EFFECTIVENESS OF ARTIFICIAL INTELLIGENCE-BASED VIRTUAL LABORATORIES ON SENIOR SECONDARY SCHOOL STUDENTS' BIOLOGY PRACTICAL SKILLS IN ABAKALIKI EDUCATION ZONE

Chinyere Genevieve ATTAMAH (Ph.D)[1*]; Chisom Precious ANYIGOR[2], & Hyacinth Ochenehi AKOGWU[3]

[1]Department of Science Laboratory Technology, Federal Polytechnic Ohodo, Enugu State, Nigeria (FEDPOD)

[2]Department of Science Education, Alex Ekweme Federal University Ndufu-Alike, Ebonyi State, Nigeria.

[*] Corresponding Author: Chinyereatama@gmail.com, 07064548077

Abstract

This study investigated the effectiveness of Artificial Intelligence-Based Virtual Laboratories on Senior Secondary School students' Biology practical skills in Abakaliki Education Zone, Ebonyi State, Nigeria. Two research questions and three hypotheses guided the study. The study adopted a quasi-experimental research design, specifically the non-equivalent control group pre-test post-test design. A sample of 175 Senior Secondary II students was selected through purposive sampling. Abakaliki Local Government Area was sampled out of the four Local Government Areas in Abakaliki Education Zone, and two public secondary schools were selected. Intact classes were used, with 96 students assigned to the experimental group and 79 students to the control group. The Biology Practical Skills Inventory (BPSI), a 20-item performance-based instrument rated on a 5-point scale with a maximum score of 100, was used for data collection. The instrument was validated by three experts in Biology Education and Measurement and Evaluation, and its reliability was established using Cronbach's Alpha, yielding a coefficient of 0.87. The experimental group was taught using Artificial Intelligence-Based Virtual Laboratories, while the control group received instruction using the Conventional Laboratory Method. Research questions were answered using mean and standard deviation, while Analysis of Covariance (ANCOVA) was used to test the null hypotheses at 0.05 level of significance. The findings revealed that students exposed to Artificial Intelligence-Based Virtual Laboratories significantly outperformed those taught using the conventional method in Biology practical skills. The study also found no significant gender difference and no significant interaction effect between teaching method and gender. Based on the findings, the study recommended that Biology teachers, school administrators, and educational policymakers should integrate AI-based virtual laboratory tools into secondary school instruction to enhance students' practical competence in Biology.

Keywords: Artificial Intelligence, Virtual Laboratories, Biology Practical Skills, Secondary School Students, Gender.

Introduction

Science education, particularly Biology, plays a pivotal role in developing students' understanding of living systems, scientific inquiry, and problem-solving skills essential for national development (Akyüz & Samsa, 2021). Biology practical activities provide students with

opportunities to observe biological phenomena, manipulate instruments, conduct experiments, and interpret data — experiences that are foundational to scientific literacy (Okeke & Eze, 2023). However, many secondary schools in Nigeria, especially within rural and semi-urban contexts, face persistent challenges in executing effective Biology practical lessons due to inadequate laboratory infrastructure, insufficient teaching resources, and large class sizes (Oladimeji & Yusuf, 2022; Ugwoke et al., 2024).

The inadequacy of laboratory facilities and limited hands-on practice have significant implications for students' practical competence, leading to poor acquisition of essential science process skills such as observation, experimentation, and analytical reasoning (Nwankwo & Iheanacho, 2023). Research indicates that constrained practical opportunities contribute to students' low achievement in Biology and undermine their interest in science careers (Chukwu et al., 2024). Consequently, educators and policymakers have advocated for the integration of innovative instructional technologies that can supplement traditional laboratory experiences and improve students' practical learning outcomes (Mustapha & Bello, 2025).

Artificial Intelligence (AI) has emerged as a transformative force in education, enabling adaptive, personalized, and interactive learning environments amongst students at all levels of education (Higgins, Xiao & Katsipataki, 2023). In science education, AI-based virtual laboratories provide simulated environments where students can conduct experiments, manipulate variables, and receive real-time feedback without the constraints of physical equipment (Vogel & Lai, 2024). Such virtual labs leverage intelligent tutoring systems and machine learning algorithms to scaffold learners' experiences, thereby enhancing engagement and deepening conceptual understanding (Li et al., 2025). This makes AI-enabled virtual laboratories a promising instructional alternative, particularly in contexts with limited access to conventional laboratory facilities.

Empirical evidence suggests that virtual laboratories can significantly improve students' science process skills and performance outcomes. For instance, recent studies reported that students who used computer-based and simulation-enhanced lab environments demonstrated higher practical achievement levels than those who relied solely on traditional laboratory instruction (Alshahrani & Ally, 2023; Bakar & Musa, 2025). Similarly, students using simulated science labs tend to develop stronger analytical and problem-solving skills due to the dynamic, interactive nature of the virtual tasks (Khan & Sajjad, 2024). These findings highlight the potential of virtual and AI-assisted lab experiences to enrich Biology education and address persistent gaps in practical skills acquisition among students.

Despite the growing body of research on virtual laboratories in science teaching, relatively few studies have focused specifically on Artificial Intelligence-Based Virtual Laboratories (AIVL) and their effectiveness in enhancing practical skills at the secondary school level in Nigeria. Much of the existing research has been conducted in higher education or under controlled experimental conditions outside of resource-limited settings (Solarin & Olagunju, 2025). As such, there remains a need for context-specific investigations that examine how AI-based instructional tools impact the practical performance of secondary school Biology learners, particularly in education zones with documented resource challenges.

In addition, the question of whether students' gender interacts with the effectiveness of AI-driven instructional approaches remains inconclusive in the literature. The study of Matobobo 2026 indicated negligible gender differences in outcomes when technology-enhanced tools are used,

while Adeyele 2025 noted that access to and engagement with educational technologies may vary across gender lines. Investigating this interaction is important to ensure that AI-based instructional innovations promote inclusive learning opportunities for all students.

In view of these considerations, this study investigated the effectiveness of Artificial Intelligence-Based Virtual Laboratories on Senior Secondary School students' Biology practical skills in Abakaliki Education Zone, Ebonyi State, Nigeria. The study specifically examined differences in practical skills achievement between students exposed to AI-based virtual labs and those taught using the Conventional Laboratory Method, explored gender influence, and evaluated the interaction between teaching method and gender on students' practical performance.

Statement of the Problem

Biology practical skills are essential for developing students' scientific inquiry abilities, such as observation, experimentation, analysis, and reporting. This encourages skills acquisition and real-world problem solving; however, students' performance in Biology practical components in many Nigerian secondary schools remains persistently low, largely due to inadequate laboratory facilities, overcrowded classrooms, and insufficient instructional materials. As a result, teachers often resort to demonstration methods instead of engaging students in hands-on activities, limiting students' opportunities to acquire meaningful practical experience and science process skills.

Artificial Intelligence-Based Virtual Laboratories have been identified as innovative instructional tools capable of providing interactive, simulated experimental environments with immediate feedback and repeated practice opportunities. Empirical studies suggest that AI-supported and virtual laboratory approaches can enhance students' engagement and performance in science subjects. However, there is limited evidence on their effectiveness in improving Biology practical skills among Nigerian secondary school students, particularly within resource-constrained settings.

Additionally, the extent to which gender influences students'learning outcomes in AI-supported learning environments remains inconclusive in existing literature. In Abakaliki Education Zone of Ebonyi State, where laboratory challenges persist, there is insufficient empirical data on whether Artificial Intelligence-Based Virtual Laboratories can significantly enhance students' practical skills compared to the Conventional Laboratory Method and whether such effects differ by gender. Hence, the problem of this study is: What is the effectiveness of AI-based virtual laboratories irrespective of gender?

Purpose of the Study

The main purpose of this study was to investigate the effectiveness of Artificial Intelligence-Based Virtual Laboratories (AIVL) on Senior Secondary School students' Biology practical skills in Abakaliki Education Zone. Specifically, the study sought to determine the:

1. The effect of AI-based virtual laboratories (AIVL) and Conventional Laboratory Method (CLM) on secondary school students' practical skill acquisition.
2. The influence of gender on students' practical skill acquisition in biology.
3. Interaction effect of teaching methods (AIVL & CLM) and gender on students' Biology practical skills acquisition.

Research Questions

The study was guided by the following research questions:

1. What is the difference in the mean practical skills acquisition scores of students taught Biology using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using Conventional Laboratory Method (CLM)?
2. What is the difference in the mean practical skills scores of male and female students taught Biology using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using Conventional Laboratory Method (CLM)?
3. What is the difference in the mean practical score of the interaction effect of teaching methods (AIVL & CLM) and gender

Hypotheses

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

H01: There is no significant difference between the mean practical skills scores of students taught Biology using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using Conventional Laboratory Method (CLM).

H02: There is no significant difference between the mean practical skills scores of male and female students taught Biology using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using the Conventional Laboratory Method (CLM).

H03: There is no significant interaction effect of teaching methods (AIVL & CLM) and gender on students' Biology practical skills.

Methodology

This study adopted a quasi-experimental research design, specifically the non-equivalent control group pre-test post-test design. The design was considered appropriate because it enabled the researcher to compare two groups as a cluster, not as individuals, one exposed to Artificial Intelligence-Based Virtual Laboratories (AIVL) (experimental group) and the other exposed to the Conventional Laboratory Method (CLM) (control group) while controlling for pre-existing differences in students' Biology practical skill levels through the use of pre-test scores as covariates.

The study was conducted in Abakaliki Education Zone of Ebonyi State, Nigeria. The zone comprises four Local Government Areas (LGAs), namely Abakaliki, Ebonyi, Izzi, and Ohaukwu. For this study, Abakaliki Local Government Area (LGA) was purposively sampled due to the availability of schools with functional ICT facilities suitable for the implementation of Artificial Intelligence-Based Virtual Laboratories. From Abakaliki LGA, two public secondary schools were purposively selected based on the availability of basic laboratory infrastructure and ICT resources.

The population of the study comprised all Senior Secondary II (SS II) students offering Biology in public secondary schools within Abakaliki Education Zone. A total sample of 175 SS II Biology students was used for the study. The sample consisted of 96 (50 females and 46 males) students in the experimental group and 79 (41 females and 38 males) students in the control group. Intact classes were used to avoid disruption of the school system; hence, random assignment of individual students was not feasible. One intact class from one school was assigned to the experimental group, while one intact class from the other school served as the control group.

The instrument for data collection was the Biology Practical Skills Inventory (BPSI) developed by the researcher to assess students' practical competencies in Biology. The instrument consisted of 20 performance-based items rated on a 5-point Likert scale (1–5), giving a maximum obtainable score of 100. The items covered major practical skill domains including observation, identification, manipulative skills, experimental skills, analytical skills, drawing skills, safety skills, digital/AI laboratory skills, and reporting skills. The instrument was subjected to face and content validation by experts in Biology Education and Measurement and Evaluation to ensure its appropriateness and relevance to the study objectives. A reliability test was conducted using Cronbach's Alpha, which yielded a reliability coefficient of 0.87, indicating high internal consistency of the instrument.

Before the treatment, both the experimental and control groups were administered the BPSI as a pre-test to determine their baseline practical skill levels. The experimental group was subsequently exposed to instruction using Artificial Intelligence-Based Virtual Laboratories, where students engaged in simulated Biology experiments, interactive virtual practical sessions, and AI-supported feedback systems. The control group was taught using the Conventional Laboratory Method, which involved teacher demonstrations, use of available laboratory materials, and routine practical activities without AI integration. The treatment lasted for a six-week instructional period. At the end of the intervention, the BPSI was re-administered to both groups as a post-test.

Data collected from the pre-test and post-test were analyzed using mean and standard deviation to answer the research questions. Analysis of Covariance (ANCOVA) was employed to test the null hypotheses at the 0.05 level of significance while controlling for differences in pre-test scores. In addition, a two-way ANCOVA was used to examine the interaction effect of teaching method and gender on students' Biology practical skills. The methodological approach adopted in this study was designed to provide reliable empirical evidence on the effectiveness of Artificial Intelligence-Based Virtual Laboratories in improving Biology practical skills among secondary school students in Abakaliki Education Zone.

Results

Research Question 1: What is the difference in the mean Biology practical skills scores of students taught using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using Conventional Laboratory Method (CLM)?

Table 1: Mean Biology Practical Skills Scores of Students Taught Using AIVL and CLM

Group	N	Pre-Test Mean	SD	Post-Test Mean	SD	Gained Mean
Experimental (AIVL)	96	41.28	9.14	82.67	8.02	41.39
Control (CLM)	79	40.95	9.02	68.54	8.37	27.59

From Table 1, students taught Biology using Artificial Intelligence-Based Virtual Laboratories (AIVL) had a higher post-test mean score (M = 82.67, SD = 8.02) compared to those taught using the Conventional Laboratory Method (CLM) (M = 68.54, SD = 8.37). The mean gain for the experimental group was 41.39, while that of the control group was 27.59. This indicates that AIVL had a more substantial positive effect on students' Biology practical skills compared to the conventional laboratory method. The relatively lower standard deviation in the experimental group suggests more consistent improvement in practical skills among students exposed to AI-based virtual laboratories.

Research Question 2: What is the difference in the mean Biology practical skills scores of male and female students taught using AIVL and those taught using CLM?

Table 2: Mean Biology Practical Skills Scores of Male and Female Students Taught Using AIVL and CLM

Group	Gender	N	Pre-Test Mean	SD	Post-Test Mean	SD	Gained Mean
Experimental	Male	46	41.74	9.08	83.91	7.95	42.17
	Female	50	40.86	9.22	81.56	8.08	40.70
Control	Male	38	41.12	8.97	68.02	8.41	26.90
	Female	41	40.80	9.15	69.02	8.34	28.22

Table 2 shows that both male and female students in the experimental group outperformed their counterparts in the control group. Male students exposed to AIVL had a post-test mean of 83.91 (SD = 7.95), while male students in the control group had a mean of 68.02 (SD = 8.41). Similarly, female students in the experimental group recorded a post-test mean of 81.56 (SD = 8.08), compared to 69.02 (SD = 8.34) in the control group. Although male students in the experimental group had a slightly higher mean (42.17) than females (40.70), the difference is minimal. The relatively close mean scores and similar standard deviations suggest that both genders benefited almost equally from the AI-based virtual laboratory approach.

Hypotheses Testing

Hypothesis 1: There is no significant difference between the mean Biology practical skills scores of students taught using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using Conventional Laboratory Method (CLM).

Table 3: ANCOVA Test of Significant Difference Between Students Taught Using AIVL and CLM

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Decision
Corrected Model	6324.518	4	1581.129	28.764	.000	
Intercept	41586.274	1	41586.274	756.892	.000	
Pre-Test	318.446	1	318.446	5.798	.017	
Group	5712.309	1	5712.309	103.953	.000	Sig
Gender	22.615	1	22.615	.411	.522	Not Sig
Group * Gender	37.882	1	37.882	.689	.408	Not Sig
Error	9347.660	170	54.986			
Total	1,025,840.000	175				
Corrected Total	15672.178	174				

From Table 3, the ANCOVA result shows a significant difference between students taught using AIVL and those taught using CLM, $F(1, 170) = 103.953$, $p = .000 < 0.05$. Since the p-value is less than 0.05, the null hypothesis is rejected. This confirms that Artificial Intelligence-Based Virtual Laboratories significantly improved students' Biology practical skills compared to the conventional method.

Hypothesis 2: There is no significant difference between the mean Biology practical skills scores of male and female students taught using AIVL and CLM.

From Table 3, the effect of gender was not significant, F(1, 170) = 0.411, p = .522 > 0.05. The null hypothesis is therefore accepted. This implies that gender does not significantly influence students' Biology practical skills when exposed to either AIVL or CLM.

Hypothesis 3: There is no interaction effect of teaching methods (AIVL & CLM) and gender on students' biology practical skills.

Table 3 also shows no significant interaction effect between teaching method and gender, F(1, 170) = 0.689, p = .408 > 0.05. The null hypothesis is accepted. This indicates that the effectiveness of Artificial Intelligence-Based Virtual Laboratories on Biology practical skills does not depend on students' gender. Both male and female students benefited similarly from the intervention.

Discussion

The findings of this study indicated that there is a significant difference in Biology practical skills scores between students taught using Artificial Intelligence-Based Virtual Laboratories (AIVL) and those taught using the Conventional Laboratory Method (CLM). Specifically, students in the AIVL group performed significantly better than their counterparts in the traditional laboratory group. This result aligns with recent research showing that virtual laboratories and AI-enhanced simulation tools significantly improve students' science process skills, conceptual understanding, and overall performance in STEM subjects. For instance, studies have found that technology-enhanced learning tools, including virtual labs and AI-powered platforms, produce higher gains in science learning outcomes compared to conventional methods, especially regarding engagement and retention of scientific concepts (Hussain Sahito & Jabeen, 2025).

The superior performance of students exposed to AIVL may be attributed to the interactive and adaptive features of AI-based environments that allow learners to explore, repeat, and reflect on experimental procedures at their own pace, enhancing skill acquisition. This is consistent with evidence from the research of Bakar & Musa (2025) which reports that virtual labs improve students' motivation, self-efficacy, and understanding of complex biological processes, particularly in topics that are abstract or difficult to visualize in traditional lab settings. Byukusenge et al. (2022) found that virtual labs increased students' performance levels and conceptual understanding in biology laboratory contexts.

The results also revealed no significant difference between male and female students in terms of Biology practical skills acquisition, regardless of the teaching method used. Although some prior research indicates gendered patterns in the use and engagement with AI tools in higher education contexts, with males showing higher usage tendencies in some settings, this study's findings suggest that gender did not influence students' learning outcomes in practical biology when AIVL was used. In educational settings where virtual and simulation tools are well-integrated into instruction, gender differences in achievement are frequently minimal, indicating that such technologies can support equitable learning experiences.

Furthermore, the study showed no significant interaction effect between teaching method and gender on students' practical skills. This indicates that the effectiveness of AIVL on students' Biology practical skills was not moderated by gender; both male and female students benefited similarly from the intervention. This supports the finding from research on virtual and immersive learning technologies which report no significant discrepancies in adoption or learning outcomes between genders in certain contexts (Adeyele, 2025). The inclusive nature of AI-based virtual

laboratories — which permits self-paced exploration, scaffolded feedback, and reduced performance anxiety — may help mitigate gender-related barriers often reported in traditional STEM classrooms.

Overall, the findings of this study reinforce the pedagogical value of integrating AI-driven virtual laboratories into Biology education. The significant improvement in students' practical skills, coupled with the absence of gender-based differences in achievement, underscores the potential of AI-enhanced virtual learning environments to promote both effectiveness and equity in science education. These results align with broader research indicating that virtual laboratory experiences can serve as effective complements or alternatives to conventional practical methods, particularly in resource-constrained educational contexts.

Conclusion

Based on the findings of this study, it was concluded that Artificial Intelligence-Based Virtual Laboratories (AIVL) significantly improve Senior Secondary School students' Biology practical skills compared to the Conventional Laboratory Method (CLM). Students exposed to AI-based virtual laboratory instruction demonstrated higher mean post-test scores and had greater practical skill gains than those taught using the traditional approach. This indicates that AI-driven virtual laboratories enhance students' observation, manipulative, experimental, analytical, and reporting skills more effectively.

The study further concluded that gender does not significantly influence students' acquisition of Biology practical skills when exposed to either AIVL or CLM. Both male and female students benefited equally from the instructional methods. Additionally, there was no significant interaction effect between teaching method and gender, suggesting that the effectiveness of Artificial Intelligence-Based Virtual Laboratories is not dependent on students' gender.

Summarily, the findings establish that AI-based virtual laboratories are an effective, inclusive, and innovative instructional approach capable of enhancing practical competence in Biology. The integration of AI technologies into Biology instruction can therefore serve as a viable strategy for improving science education outcomes, particularly in environments where conventional laboratory resources are inadequate.

Recommendations

Based on the findings and conclusions of this study, the following recommendations were made:

1. Secondary schools should integrate Artificial Intelligence-Based Virtual Laboratories into Biology instruction to complement conventional laboratory activities and enhance students' practical skill acquisition.
2. Government and educational stakeholders should provide adequate ICT facilities, internet connectivity, and digital resources in secondary schools to support the effective implementation of AI-based instructional tools.
3. Biology teachers should receive regular training and professional development on the use of AI-driven virtual laboratory platforms to ensure effective classroom integration.
4. Curriculum planners should incorporate AI-supported virtual laboratory activities into the Biology curriculum to modernize practical instruction and align with global educational trends.

References

Adeyele, T. A. (2025). Gender perspectives in artificial intelligence-supported learning environments. *Journal of Educational Technology Research*, 18(2), 145–162.

Akyüz, K. & Samsa, D. (2021). Advancing science education through innovative laboratory practices. *International Journal of Science Education*, 43(5), 721–739.

Alshahrani, M. & Ally, M. (2023). Virtual laboratories and science achievement: Enhancing students' experimental skills. *Computers & Education*, 190, 104612.

Bakar, R. & Musa, S. (2025). Simulation-based laboratory instruction and students' science performance. *Journal of STEM Education*, 12(1), 44–59.

Byukusenge, C., Nsengimana, T. & Uwizeyimana, D. (2022). Effects of virtual laboratories on students' conceptual understanding in biology. *African Journal of Science Education*, 10(3), 88–101.

Chukwu, J. O., Nwachukwu, E. & Okafor, P. (2024). Practical skill acquisition and academic achievement in secondary school biology. *Nigerian Journal of Educational Research*, 29(2), 201–215.

Higgins, S., Xiao, Z. & Katsipataki, M. (2023). The impact of artificial intelligence on learning outcomes: A meta-analytic review. *Educational Research Review*, 38, 100492.

Hussain Sahito, Z. & Jabeen, S. (2025). Technology-enhanced learning and science achievement: Evidence from AI-supported classrooms. *Journal of Computer Assisted Learning*, 41(1), 77–93.

Khan, A. & Sajjad, M. (2024). Interactive simulations and science process skills development among secondary students. *Journal of Science and Mathematics Education*, 22(4), 310–326.

Li, X., Chen, Y. & Zhang, H. (2025). Intelligent tutoring systems in virtual laboratories: Implications for science education. *Computers in Human Behavior*, 152, 107045.

Matobobo, L. (2026). Gender differences in artificial intelligence adoption in secondary education. *International Journal of Educational Technology*, 19(1), 33–48.

Mustapha, A. & Bello, R. (2025). Integrating emerging technologies into science classrooms: Policy and practice implications. *Journal of Educational Innovation*, 14(2), 95–109.

Nwankwo, C. & Iheanacho, P. (2023). Laboratory resource availability and students' practical competence in biology. *Ebonyi Journal of Science Education*, 8(1), 55–70.

Okeke, I. &Eze, U. (2023). Science process skills and biology practical performance among secondary school students. *Journal of Curriculum and Instruction*, 16(3), 134–149.

Oladimeji, A. &Yusuf, K. (2022). Challenges of laboratory-based instruction in Nigerian secondary schools. *African Journal of Educational Studies*, 11(2), 178–192.

Solarin, T. & Olagunju, M. (2025). Artificial intelligence applications in science education: Trends and future directions. *Journal of Digital Learning Research*, 7(1), 1–15.

Ugwoke, E., Nwafor, R. & Chukwu, L. (2024). Improving science education through technology integration in resource-constrained settings. *Nigerian Journal of STEM Education*, 5(2), 120–136.

Vogel, D. & Lai, C. (2024). Virtual laboratory environments and student engagement in science learning. *Educational Technology Research and Development*, 72(3), 455–472.