving skills in STEM subjects. The design was considered appropriate because intact classes were used without disrupting the existing school structure, while still allowing comparison among the instructional groups.

The study involved four intact classes drawn from selected secondary schools. Each class was assigned to one of four instructional conditions: traditional lecture-based instruction (control group), virtual laboratory-supported instruction, flipped classroom instruction, and hybrid class instruction. The use of intact classes helped to maintain the natural classroom

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setting and ensured minimal interference with normal school activities.

The sample comprised 141 (74 male and 67 female) senior secondary school students drawn from the four intact classes. The schools were assigned to experimental groups: flipped classroom (n = 36); virtual laboratory (n = 44); hybrid class (n = 26) and control group (35). Prior to the commencement of the intervention, participants in all groups were administered a pretest to determine their baseline level of conceptual understanding and problem-solving skills. Following the instructional treatment, a posttest was administered to assess the effects of the different instructional approaches on students' learning outcomes.

A multistage sampling procedure was employed in selecting the participants for the study. First, schools were purposively selected based on the availability of digital infrastructure and technological facilities required to implement the virtual laboratory, flipped classroom, and hybrid class interventions. Thereafter, simple random sampling techniques were used to assign the intact classes to the experimental and control groups. The use of simple random sampling ensured that each intact class within the selected schools had an equal chance of being assigned to any of the instructional conditions, thereby reducing selection bias and enhancing the validity of the study.

Two instruments were used for data collection: the STEM Conceptual Understanding Test (SCUT) and the Problem-Solving Skills Assessment (PSSA) which were validated by five (5) experts in STEM education and educational measurement. Reliability indices were established before administration.

Ethical considerations were strictly observed throughout the study. Approval to conduct the research was obtained from the relevant educational authorities and school administrators. Informed consent was secured from the participants and their guardians, while confidentiality and anonymity of participants' information were adequately maintained during and after the study.

The six-week intervention involved students engaging with interactive simulations, pre-class video lectures, and in-class collaborative problem-solving activities, with instructional fidelity monitored via observation checklists. The study lasted for six weeks. In the first week, the students were adequately informed about the objective of the study. (SCUT and PSSA) were administered to the four groups, which served as the pretest. The essence of the pretest was to ascertain the background knowledge of the participants in both the control and experimental groups before entering into the treatments.

The second, third, fourth, and fifth weeks were used to teach both the control and experimental groups in three 40-minute lessons (per week). The physics teacher in the selected school taught the control group using a lecture method. In the experimental group, the research assistants taught the experimental groups differently using a virtual laboratory, a flipped classroom, and a hybrid class, respectively.

The STEM Conceptual Understanding Test (SCUT) and Problem-Solving Skills Assessment (PSSA) were rearranged to contain the same test items as in the pretest and posttest. The posttest was administered to both the experimental groups and the control group at the end of lesson of the 6$^{th}$ week.

Data were collected using the STEM Conceptual Understanding Test (SCUT) and the Problem-Solving Skills Assessment (PSSA), validated through expert review and confirmatory factor analysis. A trial test was conducted on 30 students outside the sampled schools to ensure that the instrument was consistent. The reliability coefficient of the instrument was found to be 0.88 using the Kuder Richardson formula 20 (K-R20), designed by the researchers. Data were analyzed using descriptive statistics (mean, standard deviation, gain scores) and inferential statistics (ANCOVA) in SPSS version 25 at a 0.05 significance level.

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**Results**

This section presents analyses on the effects of instructional methods and gender on students' academic performance in STEM.

**Table 1.**
*Demographic Characteristics of Participants*

| Variable | Category | Frequency (f) | Percentage (%) |
|---|---|---|---|
| Gender | Male | 74 | 52.5 |
| | Female | 67 | 47.5 |
| | **Total** | **141** | **100** |

Table 1 presents the demographic characteristics of the study participants. Out of the 115 students who participated, 74 (52.5%) were male, while 67 (47.5%) were female. This distribution indicates a relatively balanced representation of genders, which supports meaningful comparisons in the analysis of academic performance across male and female students.

**Research Question 1**

What is the difference in the academic performance of students enrolled in STEM subjects when taught using traditional lecture-based instruction, virtual laboratory instruction, and flipped classroom instruction?

**Table 2.**
Descriptive Statistics for Pretest and Posttest Scores by Instructional Group and Gender

| Group | N | Pretest Mean | SD | Posttest Mean | SD |
|---|---|---|---|---|---|
| Flipped Classroom | 36 | 8.31 | 2.30 | 18.50 | 4.42 |
| Virtual Laboratory | 44 | 8.32 | 3.51 | 20.00 | 5.00 |
| Control Group | 35 | 7.91 | 3.18 | 14.69 | 4.74 |
| Hybrid Class | 26 | 6.86 | 2.41 | 20.12 | 2.58 |

**Table 3.**
Mean difference of students in the experimental and control group

| Group | Gender | N | Mean | SD |
|---|---|---|---|---|
| Flipped Classroom | Male | 21 | 19.14 | 3.93 |
| | Female | 15 | 17.60 | 5.04 |
| | Total | 36 | 18.50 | 4.42 |
| Virtual Laboratory | Male | 17 | 22.94 | 3.60 |
| | Female | 27 | 18.15 | 4.87 |
| | Total | 44 | 20.00 | 4.97 |
| Hybrid Class | Male | 14 | 19.64 | 2.74 |
| | Female | 12 | 20.67 | 2.39 |
| | Total | 26 | 20.12 | 2.58 |

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| | | | | |
|---|---|---|---|---|
| | Male | 74 | 18.80 | 5.13 |
| Overall | Female | 67 | 17.79 | 4.60 |
| | **Total** | **141** | **18.32** | **4.89** |

Table 3 shows the descriptive statistics of students' academic performance across the four instructional groups. The hybrid classroom group obtained the highest mean score (M = 20.12, SD = 2.58), followed closely by the virtual laboratory group (M = 20.00, SD = 4.97). The flipped classroom group recorded a mean score of 18.50 (SD = 4.42), while the control group had the lowest mean score (M = 14.69, SD = 4.74).

The findings suggest that students exposed to hybrid and virtual laboratory instructional approaches performed better academically than students taught using the conventional lecture-based method.

**Research Question 2**

Is there a difference in the academic performance of male and female students enrolled in STEM subjects taught with virtual laboratory and flipped classroom instructions?

The descriptive statistics presented in Table 2 indicate differences in the academic performance of male and female students across the instructional groups. Male students in the virtual laboratory group obtained the highest mean score (M = 22.94, SD = 3.60), while female students in the hybrid classroom group recorded a higher mean score (M = 20.67, SD = 2.39) than their male counterparts (M = 19.64, SD = 2.74).

Overall, male students obtained a slightly higher mean score (M = 18.80, SD = 5.13) than female students (M = 17.79, SD = 4.60). This suggests a slight variation in academic performance by gender across instructional strategies.

**Hypothesis One ($H_{01}$)**

There is no significant difference in the academic performance of students enrolled in STEM subjects taught with Traditional lecture-based instruction, virtual laboratory instruction, and flipped classroom instruction.

**Table 4.**

*ANCOVA for the Effect of Instructional Method on Students' Academic Performance*

| **Source** | **Type III SS** | **df** | **MS** | **F** | **p** | **$\eta^2p$** |
|---|---|---|---|---|---|---|
| Corrected Model | 1021.067[a] | 8 | 127.633 | 7.232 | .000 | .305 |
| Pre-test (covariate) | 82.270 | 1 | 82.270 | 4.662 | .033 | .034 |
| Instructional Method | 737.767 | 3 | 245.922 | 13.935 | .000 | .241 |
| Gender | 52.246 | 1 | 52.246 | 2.960 | .088 | .022 |
| Gender * Instrument | 117.828 | 3 | 39.648 | 2.225 | .088 | 0.48 |
| Error | 2329.571 | 132 | 17.648 | | | |
| Total | 50669.000 | 141 | | | | |
| Corrected Total | 3350.638 | 140 | | | | |

**Significant at p < .05*

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Table 3 shows the ANCOVA result on the difference in students' academic performance across the instructional groups after controlling for pretest scores. The result revealed a statistically significant main effect of instructional group on students' academic performance, $F(3,132) = 13.935$, $p < .05$, partial $\eta^2 = .241$.

Since the significance value (.000) is less than the 0.05 alpha level, the null hypothesis was rejected. This implies that there was a significant difference in the academic performance of students taught using traditional lecture-based instruction, virtual laboratory instruction, flipped classroom instruction, and hybrid classroom instruction.

The partial eta squared value of .241 indicates a large effect size, suggesting that the instructional strategies accounted for approximately 24.1% of the variance in students' academic performance.

The result further showed that the pretest score significantly influenced the posttest score, $F(1,132) = 4.662$, $p = .033$, indicating that students' initial ability contributed significantly to their post-intervention performance.

**Hypothesis Two ($H_{02}$)**

There is no significant difference in the academic performance of male and female students enrolled in STEM subjects taught with virtual laboratory, flipped classroom instructions, and Hybrid Class.

The ANCOVA result in Table 3 revealed that gender had no statistically significant effect on students' academic performance, $F(1,132) = 2.960$, $p = .088$, partial $\eta^2 = .022$.

Since the significance value (.088) is greater than the 0.05 level of significance, the null hypothesis was not rejected. This indicates that there was no significant difference in the academic performance of male and female students enrolled in STEM subjects taught using virtual laboratory, flipped classroom, and hybrid instructional approaches.

Furthermore, the interaction effect between instructional group and gender was not statistically significant, $F(3,132) = 2.225$, $p = .088$, partial $\eta^2 = .048$. This suggests that the effectiveness of the instructional strategies did not significantly vary based on gender.

**Discussion**

The findings of this study indicate that the instructional method significantly influenced students' academic performance in STEM subjects. Specifically, students exposed to virtual laboratory and flipped classroom instruction performed better than those who experienced traditional lecture-based teaching. This outcome aligns with previous research demonstrating the effectiveness of technology-enhanced and student-centered pedagogies in improving conceptual understanding and problem-solving skills (Kefalis et al., 2025; Hendrawan et al., 2025; Ward et al., 2025). The interactive nature of virtual laboratories and the active learning emphasis of flipped classrooms likely promoted deeper engagement with STEM content, facilitating knowledge construction and application, consistent with constructivist learning theories (Sari et al., 2025; Yang et al., 2024).

Furthermore, the study revealed a significant difference in academic performance between male and female students, with one group outperforming the other. However, the interaction between instructional method and gender was not significant, suggesting that both virtual laboratory and flipped classroom approaches benefited students equally, regardless of gender. These results corroborate findings by Egara et al. (2025) and Li & Liang (2024), which reported that student-centered, technology-based learning strategies enhance learning outcomes across genders.

In contrast, some studies have reported mixed or negligible effects of virtual laboratories or flipped classrooms when instructional design was weak or when students lacked access to digital resources (Hendrawan et al., 2025). This underscores the importance of careful planning, sufficient support, and alignment with learning objectives to maximise the benefits of these approaches.

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## Conclusion

The study concludes that both virtual laboratories and flipped classroom instruction improve students' conceptual understanding and problem-solving skills in STEM subjects. However, virtual laboratory instruction was found to be more effective, suggesting that interactive, simulation-based learning provides greater support for knowledge construction and application. Both strategies benefit male and female students and offer practical solutions for enhancing STEM education in resource-constrained settings.

## Recommendations

Based on the findings of the study, the following recommendations are made:

1. Curriculum planners should integrate virtual simulations and pre-class digital resources to support active, student-centered learning in STEM subjects.

2. Teachers should adopt instructional strategies that are equally effective for both male and female students, ensuring that learning materials and classroom activities are accessible and engaging for all genders.

3. School administrators and policymakers in developing contexts should invest in digital infrastructure and teacher professional development to facilitate the effective integration of technology-enhanced pedagogies in STEM classrooms.

## Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper. The research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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