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Full Length Paper

Effectiveness of Virtual Laboratory-Based Instruction on Students' Academic Performance In Biology in Likuyani, Kakamega County, Kenya

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Abstract

Despite its importance in the science curriculum and its relevance to national development goals, students in most Kenyan secondary schools continue to record low achievement in biology across all three papers in national examinations. For instance, there has been persistent low biology performance among learners in Likuyani Sub-County, Kakamega County, with a national mean score of 2.85 between 2019 and 2023. Thus, this study sought to investigate the effectiveness of integrating Virtual Laboratory-Based Instruction (VLBI) into the teaching of biology practical lessons on students' academic performance and conceptual understanding in secondary schools in Likuyani Sub-County, Kakamega County, Kenya. The study employed a quasi-experimental mixed-methods design. A total of 339 Form Three hundred and seventy-one students (271 experimental, 68 control) and 46 biology teachers from public secondary schools participated. Data were collected using Biology Achievement Tests (pre- and post-tests), structured questionnaires, interview schedules and classroom observation checklists. Quantitative data were analysed using SPSS Version 25.0 through z-tests and ANOVA, while qualitative data were thematically analysed. Pre-test results confirmed baseline equivalence between groups ($z = 1.21$, $p = 0.226$). Post-test scores indicated a statistically significant improvement in the experimental group ($M = 66.37$, $SD = 8.68$) compared to the control group ($M = 49.93$, $SD = 7.31$), with $z = 15.94$, $p < 0.001$. Thematic analysis further revealed enhanced student engagement, motivation and conceptual clarity, especially in complex topics such as genetics, cell structure and ecology. The findings demonstrated that VLBI has a positive impact on both academic performance and conceptual understanding in biology, particularly in resource-constrained settings. These insights are critical for curriculum developers, policymakers and educators dedicated to improving science education outcomes through innovative instructional strategies.

Keywords: Biology, Instruction, Performance, Students, Virtual laboratory

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INTRODUCTION

Biology is a practical and experimental science that occupies a central place in the Kenyan secondary school curriculum. It equips learners with the knowledge, skills, and attitudes necessary for careers in healthcare, agriculture, environmental conservation, and biotechnology (Kenya Institute of Curriculum Development [KICD], 2022). To achieve these educational goals, the curriculum emphasises practical work by requiring students to conduct laboratory investigations, manipulate specimens, and draw evidence-based conclusions. However, persistent infrastructural and logistical challenges continue to undermine the effective delivery of hands-on practical lessons in many Kenyan schools, particularly in Likuyani, Kakamega County. In response to these constraints, Virtual Laboratory-Based Instruction (VLBI) has emerged as an innovative and scalable alternative to traditional laboratory teaching. VLBI refers to the use of computer-based simulations and interactive digital platforms to replicate laboratory experiences in a virtual environment. These platforms allow students to conduct experiments, observe outcomes, manipulate variables, and analyse data, often with the added benefits of safety, accessibility, and repeatability (Byukusenge et al., 2022; Mulyadi, 2024). In biology education, virtual laboratories have proven especially effective in delivering practical content in topics such as genetics, cell structure, and ecology, which may be conceptually difficult or resource-intensive to demonstrate physically.

Global studies have increasingly confirmed the pedagogical value of VLBI in science education. For instance, Byukusenge et al. (2022) demonstrated that students using virtual laboratories exhibited improved conceptual understanding and higher motivation levels compared to those in conventional lab settings. Similarly, Kebande (2024), while working in the domain of cybersecurity education, found that virtual lab users demonstrated enhanced engagement, suggesting broad applicability across practical disciplines. These findings support the claim that VLBI facilitates deeper cognitive processing and promotes learner autonomy by allowing students to experiment at their own pace. The use of virtual laboratories gained heightened relevance during the COVID-19 pandemic, which disrupted traditional classroom-based teaching and highlighted the vulnerability of practical science education in low-resource settings (Hodges et al., 2020). In this context, VLBI provided a viable solution for continuing practical instruction remotely. Even after schools reopened, the experience revealed the long-term potential of virtual labs in complementing physical laboratory sessions and mitigating infrastructural limitations.

Despite international progress, Kenya continues to face systemic barriers to the widespread adoption of VLBI. According to recent national reports, fewer than 40% of public secondary schools possess fully functional computer labs, and many lack reliable internet access or adequate digital devices (Ministry of ICT, Innovation and Digital Economy, 2024; MoE, 2024). Teacher capacity also remains a critical issue, with only 24.6% of teachers having received formal training in digital pedagogy by 2023 (Ndirangu & Kinyanjui, 2025). These gaps are especially pronounced in rural sub-counties such as Likuyani in Kakamega County, where resource disparities limit students' exposure to meaningful practical experiences in the biology discipline. This inadequacy is reflected in national examination outcomes. The Kenya Certificate of Secondary Education (KCSE) allocates 40% of the final biology score to Paper 3, the practical component which assesses students' ability to conduct experiments, record observations and interpret scientific data. However, many students underperform in this section due to limited practical exposure (Odhiambo et al., 2023). In Likuyani Sub-County, KCSE Biology performance from 2019 to 2023 consistently fell below the national average, as shown in Table 1.

Table 1: KCSE Biology Performance in Likuyani Sub-County and National Averages (2019–2023)

Performance	Year	2019	2020	2021	2022	2023	Average
National	KCSE Average Score (%)	25.54	29.50	32.98	32.39	33.45	**30.77**
	Mean Grade Score	D-	D-	D	D	D-	**D**
Likuyani Sub-County	KCSE Average Score (%)	24.37	26.79	28.53	26.34	30.29	**27.26**
	Mean Grade Score	E	D-	D-	D-	D-	**D-**

Source: Likuyani Sub-County SCDE KNEC Report (2023)

Notably, Table 1 presents the KCSE Biology performance trends for Likuyani Sub-County compared to national averages between 2019 and 2023. Nationally, the average scores ranged from 25.54 per cent in 2019 to 33.45 per cent in 2023, translating to a consistent mean grade of D- to D. In contrast, Likuyani Sub-County recorded slightly lower performance, with averages ranging from 24.37 per cent in 2019 to 30.29 per cent in 2023, corresponding to mean grades of E to D-. The overall five-year average stood at 30.77 per cent nationally against 27.26 per cent in Likuyani, reflecting a persistent performance gap below the national level (Likuyani Sub-County SCDE KNEC Report, 2023).

Virtual Laboratories in Biology Education

Biology education fundamentally depends on practical experiences that allow students to connect theoretical knowledge with real-world biological phenomena (Smith & Jones, 2022). Traditional laboratory sessions, which involve direct observation and hands-on experiments, are crucial in strengthening conceptual understanding and developing scientific inquiry skills (Mukhtar et al., 2022). However, most educational institutions, particularly in low-resource settings, face challenges such as insufficient laboratory facilities, safety concerns, and limited access to equipment. These constraints limit students' opportunities for experiential learning and practical engagement (Smith & Jones, 2022).

Globally, the adoption of VLs reflects an ongoing shift toward digital and competency-based education models (Chen et al., 2023). Modern VL platforms increasingly incorporate cutting-edge technologies, including augmented reality (AR), virtual reality (VR), and artificial intelligence (AI), enabling immersive and adaptive learning experiences (Osei et al., 2021). These innovations provide real-time feedback and tailored learning pathways, thereby enhancing the efficacy of virtual labs as pedagogical tools (Smith & Jones, 2022). The COVID-19 pandemic further demonstrated the value of VLs by ensuring the continuity of science education during extended school closures and remote learning periods (Chen et al., 2023).

Virtual Laboratories (VLs) have emerged as a transformative solution that addresses these challenges by providing interactive digital environments that simulate real laboratory experiments (Osei et al., 2021). Through VLs, students can conduct virtual experiments, manipulate variables, and visualise biological processes safely and flexibly (Smith & Jones, 2022). Studies have consistently demonstrated that VLs enhance learners' understanding of complex biological concepts, practical competencies, and motivation across key areas such as genetics, cell biology, and biotechnology (Osei et al., 2021; Njoroge & Mwangi, 2023). VLs thus offer an alternative or complementary approach to traditional labs, especially in contexts where physical infrastructure is lacking.

In East Africa, virtual laboratories are gaining recognition through national education reforms and collaborative initiatives. Kenya's competency-based curriculum (CBC) integrates digital tools, such as VLs, to promote inquiry-driven and student-centered learning approaches in biology (KICD, 2023). Rwanda's STEM Powering Youth programme, developed in partnership with institutions like MIT, incorporates virtual labs to broaden STEM access and improve educational outcomes (Niyonkuru et al., 2022). Meanwhile, the Open University of Tanzania (OUT) utilises virtual labs within its Open and Distance Learning (ODL) framework, offering multimedia content and digital assessments that cater to learners in remote areas (Makoye & Kalambo, 2021).

Prominent platforms like Labster, PhET Interactive Simulations, and BioMan Biology exemplify the scalability and flexibility of virtual labs. These tools provide students with safe environments to repeat experiments, practise techniques, and explore scientific phenomena independently – advantages particularly relevant for schools constrained by limited physical resources (Kimani & Waweru, 2023). The autonomy offered by VLs supports differentiated instruction, allowing learners with varying abilities and learning styles to engage effectively with biology content (Okono et al., 2023).

Despite their promise, VLs face significant barriers to widespread adoption in East Africa. Poor ICT infrastructure, including unreliable electricity, low bandwidth internet, and insufficient hardware, remains a fundamental challenge (Mwangi et al., 2022). Additionally, most educators lack the necessary training and digital literacy skills to integrate VLs effectively into their pedagogy (Otieno & Ndungu, 2024). Rural schools are disproportionately affected by these limitations, exacerbating educational inequities (Ndegwa & Kamau, 2023).

Policy frameworks in Kenya, such as the National ICT Policy (2019) and the ICT Authority Strategy Plan (2024-2027), prioritise expanding digital infrastructure and teacher capacity development to support VL implementation. Nevertheless, gaps persist in infrastructure maintenance and teacher support, limiting the potential benefits of these technologies (Muthoni & Karanja, 2023). Sustainable VL integration demands a comprehensive approach that combines infrastructural investment with continuous professional development and alignment with curricular objectives (Nyambura & Mwiti, 2023).

Beyond enhancing practical skills, VLs also facilitate collaborative and personalised learning. Most platforms incorporate social learning features, discussion forums, peer collaboration tools, and group project capabilities that promote communication, teamwork, and knowledge sharing, mirroring real-world scientific research practices (Muturi & Wanjohi, 2022; Otieno & Ndungu, 2024). This connectivity enables students from diverse locations to engage in joint inquiry, fostering a collaborative learning culture. Adaptive learning technologies embedded within some virtual labs further individualise instruction by adjusting content difficulty and pacing based on learner performance. These systems provide immediate feedback and recommend personalised study paths, supporting self-directed learning and improving educational outcomes (Wambua & Njeri, 2021; Kim et al., 2023). Such personalised learning aligns well with contemporary competency-based education principles that emphasise learner autonomy and mastery.

MATERIALS AND METHODS

This study adopted a quasi-experimental explanatory sequential mixed-methods design to rigorously assess the impact of Virtual Laboratory-Based Instruction (VLBI) on student learning outcomes in biology. The quantitative component involved two groups: an experimental group exposed to virtual laboratory instruction and a control group receiving traditional hands-on laboratory teaching. Pre-test and post-test assessments were administered to both groups to measure and compare changes in academic performance attributable to the instructional method (Creswell & Creswell, 2023). To complement the quantitative data and provide a more profound understanding of the instructional context, the qualitative phase employed descriptive surveys and semi-structured interviews with students and teachers involved in the study. This approach explored participants' experiences, attitudes, and perceived challenges regarding the use of virtual laboratories, thereby enriching the interpretation of the quantitative results (Johnson & Christensen, 2022). The integration of quantitative and qualitative findings through this mixed-methods approach ensured robust triangulation, enhancing the validity, reliability, and practical relevance of the study's conclusions.

Data Analysis

Impact of Virtual Laboratory Instruction on Students' Academic Performance in Biology

A comparison of academic performance between students taught using Virtual Laboratory-Based Instruction (VLBI) and those taught via traditional laboratory methods was done. Pre- and post-test scores were analysed descriptively (means, standard deviations) and inferentially using an independent sample z-test.

RESULTS

Student Performance Improvements

The study sought to assess students' perceptions of their academic performance improvements following the use of virtual laboratories in biology.The results indicated that 50.2% of students reported slight improvements, while 35.4% reported considerable gains in their grades after using virtual laboratories. A minority of 14.4% noted no change in their academic performance, as illustrated in Figure 1.

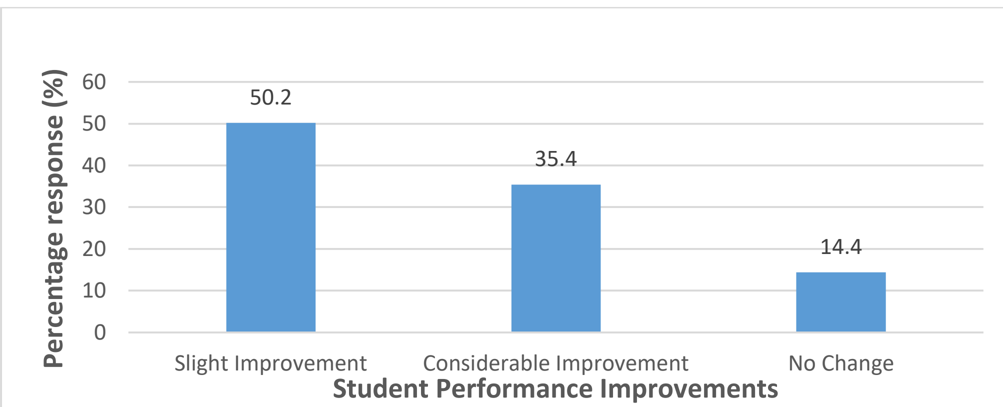

Figure 1: Student-reported grade improvements

Teachers' Observations on Student Outcomes

The study sought to capture teachers' perceptions of student performance and engagement following the integration of virtual laboratories. Majority, 80% of teachers observed improvements in students' KCSE Biology performance following virtual lab use. Similarly, 80% of teachers agreed or strongly agreed that student engagement increased during lessons incorporating virtual simulations as shown in Table 2.

Table 2: Teachers' observations on student outcomes

Indicator	Response	Percentage (%)
KCSE Biology Performance	Improved	80.0
	No Change	20.0
Student Engagement	Strongly Agree	28.0
	Agree	52.0
	Neutral/Disagree	20.0

Administrators' Perspectives on Student Performance Trends

The study assessed school administrators' views on student performance trends following the adoption of virtual laboratories. The data indicated that 63.6% of administrators observed improved student performance attributed to the use of virtual labs, while 36.4% reported no noticeable change, as illustrated in Figure 2.

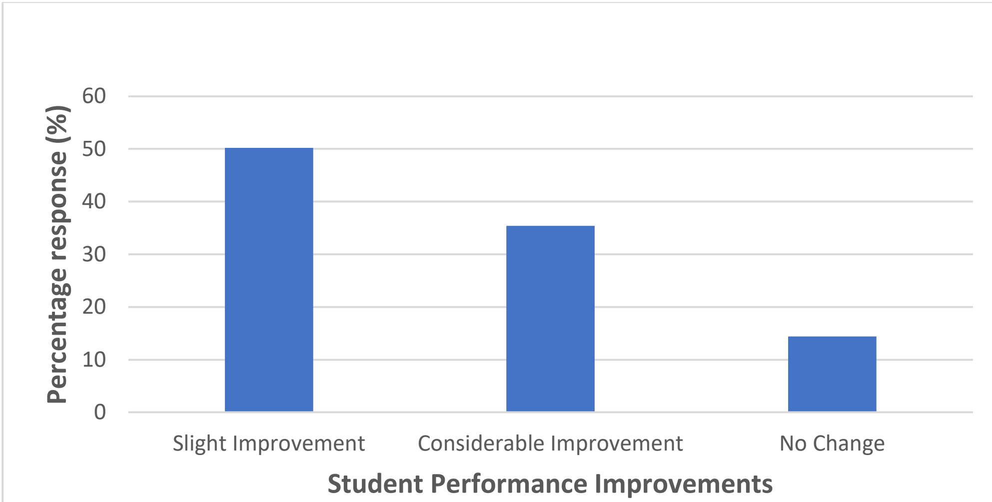

Figure 2: Administrators' perspectives on student performance trends

Pre-test scores

A pre-test was administered to both the experimental and control groups at the beginning of the study to evaluate their initial cognitive ability in biology. The findings established that the experimental group had a mean score of 45.65, compared to a slightly lower mean of 44.82 for the control group. The standard deviations were 5.85 and 5.27, respectively, indicating similar performance levels between the two groups before the intervention, as presented in Table 3.

Table 3: Students' mean and standard deviation in the pre-test

Group Type	Number	Mean	SD
Experimental group	271	45.65	**5.85**
Control group	68	44.82	**5.27**

To determine if the difference in pre-test scores was statistically significant, a z-test was conducted. The results are summarized in Table 4.

Table 4: Z-Test for equality of means in pre-test scores

z-value	p-value	Significance Level (α)
1.21	0.226	0.05

Since the p-value (0.226) is greater than $\alpha = 0.05$, the null hypothesis (H_{04}), which states that there is no significant difference in biology performance between students taught using virtual labs and those taught using traditional methods at the pre-test stage, was thus accepted. This confirmed that both groups had equivalent cognitive baselines, ensuring that any subsequent differences in performance can be attributed to the instructional interventions.

Post-test scores

A post-test was administered to both the experimental and control groups three weeks after the instructional period to assess learning outcomes. The findings established that the experimental group attained a mean score of 66.37 with a standard deviation of 8.68, whereas the control group had a lower mean score of 49.93 and a standard deviation of 7.31, as shown in Table 5. These results indicated that students exposed to virtual laboratory instruction performed significantly better than those who received traditional instruction, as evidenced by the higher average score in the experimental group.

Table 5: Students' mean and standard deviation in post-test

Group Type	Number	Mean	SD
Experimental group	271	66.37	8.68
Control group	68	49.93	7.31

Hypothesis Testing

The hypothesis is that there is no significant difference in biology academic performance between students taught using virtual lab-based instruction and those taught using traditional methods. This hypothesis was tested using a z-test to compare the post-test scores between the experimental and control groups. The analysis yielded a z-value of 15.94 and a p-value of 0.000. Since the p-value is less than the significance level ($p < 0.05$), the null hypothesis was rejected, as illustrated in Table 6. This result implied that there was a statistically significant difference in biology academic performance between students taught using virtual lab-based instruction and those taught using traditional methods. The higher mean score in the experimental group is thus attributed to the use of virtual laboratories during instruction.

Table 6: Z-Test for equality of means in post-test

z-value	Df	p-value	Level of Significance (α)
15.94	—	0.000	0.05

DISCUSSION

The analysis of pre-test scores revealed that students in both the experimental and control groups had comparable baseline academic abilities in Biology. The z-test for equality of means showed no statistically significant difference ($z = 1.21$, $p = 0.226 > \alpha = 0.05$), confirming that the groups were equivalent prior to the intervention. This equivalence is essential, as it ensures that any observed differences in post-test performance can be confidently attributed to the instructional approaches used rather than pre-existing disparities. Post-test results demonstrated that students exposed to Virtual Laboratory-Based Instruction (VLBI) achieved a significantly higher mean score ($M = 66.37$, $SD = 8.68$) compared to their counterparts taught through traditional laboratory methods ($M = 49.93$, $SD = 7.31$). The z-test confirmed this difference as statistically significant ($z = 15.94$, $p = 0.000 < \alpha = 0.05$), indicating that the use of virtual labs had a positive impact on students' academic achievement in Biology.

The enhanced performance of the experimental group can be attributed to several unique features of virtual labs. These include interactive simulations that allow repeated experimentation, immediate feedback mechanisms, and increased learner autonomy, all of which foster inquiry-based learning and deeper conceptual understanding. Unlike traditional laboratories, where students often take a more passive role, virtual labs encourage active engagement and critical thinking, which contribute to improved academic outcomes (Mwangi & Ndung'u, 2022; Otieno & Wambugu, 2023).

Teachers' observations supported these quantitative findings, with 80% reporting improvements in students' KCSE Biology performance and increased engagement during virtual lab lessons. The reported gains were linked to virtual labs' ability to stimulate curiosity, motivation, and active participation. Similarly, 63.6% of school administrators acknowledged improvements in student academic performance following virtual lab adoption, though some noted challenges related to infrastructure and implementation inconsistencies that may limit overall effectiveness (Byukusenge, 2022; Bazie, 2024). These findings align with prior studies on the effectiveness of virtual laboratories, particularly in settings where access to physical labs is limited. For example, related studies by Mbogo and Wambugu (2021) and Kamau, (2020) highlighted how virtual labs enhance understanding and retention of biological concepts. Furthermore, the role of simulations in promoting active, student-centered learning has been widely documented (Mwangi & Ndung'u, 2022; Otieno & Wambugu, 2023).

Supporting Qualitative Evidence

Qualitative data from students, teachers and administrators reinforced the quantitative findings, particularly regarding the impact of Virtual Laboratory Instruction on students' academic performance in Biology

- A student from Z1 school stated:

"Yes, I perform better in biology since using virtual labs. I understand faster than when the teacher just writes on the board."

- From Y3:

"I scored higher in the last CAT because I could repeat the simulations at home before the test."

- A teacher from X2 noted:

"Since we adopted virtual labs, our mean grade in KCSE biology improved from D+ to C."

- An administrator from Z2 added:

"Teachers report that students are more engaged and motivated during virtual lab sessions compared to traditional lessons."

- A teacher from N1 emphasized:

"Some students perform better because virtual labs allow repeated practice and visualization, which is not possible in traditional dissections."

- However, a student from Y2 cautioned:

"Virtual labs cannot fully replace traditional labs because we still need to handle real specimens."

Virtual labs contributed positively to student performance by increasing engagement, enabling self-paced revision, and improving conceptual understanding. However, the consensus across most schools supports a blended approach, where virtual labs supplement rather than replace hands-on, traditional lab experiences. This hybrid model offers the most comprehensive educational benefit, accommodating both theoretical and practical learning dimensions.

Conclusion

The study findings provided clear evidence that the integration of virtual laboratories in biology instruction enhances student learning outcomes. The significant improvement in post-test performance among the experimental group demonstrated that virtual labs are not only effective in supporting conceptual understanding but also in fostering measurable academic gains. This suggested that virtual laboratories can serve as a powerful pedagogical tool in strengthening cognitive achievement in science education, particularly in contexts where access to physical laboratories may be limited.

There is a pedagogical value of virtual laboratories in promoting student engagement and motivation. Teachers' observations affirmed that the use of virtual simulations captured learners' attention and sustained active participation in lessons, while administrators reported noticeable trends of improved academic performance among students exposed to the intervention.

Engagement is an essential precursor to deep learning, and these findings affirmed that technology-enhanced learning environments contributed to creating interactive and stimulating conditions that are conducive to improved performance.

Virtual laboratories are viable alternatives or supplements to conventional teaching strategies in biology. Their ability to provide interactive, repeatable, and risk-free experiments allowed learners to explore scientific concepts more comprehensively, thereby bridging the gap between theory and practice.

Virtual laboratories are an innovative instructional approach that aligns with modern education needs, particularly in fostering 21st-century skills such as problem-solving, critical thinking, and digital competence.

Recommendations

Teachers should integrate virtual laboratories into biology instruction as a supplement to physical laboratories, particularly in resource-constrained schools, to enhance conceptual understanding and academic performance.

Teacher training programmes should incorporate professional development on the use of virtual laboratories to build pedagogical capacity and ensure meaningful integration into classroom practice.

School administrators should allocate resources and provide infrastructure support, including reliable internet and computer access, to facilitate effective adoption of virtual laboratory technologies.

Curriculum developers should embed virtual laboratory modules in science curricula to ensure alignment with learning objectives and promote the acquisition of 21st-century skills such as problem-solving and digital literacy.

Policymakers should consider institutionalising virtual laboratory interventions at national and regional levels to reduce disparities in access to quality science education across schools.

REFERENCES

Bazie, P. (2024). The role of virtual learning environments in enhancing STEM education outcomes in rural Africa. *Journal of Educational Technology and Innovation*, 11(2), 45–58.

Byukusenge, C. (2022). Exploring student engagement through virtual labs in East African secondary schools. *African Journal of Digital Pedagogy*, 9(1), 33–49.

Byukusenge, C., Nsanganwimana, F., & Tarmo, A. P. (2022). Effectiveness of virtual laboratories in teaching and learning biology: A review of literature. *International Journal of Learning, Teaching and Educational Research, 21*(6), 1–17. https://doi.org/10.26803/ijlter.21.6.1

Byukusenge, C., Nsanganwimana, F., & Tarmo, A. P. (2023). Exploring students' perceptions of virtual and physical laboratory activities and usage in secondary schools. *International Journal of Learning, Teaching and Educational Research*, 22(5), 1–12. https://doi.org/10.26803/ijlter.22.5.22

Chen, L., Zhang, Y., & Wang, X. (2023). Virtual labs and science learning continuity during COVID-19. *International Journal of Digital Learning*, 12(1), 25–39.

Creswell, J. W., & Creswell, J. D. (2023). *Research design*: Qualitative, quantitative and mixed method approaches (6th ed.). SAGE Publications.

Hodges, C., Moore, S., Lockee, B., Trust, T., & Bond, A. (2020). The difference between emergency remote teaching and online learning. *EDUCAUSE Review*, 27(1), 1–12.

Johnson, B., & Christensen, L. (2022). *Educational research*: Quantitative, qualitative and mixed approaches (7th ed.). SAGE Publications.

Kamau, J. (2020). Virtual laboratories and student performance in secondary school science subjects: A Kenyan case study. *Journal of Science Education Research*, 18(3), 120–135.

Kebande, V. (2024). Virtual labs in cybersecurity education: Engagement and skill acquisition. *African Journal of ICT in Education*, 9(1), 34–48.

Kenya Institute of Curriculum Development. (2022). *Biology curriculum support materials for secondary schools*. KICD.

Kenya Institute of Curriculum Development. (2023). *Curriculum framework for competency-based education*. KICD.

Kim, S., Lee, J., & Park, M. (2023). Adaptive learning systems in virtual laboratories: A review of benefits and limitations. *Journal of Science Education and Technology*, 32(2), 101–117.

Kimani, T., & Waweru, M. (2023). Use of Labster and BioMan in Kenyan secondary schools: A case study. *East African Educational Technology Journal*, 7(1), 15–29.

Likuyani Sub-County SCDE. (2023). *KCSE Biology performance report* (2019–2023). Kenya National Examinations Council.

Makoye, D., & Kalambo, P. (2021). The role of virtual labs in open and distance learning at the Open University of Tanzania. *Journal of Open Learning*, 10(2), 50–62.

Mbogo, J., & Wambugu, P. (2021). Enhancing biology performance through virtual laboratory simulations in Kenyan schools. *International Journal of Science Pedagogy*, 16(4), 88–102.

Ministry of Education. (2024). *Status of ICT integration in public secondary schools*.Government of Kenya.

Ministry of ICT, Innovation and Digital Economy. (2024). *Annual ICT infrastructure audit report*. Government of Kenya.

Mukhtar, M., Ali, A., & Kamau, R. (2022). The role of laboratory work in science education in developing countries. *Journal of Educational Practices*, 14(3), 120–135.

Mulyadi, M. (2024). Virtual laboratories in science learning: An emerging pedagogical shift. *International Journal of STEM Education*, 11(1), 78–88.

Muthoni, R., & Karanja, S. (2023). Implementation challenges of ICT policies in public schools in Kenya. *ICT in Education Policy Journal*, 8(2), 112–130.

Muturi, P., & Wanjohi, F. (2022). Collaborative learning in virtual environments: A study of secondary schools in Nairobi. *Journal of Digital Pedagogy*, 6(4), 85–98.

Mwangi, D., & Ndung'u, S. (2022). Interactive simulations and conceptual mastery in biology education. *East African Journal of Educational Research*, 7(1), 59–71.

Mwangi, J., Otieno, M., & Kariuki, D. (2022). Barriers to virtual lab adoption in rural Kenyan schools. *African Journal of Digital Education*, 5(1), 40–52.

Ndegwa, P., & Kamau, L. (2023). Equity and access in virtual science education: A rural perspective. *East African Education Review*, 10(1), 22–36.

Ndirangu, C., & Kinyanjui, A. (2025). Teacher training in digital pedagogy: Trends and challenges in Kenya. *Teacher Education Quarterly*, 14(2), 59–73.

Niyonkuru, F., Uwase, A., & Nsengimana, A. (2022). STEM Powering Youth: Leveraging virtual labs in Rwandan schools. *Journal of African STEM Education*, 9(2), 77–90.

Njoroge, P., & Mwangi, T. (2023). Impact of virtual labs on student performance in biology: Evidence from Kenya. *Journal of Educational Innovation*, 13(1), 99–110.

Nyambura, M., & Mwiti, E. (2023). Aligning virtual labs with curriculum goals: Policy recommendations. *Kenya Education Policy Review*, 12(3), 65–78.

Odhiambo, J., Wekesa, C., & Mugo, P. (2023). Assessing practical skills in KCSE Biology: Gaps and opportunities. *Kenya Journal of Science Education*, 18(2), 143–158.

Okono, E., Wangila, E., & Chebet, A. (2023). Effects of virtual laboratory-based instruction on the frequency of use of experiment as a pedagogical approach in teaching and learning of physics in secondary schools in Kenya. *African Journal of Empirical Research, 4*(2), 116–132. https://doi.org/10.51867/ajernet.4.2.116

Osei, D., Boateng, E., & Asare, F. (2021). Virtual simulations and biology education: A comparative study. *International Journal of Educational Research*, 46(4), 214–228.

Otieno, J., & Ndungu, P. (2024). Digital literacy and teacher readiness for virtual labs in Kenya. *Journal of ICT in Teaching and Learning*, 11(2), 33–47.

Otieno, M., & Wambugu, L. (2023). Virtual versus physical labs: A comparative study in secondary biology education in Kenya. *Journal of Digital Learning and Pedagogy*, 10(2), 78–92.

Smith, L., & Jones, R. (2022). Technology-enhanced learning in science education: Trends and future directions. *Journal of Modern Pedagogy*, 29(1), 1–15.

Wambua, K. & Njeri, M. (2021). Personalized learning and academic performance in virtual biology labs. *African Journal of Education and Technology*, 6(3), 100–114.