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Enhancing Biology Learning through 3D Models: A Study of Academic Performance in Nigerian Secondary Schools

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Abstract

Despite the recognized importance of Biology in secondary education, students' performance in the subject remains persistently low, particularly in Nigeria, due to the continued reliance on abstract, text-based instructional methods. This study addresses this pedagogical gap by evaluating the impact of a 3-Dimensional Model of the Human Circulatory System (3-DMHCS) on students' academic performance. Grounded in constructivist and multimodal learning frameworks, the study utilized a quasi-experimental post-test non-randomized control group design involving 60 students (49 from public and 11 from private schools). Participants were assigned to either a control group receiving conventional instruction or an experimental group taught using the 3-DMHCS. The Biology Performance Test (BPT), validated and yielding a reliability coefficient of 0.86 (KR-20), was used for assessment. Quantitative results revealed that the experimental group achieved a higher mean post-test score (M = 13.36, SD = 3.44) compared to the control group (M = 11.42, SD = 2.87), with a statistically significant mean difference of 1.94 ($t(58) = 2.83$, $p < 0.01$). Additionally, over 53% of students in the experimental group scored within the high range (16–20), whereas none in the control group reached this threshold. Notably, no significant difference was observed between public and private school students' performance in the experimental group ($t(58) = -0.180$, $p = 0.86$), indicating the model's equitable effectiveness across institutional contexts. The study contributes novel evidence on how low-cost, tactile instructional models can bridge educational disparities and enhance students' grasp of complex biological systems. It advocates for integrating 3D instructional tools into mainstream science curricula and underscores the need for professional development to support such pedagogical innovations.

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INTRODUCTION

Biology, a cornerstone of science education, plays an essential role in fostering scientific literacy, promoting public health awareness, and preparing students for careers in healthcare, environmental science, and biotechnology. In Nigeria, the subject is embedded in the senior secondary school curriculum to equip learners with relevant knowledge and practical skills for personal and national development (Nanglu et al., 2023). Despite its fundamental relevance, there remains a persistent challenge: the academic performance of students in Biology continues to decline, as reflected in national examination results such as the West African Examination Council (WAEC) and the National Examination Council (NECO) (Chukwu & Arokoyu, 2019).

This decline in performance is multifaceted, encompassing disparities in instructional quality, inadequate learning resources, and the ineffectiveness of traditional teaching approaches. A significant concern is the systemic disparity between private and public schools. Studies indicate that students in private schools often outperform their public-school counterparts due to better facilities, structured learning environments, and higher levels of teacher preparedness (Abidoye et al., 2023; Olutola, 2020). Conversely, students in public schools face a convergence of structural deficits including overcrowded classrooms, poorly trained teachers, and limited access to teaching aids, all of which hinder academic success (Abidoye et al., 2023). Moreover, parental involvement and socio-cultural support have been identified as critical determinants of students' academic outcomes in Biology (Udoinyang & Ogbonnaya-Ngwu, 2024). Students lacking such support systems frequently struggle with low motivation and test anxiety, both of which negatively influence academic performance (Onoshakpokaiye & Okigbo, 2023).

Beyond socio-economic and institutional factors, the teaching methods adopted in classrooms have a profound impact on students' comprehension of Biology. Traditional pedagogies, largely characterized by lecture-based instruction, have failed to sufficiently engage students or facilitate deep understanding of complex biological concepts such as the human circulatory system (Etobro & Fabinu, 2017). These methods promote passive learning and do little to stimulate critical thinking or practical application of theoretical knowledge (Ewais et al., 2024; Nurdin, 2021). This pedagogical inertia is particularly problematic in topics involving abstract or multi-dimensional content, where students often struggle to visualize biological structures and processes (Deng et al., 2025; Manishimwe et al., 2023).

To bridge this pedagogical gap, contemporary scholarship increasingly advocates for the adoption of interactive and learner-centered instructional strategies. These include the use of collaborative learning, problem-based learning, and, notably, instructional media that leverage visual and tactile modalities (Luwoye et al., 2023; Nwankwo et al., 2024). The human circulatory system, a key topic in secondary Biology, exemplifies a content area that benefits significantly from such innovations due to its anatomical and physiological complexity. Studies have shown that using three-dimensional (3D) instructional models significantly improves students' understanding by facilitating spatial reasoning and promoting active engagement with biological content (Kasuga et al., 2022; Lantzouni et al., 2024).

In educational settings with limited resources, the integration of low-cost technological tools represents a practical and effective solution. These tools, including locally fabricated 3D models and multimedia applications, provide learners with visual representations that support deeper conceptual understanding and retention (Ahmed & Odewumi, 2020; Nihuka & Matemu, 2024). Empirical evidence underscores the superior performance of students exposed to such tools, compared to those instructed through conventional means (Nomsoor et al., 2021; Wasehudin et al., 2022). Furthermore, studies reveal that tactile learning—where students physically manipulate learning models—not only enhances comprehension but also fosters enthusiasm for learning (O. & Chinonyelum, 2022; Puger, 2023).

The challenge, however, lies not only in the availability of these tools but also in educators' ability to effectively integrate them into the curriculum. Numerous studies point to a significant gap in teacher preparedness, particularly regarding the use of modern pedagogical techniques and educational technology (Bamigbade et al., 2021; Falemu &

Akinwumi, 2023). Teachers who are not adequately trained are less likely to adopt innovative methods or leverage technology to enhance instruction, thereby limiting students' learning experiences (Alonge et al., 2021; Ogundare et al., 2023). The situation is exacerbated by high teacher workloads and limited access to continuous professional development programs, both of which restrict opportunities for pedagogical improvement (Abidoye & Abidoye, 2023). Consequently, equipping teachers with the necessary skills to utilize instructional models and interactive media is imperative to reforming Biology education in Nigeria.

In addition to classroom instruction, effective school management and systemic support are indispensable to educational reform. Strategic leadership, consistent supervision, and the involvement of all educational stakeholders—including administrators, parents, and policymakers—create enabling environments for instructional innovation (Ayeni & Bamire, 2022; Ononuju et al., 2023). Institutions that prioritize instructional quality and resource allocation are better positioned to support scientific literacy among students. The marginalization of Biology as a core subject for non-science students, as recently witnessed in Nigeria, poses further risks to public health education, scientific reasoning, and national development (Harrandah, 2024; Usman et al., 2023). The removal of Biology from core curricula could amplify inequities and reduce students' exposure to essential biological knowledge, especially in public schools that already struggle with instructional quality (Ala et al., 2022; Baiden & Agbene, 2022).

Given these challenges and the demonstrated benefits of interactive learning, this study investigates the impact of a locally developed 3D model of the human circulatory system on students' academic performance in Biology. This model, designed and validated by experts, offers a practical alternative to high-cost technological tools often inaccessible in public schools. By comparing student outcomes in experimental and control groups across both private and public schools, the study seeks to determine whether such a model can bridge performance gaps and foster a more equitable learning environment. The novelty of the study lies in its empirical validation of a cost-effective and scalable instructional intervention suitable for diverse educational settings.

The scope of the study encompasses senior secondary students in Ilorin, Nigeria, with the objective of assessing whether the use of a 3D instructional model enhances academic performance and whether differences persist based on school ownership. The study hypothesizes that there is no significant difference in students' academic performance based on school ownership when taught using the 3D model. This investigation contributes to the growing body of literature advocating for low-cost, interactive, and pedagogically sound instructional tools in science education, particularly in developing countries.

METHOD

Research Design

This study adopted a quasi-experimental post-test non-randomized control group design to examine the effect of a locally constructed 3-Dimensional Model of the Human Circulatory System (3-DMHCS) on students' academic performance in Biology. This design was selected due to its suitability for educational environments where random assignment of participants is impractical, particularly in intact classroom settings. The design enabled a comparison of student outcomes between an experimental group exposed to the 3D model and a control group taught with conventional instructional methods. Such an approach is commonly employed in evaluating educational innovations where logistical and ethical constraints preclude randomization, yet a need persists to determine causal impacts

(Kaewyongphang et al., 2024; Zorluoğlu et al., 2022). The schematic layout consisted of two groups, showed in Table 1.

Table 1. Research design layout

Groups	Treatment	Post-test
Experimental Group 1	3-DMHCS	O_1
Control group 2	Conventional Method	O_2

Only post-test assessments were conducted to determine learning gains resulting from the intervention.

Population and Sample

The population of this study comprised all senior secondary school students in Ilorin, Kwara State, Nigeria. The sample was selected through a simple random sampling technique, targeting two intact classes from two secondary schools—one government-owned (public) and one privately owned. These schools were selected to reflect institutional diversity and to enable comparative performance analyses. The total number of participants was 60 students, with 35 in the experimental group and 25 in the control group. This sampling approach ensured that the groups were reasonably comparable in terms of demographics, albeit without randomization, which aligns with best practices for quasi-experimental studies in classroom research (Cai et al., 2023; Zorluoğlu et al., 2022).

Instructional Instrument: The 3D Model (3-DMHCS)

The instructional treatment employed in the experimental group was the 3-DMHCS—a locally designed and developed physical model intended to visually and tangibly represent the human circulatory system. The model was constructed by the lead researcher and validated by experts from the Department of Educational Technology at the University of Ilorin (Olumorin et al., 2021). Its design aimed to enhance visualization and student interaction with complex biological content, consistent with research affirming the benefits of tactile and visual instructional tools in promoting conceptual understanding in science (Bonorden & Papenbrock, 2022; Lantzouni et al., 2024).

The model was aligned with the Nigerian senior secondary Biology curriculum, ensuring its pedagogical appropriateness. It was designed using accessible, low-cost materials, enabling replication across under-resourced schools. The application of the model involved direct student engagement during instructional sessions, where students could observe, identify, and manipulate components of the circulatory system. This interactivity was intended to foster deeper learning and retention, supporting findings from studies on interactive STEM tools in education (Shudayfat & Alsalhi, 2023).

Assessment Instrument: Biology Performance Test (BPT)

Student achievement was measured using a custom-developed Biology Performance Test (BPT), which consisted of 20 multiple-choice items designed to assess comprehension of the human circulatory system. The BPT was developed based on standard curriculum objectives and validated by three experienced secondary school Biology teachers. Reliability testing was conducted using the Kuder-Richardson Formula 20 (KR-20), yielding a coefficient of 0.86, indicating high internal consistency.

Accompanying the BPT, a structured Lesson Note (LN) was prepared for uniformity in lesson delivery across both groups. This lesson note was also reviewed and validated by subject matter experts to ensure alignment with pedagogical standards and curricular goals.

The validation and reliability testing of instructional and assessment instruments ensured the robustness of the study's internal validity (Cheng et al., 2021; Kaewyongphang et al., 2024).

Data Collection and Analysis

Instructional sessions were conducted over a standard lesson period, after which the BPT was administered to both groups. Data from the post-test were analyzed using both descriptive statistics (mean scores, percentages, standard deviations) and inferential statistics. A t-test for independent samples was used to determine the significance of the differences in academic performance between the experimental and control groups, as well as between public and private school students.

The statistical analysis was conducted at a significance level of 0.05. While the non-randomized nature of the sample introduced potential limitations, efforts were made to mitigate these through careful matching of school types and instructional exposure. The quasi-experimental design, although susceptible to confounding variables, provided a pragmatic and contextually appropriate method for evaluating the effectiveness of instructional innovation in real classroom settings (Zorluoğlu et al., 2022). Future studies are encouraged to incorporate additional control measures, such as pre-tests or ANCOVA, to adjust for initial group differences and improve generalizability.

Ethical Considerations

The study adhered to stringent ethical guidelines to protect participants' rights and ensure the integrity of the research process. Informed consent was obtained from all respondents, who were provided with a detailed explanation of the study's objectives and their rights, including the ability to withdraw at any stage without penalty. Measures were implemented to maintain confidentiality and anonymity, such as secure data handling and the use of anonymized codes for responses. By fostering trust and transparency, these practices aligned with ethical standards in educational research and contributed to the study's credibility.

RESULTS AND DISCUSSION

Control Group Students' Post-Test Performance

The performance of students in the control group—those taught using conventional instructional methods—was evaluated using post-test scores from both public and private schools. Table 2 of the original dataset presents the distribution of these scores by frequency and percentage.

Table 2. Frequency and percentage of the post-test scores of the students in the control group in both public and private schools

Score Range	Public School (n = 21)		Private School (n = 4)	
	Frequency	%	Frequency	%
0–5	0	0.0	0	0.0
6–10	11	52.3	2	50.0
11–15	10	47.7	2	50.0
16–20	0	0.0	0	0.0

The data indicates that most students in both public and private schools scored between 6 and 15, with no students achieving high performance (16–20). In public schools, 52.3% scored within the lower category (6–10), and 47.7% scored in the average range (11–15).

Similarly, in private schools, scores were evenly split: 50% in the lower and 50% in the average range. No students in either group attained a high score.

These findings reveal the limitations of conventional instructional methods in fostering high academic achievement, consistent with existing literature emphasizing the inadequacy of traditional teacher-centered approaches in engaging learners effectively. Previous study (Oluwole et al., 2024) widespread dissatisfaction among students with conventional methods, which they attributed to lack of interaction, passive learning, and minimal hands-on engagement. Furthermore, students exposed to more collaborative, interactive learning strategies demonstrated greater retention and understanding of complex topics, including biological sciences (Sada & Adamu, 2023).

The difference in performance between students in public and private schools also mirrors prior research on the influence of institutional resources. Alordiah et al. (2023) argue that the disparity in educational infrastructure and instructional quality between public and private institutions contributes significantly to variations in academic performance. While private schools may provide a slightly better environment for learning even under traditional methods, systemic limitations in public schools—including class overcrowding and insufficient materials—continue to suppress optimal student outcomes.

These disparities also align with the broader socio-economic context in Nigeria, where resource limitations constrain public education reform. Previous studies (Hizal, 2022; Ukpe, 2023) support the result of this study that highlight how insufficient infrastructure and limited access to innovative tools negatively affect student engagement, particularly in science subjects. The relevance of school context is further underscored by Onivehu (2022), who links students' academic success with psychosocial factors such as self-esteem and perceived classroom inclusion.

Consequently, the post-test data from the control group substantiates concerns raised in the literature, especially when deployed in under-resourced environments—fall short in advancing student understanding of complex biological content. It highlights the urgent need for low-cost, interactive educational interventions that can address these limitations and uplift biology instruction quality in Nigerian secondary schools.

Experimental Group Students' Post-Test Performance

The implementation of a 3D instructional model for teaching the human circulatory system yielded significant improvements in students' academic performance compared to traditional methods. Students in the experimental group, who engaged with the 3D Model of Human Circulatory System (3-DMHCS), achieved higher scores on post-test assessments than those in the control group, indicating enhanced comprehension and retention.

Table 3. Frequency and percentage of the post-test scores of the students in the experimental group in both public and private schools

Score Range	Public School (n = 28)		Private School (n = 7)	
	Frequency	%	Frequency	%
0–5	0	0.0	0	0.0
6–10	1	3.6	0	0.0
11–15	12	42.8	5	71.5
16–20	15	53.6	2	28.5

As shown in Table 3, the performance distribution among experimental group students was noticeably skewed toward higher score ranges. In public schools, 53.6% of students scored in the highest range (16–20), while an additional 42.8% fell within the average category

(11–15). Only 3.6% of students scored between 6 and 10, and none scored below 5. For private school students, 71.5% scored in the average range (11–15), and 28.5% achieved high scores (16–20).

These findings align with a substantial body of research supporting the efficacy of three-dimensional instructional tools in enhancing student learning. Babalola et al. (2022) found that 3D models serve as crucial cognitive bridges, improving students' ability to conceptualize complex structures such as the circulatory system. By incorporating tactile and visual elements, the 3D model effectively engaged students in a multimodal learning environment, leading to better academic outcomes. Further, the use of 3D models has been shown to reduce cognitive load by presenting anatomical and physiological processes in a spatially coherent and visually stimulating format (Chen et al., 2024). The hands-on nature of the 3D model allowed students to interact directly with representations of the heart, blood vessels, and circulatory circuits, translating abstract textbook content into concrete learning experiences. This supports earlier findings by Segarra and Richard (2020), who argued that engaging multiple senses in learning promotes memory retention and conceptual clarity.

The affective and motivational dimensions of using 3D instructional tools were also evident. According to Alexander et al. (2024), integrating 3D-printed models in biology classrooms not only enhances comprehension but also boosts students' enthusiasm for science subjects. Students exposed to 3-DMHCS in this study exhibited observable excitement during lessons, often asking more in-depth questions and participating more actively than their peers in the control group. Moreover, students' ability to manipulate components of the model—such as tracing the flow of blood or identifying the roles of valves and arteries—reinforced understanding of physiological dynamics, a benefit corroborated (Subran & Mahmud, 2024). These tactile learning opportunities fostered spatial awareness, a critical skill for mastering human anatomy, and were reflected in the high proportion of students scoring between 11 and 20 on the assessment scale.

In addition to cognitive gains, the 3-DMHCS also appeared to support collaborative learning. As reported by Ramirez and Gordy (2020), working with shared 3D models allows students to discuss, hypothesize, and explain concepts to peers, creating a socially interactive learning environment. These group interactions likely contributed to students' deeper processing of information and higher academic performance. Furthermore, studies by Banerjee et al. (2023) suggest that haptic and interactive feedback mechanisms improve user immersion and learning outcomes. While the model used in this study did not integrate digital haptic feedback, the physical manipulation inherent in the 3D model provided similar kinesthetic engagement. As confirmed by previous studies (Webb et al., 2021; Wollmuth et al., 2023), these forms of active engagement are instrumental in increasing comprehension and learning retention, especially in subjects like Biology where spatial and functional relationships are central to understanding.

The data from this study corroborate prior literature advocating for innovative pedagogical strategies in science education. The 3D model not only enhanced academic achievement but also cultivated a more engaging, collaborative, and student-centered classroom experience. These findings strongly support the inclusion of low-cost, scalable 3D instructional models in the teaching of complex scientific content, particularly within under-resourced educational contexts.

Comparison of Private and Public-School Students' Performance

The comparative analysis of student performance between public and private schools provides insight into the influence of school ownership on the effectiveness of instructional innovations. Table 4 and Table 5 present the mean scores and statistical significance of students' post-test performance in both school types.

Table 4. Mean and standard deviation of the students' academic performance based on school ownership

Variable	N	Mean	Std. Deviation
Private School	11	13.36	3.44
Public School	49	13.14	3.71

The mean performance score for private school students was 13.36, while for public school students it was 13.14—a marginal difference of 0.22. The statistical analysis using an independent sample t-test revealed no significant difference in performance between students from the two school types ($t(58) = -0.180$, $p = 0.86$, $p > 0.05$). This suggests that the 3D instructional model had a uniformly positive effect on student learning, regardless of school ownership.

Table 5. Summary of the t-test analysis of private and public-school students' academic performance

School Type	N	$\bar{X}$	SD	Df	t	Sig. (2-tailed)	Remark
Private	11	13.36	3.44	58	-0.180	0.86	Not rejected
Public	49	13.14	3.71				

These findings contrast with prevailing literature highlighting disparities in educational outcomes between private and public schools. For instance, Fahm et al. (2021) and Boholano et al. (2021) emphasize that private schools often have greater access to instructional technologies and support infrastructure, which translates into better student performance. This general advantage is frequently attributed to superior funding, smaller class sizes, and higher levels of teacher preparedness in private institutions (Daramola & Aladesusi, 2022; Nuryadin et al., 2023).

Despite these systemic differences, the use of the 3-DMHCS in this study appears to mitigate those disparities, suggesting that well-designed low-cost instructional tools can provide equitable learning benefits. This result aligns with studies that advocate for resource-sensitive pedagogical innovations as equalizers in educational quality (Agyei, 2022; Banerjee et al., 2023). The tactile and visual nature of the 3D model may have leveled the instructional playing field, offering students in public schools an engaging and comprehensible means to grasp complex biological content.

However, it is important to consider that familiarity with technology and institutional readiness can still influence the long-term adaptability of such innovations. Literature shows that teachers in private schools are generally more confident and willing to integrate technology into their teaching practices, owing to better training and institutional support (Nadhif et al., 2024; Rasdiana et al., 2024). Public school teachers often face constraints such as outdated equipment, insufficient professional development opportunities, and rigid administrative structures (Adejoke et al., 2024; Yehya, 2021), which may affect sustained implementation.

Student readiness is another relevant factor. Private school students are more likely to have prior exposure to digital tools at home, which enhances their adaptability to classroom technologies (Patrick et al., 2021). In contrast, public school students may encounter steeper learning curves when introduced to unfamiliar instructional models, potentially affecting engagement and comprehension.

Nevertheless, the findings of this study demonstrate that when educational innovations such as 3D instructional models are properly implemented and supported, they can yield significant improvements across diverse school environments. This reinforces the importance of deploying accessible and effective pedagogical tools, alongside training and infrastructural support, to reduce educational inequities and improve learning outcomes system-wide (Berame, 2023; Surajudeen et al., 2022).

Discussion

This study investigated the effect of a 3-Dimensional Model of the Human Circulatory System (3-DMHCS) on students' academic performance in secondary school Biology, with comparisons across public and private schools. The findings corroborate existing theoretical and empirical literature, particularly those grounded in constructivist and multimodal learning paradigms.

Results from Table 2 indicate that students in the control group, who were instructed through conventional methods, scored predominantly in the low to average ranges, with no students attaining high scores (16–20). Specifically, 52.3% of public school students and 50% of private school students in the control group performed below average. These results align with longstanding critiques of traditional pedagogical approaches, which are often passive, text-heavy, and fail to engage diverse learning styles (Oluwole et al., 2024; Sada & Adamu, 2023). The underperformance observed reaffirms the limitations of conventional instruction in adequately conveying complex biological content such as the circulatory system.

Conversely, data from Table 3 show that the experimental group—students taught using the 3-DMHCS—demonstrated substantially improved academic outcomes. In public schools, 53.6% of students achieved high scores (16–20), and in private schools, 71.5% scored within the average range (11–15). These gains support previous studies indicating the efficacy of 3D instructional models in improving cognitive engagement and reducing abstractness in scientific learning (Alexander et al., 2024; Babalola et al., 2022). The visual and tactile properties of the 3D model enhanced spatial reasoning and conceptual clarity, particularly critical for understanding dynamic systems like human circulation (Segarra & Richard, 2020; Subran & Mahmud, 2024).

The effectiveness of the 3-DMHCS further substantiates cognitive load theory, which posits that instructional tools that externalize information spatially reduce extraneous cognitive load and enhance germane processing. By enabling learners to manipulate and visually explore anatomical components, the model fosters intuitive understanding (Banerjee et al., 2023; Chen et al., 2024). Such kinesthetic learning opportunities are particularly beneficial for complex and multilayered subjects like Biology.

Importantly, the post-test results revealed no statistically significant difference in performance between public and private school students when the 3-DMHCS was used (Table 5; $t = -0.180$, $p = 0.86$). This finding diverges from much of the literature which identifies resource disparities between school types as a major factor in academic outcomes (Boholano et al., 2021; Fahm et al., 2021). However, it suggests that well-designed, low-cost instructional innovations can mitigate systemic inequities by offering equally effective learning experiences across diverse contexts. This supports the argument that technological parity in instruction does not necessarily require high-cost investments but can be achieved through context-sensitive innovation (Agyei, 2022; Rasdiana et al., 2024).

Furthermore, the use of 3D models aligns closely with constructivist learning theories. These models promote active learning, allowing students to interact with the content physically, mentally reconstruct biological systems, and contextualize their knowledge through exploration (Gordy et al., 2020; Saeed, 2022). They also facilitate collaborative learning, enabling peer discussions, collective problem-solving, and the verbalization of understanding—components essential to Vygotsky's social constructivism (Erawati & Adnyana, 2024; Syahid et al., 2023).

The multimodal nature of 3D models makes them particularly potent in meeting the needs of diverse learners. By incorporating visual, tactile, and auditory cues, these models enrich the learning experience and cater to varying preferences and abilities (Mawadah et al., 2023; Raza et al., 2023). This inclusive characteristic enhances student engagement, promotes higher-order thinking, and fosters long-term retention, as reflected in findings that show students retained knowledge of the circulatory system better through tactile engagement (Alshamrani et al., 2021; Berton et al., 2023). Moreover, the 3-DMHCS cultivated enthusiasm and intrinsic motivation among students, reinforcing research suggesting that experiential learning environments stimulate interest in science and improve attitudes toward the discipline (Alexander et al., 2024; Wollmuth et al., 2023). This shift in motivation is crucial in a subject often perceived as difficult or abstract.

In light of these results, it is evident that incorporating 3D instructional tools in science education supports pedagogical transformation. Beyond classroom practice, these findings have implications for broader educational policy. As illustrated by successful small-scale interventions (Hurst-Kennedy et al., 2020; Mısbah et al., 2024), scalable innovations can influence national science curriculum reforms, especially when supported by structured professional development and institutional support (Nuhoğlu et al., 2024; Pan et al., 2023).

Nevertheless, the integration of 3D instructional models requires careful planning, adequate teacher training, and systemic support. Teachers must be empowered with the skills to use these tools effectively and align them with curricular goals (Irfan et al., 2024; Subedi, 2021). Furthermore, enabling environments—both in terms of resources and leadership—are necessary to institutionalize these innovations sustainably.

This study confirms that 3D instructional models serve as effective pedagogical tools that enhance students' comprehension, performance, and engagement in Biology. Their application bridges performance gaps across school types and supports a learner-centered, multimodal, and constructivist educational approach. Moving forward, education stakeholders should consider adopting such models not merely as classroom supplements but as central components in science teaching reform and teacher professional development.

CONCLUSION

This study provides strong empirical evidence supporting the use of a 3-Dimensional Model of the Human Circulatory System (3-DMHCS) as an effective instructional innovation for teaching Biology in secondary schools. Students exposed to the 3D model demonstrated markedly higher academic performance than those taught through conventional methods, indicating that visual and tactile learning significantly enhances comprehension of complex biological systems. Moreover, the absence of statistically significant performance differences between students in public and private schools affirms the model's potential to provide equitable learning experiences across diverse educational settings.

The 3-DMHCS facilitates multimodal engagement, stimulates student interest, and promotes deeper understanding through constructivist and inquiry-based learning principles. Its alignment with current educational theories underscores its relevance as a scalable pedagogical tool, particularly in under-resourced contexts where traditional instructional methods continue to underperform.

RECOMMENDATION

In light of these findings, it is recommended that educational stakeholders integrate 3D instructional models into the standard science curriculum, particularly for teaching abstract and complex topics such as the circulatory system. Teacher training programs should incorporate modules on the use of low-cost, interactive models to enhance instructional delivery and student engagement. Furthermore, education policy frameworks should support the development and validation of localized instructional tools that are context-sensitive and budget-friendly.

Policymakers are encouraged to invest in infrastructure and professional development that enable the effective implementation of such innovations, especially in public schools where resource constraints are more pronounced. Future research should explore the long-term retention effects of 3D instructional tools and their scalability across other science disciplines and geographic regions.

Author Contributions

The authors have sufficiently contributed to the study, and have read and agreed to the published version of the manuscript.

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Declaration of Interest

The authors declare no conflict of interest.

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