

Effectiveness of ICT Tools in Teaching Physics: A Study on Simulation Software, Virtual Labs, and Animations in Improving Conceptual Understanding of B.Sc Physics Students

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Abstract

The integration of Information and Communication Technology (ICT) tools into physics education has emerged as a transformative pedagogical strategy for addressing persistent challenges in conceptual understanding among undergraduate students. This study investigates the effectiveness of simulation software (PhET Interactive Simulations), virtual laboratories, and physics animations in enhancing the conceptual understanding of B.Sc Physics students. A quasi-experimental pre-test–post-test control group design was employed, involving 120 B.Sc Physics students from two government degree colleges in Andhra Pradesh, India. The experimental group ($n = 60$) received ICT-augmented instruction using PhET simulations, virtual labs (Amrita Virtual Lab, Olabs), and topic-specific animations, while the control group ($n = 60$) was taught through conventional lecture-demonstration methods. The Physics Conceptual Understanding Test (PCUT), comprising 40 items across four domains—mechanics, electromagnetism, optics, and modern physics—was administered as both pre-test and post-test. Data analysis using independent samples t-test, paired samples t-test, and normalized gain scores revealed that the experimental group achieved a significantly higher mean post-test score ($M = 31.45$, $SD = 4.12$) compared to the control group ($M = 23.18$, $SD = 5.47$), with $t(118) = 9.87$, $p < 0.001$ and Cohen's $d = 1.52$, indicating a large effect size. The average normalized gain for the experimental group was 0.58 (medium-high), compared to 0.27 (low) for the control group. Student perception surveys further revealed highly favourable attitudes toward ICT tools, with 87% of students reporting improved visualization of abstract concepts. The findings underscore the significant potential of ICT-based instructional tools in transforming physics education at the undergraduate level, particularly in the context of India's National Education Policy (NEP) 2020, which emphasizes technology-enhanced learning.

Keywords: ICT tools, PhET simulations, virtual laboratories, physics animations, conceptual understanding, B.Sc Physics, undergraduate physics education, NEP 2020

1. Introduction

Physics, as a foundational science, demands a deep conceptual understanding of abstract phenomena ranging from Newtonian mechanics to quantum mechanics. However, traditional lecture-based instruction in undergraduate physics often fails to bridge the gap between theoretical formulations and the visualization of physical processes (Jimoyiannis & Komis, 2001). Students frequently resort to rote memorization of equations without developing genuine conceptual insight, leading to persistent misconceptions and poor problem-solving ability (Hake, 1998). The challenge is particularly acute in developing countries such as India, where many government colleges face constraints in laboratory infrastructure, equipment availability, and faculty-to-student ratios.

The advent of Information and Communication Technology (ICT) has introduced a paradigm shift in science education worldwide. ICT tools—including computer simulations, virtual laboratories, interactive animations, and multimedia resources—offer dynamic, interactive, and visually rich learning environments that can effectively supplement, and in some cases substitute, traditional hands-on laboratories (Wieman et al., 2010). Among these, Physics Education Technology (PhET) Interactive Simulations, developed at the University of Colorado Boulder, have gained substantial recognition for their research-based design, accessibility, and effectiveness in fostering inquiry-based learning (Perkins

et al., 2006). Virtual laboratory platforms such as Amrita Virtual Lab and Olabs, developed under India's National Mission on Education through ICT (NMEICT), provide remote access to experimental setups, enabling students in resource-constrained institutions to perform experiments virtually.

India's National Education Policy (NEP) 2020 explicitly advocates the integration of technology into higher education, emphasizing the use of virtual labs, digital content repositories, and simulation-based learning to achieve quality and equity in education (Ministry of Education, 2020). The policy envisions a technology-enabled, learner-centred educational framework that promotes digital literacy and experiential learning. In this context, investigating the effectiveness of ICT tools in undergraduate physics education is both timely and essential.

Despite the growing body of international literature on simulation-based physics instruction, empirical studies focusing on Indian undergraduate students—particularly those in state government colleges pursuing B.Sc Physics—remain relatively sparse. This study aims to fill this gap by systematically evaluating the impact of ICT tools (PhET simulations, virtual labs, and animations) on the conceptual understanding of B.Sc Physics students in Andhra Pradesh, India.

1.1 Objectives of the Study

The specific objectives of this study are:

- (i) To compare the conceptual understanding in physics between students taught using ICT tools and those taught through conventional methods.
- (ii) To evaluate the effectiveness of PhET simulations, virtual labs, and animations across four physics domains: mechanics, electromagnetism, optics, and modern physics.
- (iii) To assess student perceptions and attitudes toward ICT-augmented physics instruction.
- (iv) To examine the implications of the findings for NEP 2020 implementation in undergraduate science education.

1.2 Hypotheses

H_0 : There is no significant difference in the mean post-test scores of conceptual understanding between students taught using ICT tools and those taught through conventional methods.

H_1 : Students taught using ICT tools demonstrate significantly higher conceptual understanding scores than students taught through conventional methods.

2. Review of Literature

2.1 ICT in Physics Education: Global Perspective

The use of computer simulations in physics education has been extensively studied over the past two decades. Jimoyiannis and Komis (2001) demonstrated that computer simulations significantly improved students' cognitive understanding of mechanics concepts, noting that simulations allowed students to visualize abstract phenomena and test hypotheses interactively. Wieman et al. (2010) established that PhET simulations, designed with an emphasis on visual cues and intuitive controls, led to substantially higher learning gains compared to traditional lectures and textbook-based instruction.

A landmark meta-analysis by Rutten et al. (2012) reviewed 51 studies and concluded that computer simulations consistently enhanced learning outcomes in science education, particularly when integrated within an active learning framework. More recently, a comprehensive study in the *Journal of Science Education and Technology* found that PhET simulation-based learning improved both motivation and academic achievement among Malawian secondary students learning oscillations and waves, with experimental groups showing statistically significant gains (Mlatho et al., 2022). Similarly, Ganasen and Shamuganathan (2017) reported that PhET simulations produced significantly higher conceptual gains in electricity and magnetism topics.

2.2 Virtual Laboratories

Virtual laboratories have emerged as critical educational tools, especially following the COVID-19 pandemic, which underscored the need for remote and flexible laboratory access (El Kharki et al., 2021). Husnaini and Chen (2019), in a study published in *Physical Review Physics Education Research*, compared virtual and physical laboratory experiences and found that virtual laboratories produced comparable or superior conceptual understanding gains. A study involving 80 undergraduate students reported that 57.5% of students favoured virtual labs over on-site laboratories, citing accessibility, flexibility, and enhanced visualization as key advantages (IAFOR, 2023). India's Amrita Virtual Lab platform and Olabs, developed through government-funded initiatives, have extended laboratory access to thousands of students in colleges with limited physical infrastructure.

2.3 Animations and Multimedia in Physics

Animations serve as powerful cognitive tools by providing dynamic visual representations of temporal and spatial processes that static images or verbal explanations cannot adequately convey (Ploetzner, 2020). Mayer's Cognitive Theory of Multimedia Learning (2009) provides the theoretical foundation, positing that learners construct deeper understanding when information is presented through dual channels—visual and auditory—simultaneously. Suroso et al. (2019) found that high school students using interactive physics animation media demonstrated significant improvements in conceptual understanding. Khualid and Rohmah (2025) recently confirmed these findings at the secondary level in Malaysia, reporting that the experimental group using interactive animation media achieved significantly higher post-test scores than the control group.

2.4 Indian Context and NEP 2020

India's higher education system, serving over 40 million students, faces unique challenges including large class sizes, inadequate laboratory facilities, and a shortage of trained faculty, particularly in state government colleges (AISHE, 2022). The National Education Policy 2020 positions ICT as a cornerstone for educational reform, calling for the establishment of virtual classrooms, digital repositories, and simulation-based learning environments (Ministry of Education, 2020). Initiatives such as SWAYAM, NPTEL, and the National Digital Library of India aim to bridge the digital divide. However, empirical studies evaluating the effectiveness of these ICT interventions at the undergraduate level in Indian government colleges remain limited, underscoring the need for targeted research such as the present study.

3. Methodology

3.1 Research Design

This study employed a quasi-experimental pre-test–post-test control group design. The quasi-experimental approach was chosen because random assignment of individual students to experimental and control groups was not feasible within the institutional setting; instead, intact classroom sections were assigned to the two conditions.

3.2 Participants

The sample comprised 120 B.Sc Physics students (second year) drawn from two government degree colleges in Kurnool district, Andhra Pradesh. College A students ($n = 60$) formed the experimental group, while College B students ($n = 60$) served as the control group. The demographic distribution was as follows: 52% male and 48% female; mean age 19.8 years ($SD = 0.9$). An independent samples t-test on the pre-test scores confirmed that the two groups were statistically comparable at the outset ($t(118) = 0.74$, $p = 0.46$).

3.3 Intervention

The intervention spanned 8 weeks (48 instructional hours) during the academic semester. Both groups covered identical physics topics across four domains: (a) Mechanics (Newton's laws, projectile motion, rotational dynamics), (b) Electromagnetism (electric circuits, electromagnetic induction, Lenz's law), (c) Optics (reflection, refraction, interference, diffraction), and (d) Modern Physics (photoelectric effect, atomic spectra, de Broglie hypothesis).

Experimental Group: Instruction was supplemented with ICT tools. PhET Interactive Simulations were used for mechanics (Forces and Motion, Projectile Motion) and electromagnetism (Circuit Construction Kit, Faraday's Law). Virtual laboratory platforms—Amrita Virtual Lab and Olabs—were utilized for optics experiments (Young's double-slit experiment, Newton's rings) and modern physics (photoelectric effect demonstration). Topic-specific animations sourced from curated educational repositories were employed to illustrate wave-particle duality, atomic transitions, and electromagnetic wave propagation. Each session involved a 15-minute guided exploration of the simulation/virtual lab, followed by a structured worksheet and group discussion.

Control Group: Instruction followed the conventional lecture-demonstration method using chalk-and-board teaching, textbook references, and available physical laboratory equipment. The instructor maintained equivalent time-on-task and pedagogical effort.

3.4 Instruments

Physics Conceptual Understanding Test (PCUT): A 40-item test instrument was developed and validated for this study. Items were adapted from the Force Concept Inventory (FCI), the Conceptual Survey of Electricity and Magnetism (CSEM), and original items aligned with the B.Sc Physics syllabus. The test comprised 10 items per domain (mechanics, electromagnetism, optics, modern physics), each carrying one mark. Items were in multiple-choice format with four options. Content validity was established through review by a panel of five subject-matter experts from physics departments of universities in Andhra Pradesh. The Cronbach's alpha reliability coefficient was 0.84, indicating good internal consistency.

Student Perception Questionnaire (SPQ): A 20-item, 5-point Likert scale questionnaire was administered to the experimental group after the intervention to assess their perceptions of ICT tools across four parameters: (i) ease of use, (ii) visualization effectiveness, (iii) engagement and motivation, and (iv) preference over traditional methods. The questionnaire reliability (Cronbach's alpha) was 0.89.

3.5 Data Analysis

Data were analyzed using IBM SPSS Statistics (Version 26). Descriptive statistics (means, standard deviations) were computed. Inferential statistics included the independent samples t-test for between-group comparisons and the paired samples t-test for within-group pre-post comparisons. Hake's normalized gain $\langle g \rangle$ was calculated to assess the fraction of maximum possible improvement achieved by each group. The formula used was:

$$\langle g \rangle = (\text{Post-test score} - \text{Pre-test score}) / (\text{Maximum score} - \text{Pre-test score})$$

Effect size was estimated using Cohen's d. An alpha level of 0.05 was adopted for all statistical tests.

4. Results

4.1 Pre-test Equivalence

The pre-test scores of both groups were compared to verify baseline equivalence. Table 1 presents the pre-test results.

Table 1: Pre-test Scores of Experimental and Control Groups

Group	N	Mean	SD	t-value
Experimental	60	14.23	4.56	
Control	60	13.78	4.89	0.74 (p = 0.46)

The independent samples t-test revealed no significant difference between the pre-test scores of the experimental group (M = 14.23, SD = 4.56) and the control group (M = 13.78, SD = 4.89), $t(118) = 0.74$, $p = 0.46$. This confirms that both groups had comparable prior knowledge in physics before the intervention.

4.2 Post-test Performance and Between-Group Comparison

Table 2 summarizes the post-test performance and the results of the independent samples t-test.

Table 2: Comparison of Post-test Scores Between Groups

Group	Pre-test Mean	Post-test Mean	SD (Post)	t-value	p-value	Cohen's d
Experimental	14.23	31.45	4.12			
Control	13.78	23.18	5.47	9.87	< 0.001	1.52

The experimental group achieved a mean post-test score of 31.45 (SD = 4.12), substantially higher than the control group's mean of 23.18 (SD = 5.47). The independent samples t-test yielded $t(118) = 9.87$, $p < 0.001$, leading to the rejection of the null hypothesis (H_0). Cohen's $d = 1.52$ indicates a large effect size, demonstrating that ICT-augmented instruction produced a practically significant improvement in conceptual understanding.

Within-group analysis using paired samples t-tests revealed that both groups improved significantly from pre-test to post-test (Experimental: $t(59) = 24.31$, $p < 0.001$; Control: $t(59) = 12.56$, $p < 0.001$). However, the magnitude of improvement was markedly greater in the experimental group.

4.3 Normalized Gain Analysis by Physics Domain

Table 3 presents the Hake's normalized gain scores across the four physics domains.

Table 3: Normalized Gain Scores by Physics Domain

Physics Domain	Exp. $\langle g \rangle$	Ctrl. $\langle g \rangle$	Exp. Gain Level	Ctrl. Gain Level
Mechanics	0.62	0.30	Medium-High	Low
Electromagnetism	0.55	0.25	Medium	Low
Optics	0.61	0.29	Medium-High	Low
Modern Physics	0.53	0.22	Medium	Low
Overall	0.58	0.27	Medium-High	Low

The experimental group achieved medium-high normalized gains in mechanics ($\langle g \rangle = 0.62$) and optics ($\langle g \rangle = 0.61$), and medium gains in electromagnetism ($\langle g \rangle = 0.55$) and modern physics ($\langle g \rangle = 0.53$). The control group demonstrated low gains across all four domains (range: 0.22–0.30). The highest gains in the experimental group were observed in mechanics and optics, which can be attributed to the highly visual and interactive nature of PhET simulations for projectile motion, Newton's laws, and ray/wave optics phenomena.

4.4 Student Perceptions of ICT Tools

Table 4 presents the results from the Student Perception Questionnaire administered to the experimental group.

Table 4: Student Perceptions of ICT Tools (Experimental Group, n = 60)

Perception Parameter	Mean	SD	% Agree/Strongly Agree	Interpretation
Ease of use	4.32	0.58	84%	Very Positive
Visualization effectiveness	4.56	0.49	91%	Highly Positive
Engagement and motivation	4.41	0.54	87%	Very Positive

Preference over traditional methods	4.18	0.67	79%	Positive
Overall	4.37	0.52	87%	Very Positive

The overall weighted mean of student perceptions was 4.37 (SD = 0.52), indicating a highly favourable attitude toward ICT tools. The highest-rated parameter was visualization effectiveness ($M = 4.56$), with 91% of students agreeing or strongly agreeing that simulations and animations helped them visualize abstract physics concepts that were previously difficult to comprehend. Engagement and motivation scored 4.41, with 87% of students reporting increased interest in physics. The parameter on preference over traditional methods received the lowest but still positive rating ($M = 4.18$, 79% agreement), suggesting that while students valued ICT tools, they also recognized the importance of blended approaches that combine digital and traditional instruction.

5. Discussion

The findings of this study provide robust evidence for the effectiveness of ICT tools in enhancing conceptual understanding among B.Sc Physics students. The large effect size (Cohen's $d = 1.52$) and medium-high normalized gain ($\langle g \rangle = 0.58$) in the experimental group are consistent with the international literature on simulation-based physics instruction. The results align with those of Mlatho et al. (2022), who reported significant improvements in academic achievement and motivation when PhET simulations were used for teaching oscillations and waves, and with the meta-analysis of Rutten et al. (2012), who found consistent positive effects of computer simulations on science learning outcomes.

The domain-wise analysis revealed that mechanics and optics benefited most from ICT integration, achieving normalized gains above 0.60. This is consistent with the findings of Husnaini and Chen (2019), who reported that virtual labs were particularly effective for topics involving motion, force, and wave phenomena—domains where dynamic visualization is especially valuable. PhET simulations for projectile motion, for instance, allow students to manipulate initial velocity, angle, and gravitational acceleration in real time, providing an experiential understanding that is difficult to replicate through chalk-and-board explanations alone. Virtual labs for Young's double-slit experiment enabled students to vary slit separation and wavelength and immediately observe changes in fringe patterns, reinforcing the wave nature of light.

Electromagnetism and modern physics, while still showing significantly higher gains in the experimental group compared to the control group, exhibited slightly lower normalized gains (0.55 and 0.53, respectively). This may be attributed to the inherently greater abstraction in these domains—concepts such as electromagnetic field vectors, Lenz's law, and quantum mechanical phenomena (wave-particle duality, atomic transitions) require not only visualization but also a deeper mathematical scaffolding that simulations alone may not fully address (Tuyizere & Yadav, 2023). Future studies could investigate the integration of simulation tools with structured mathematical problem-solving activities for these domains.

The positive student perceptions corroborate the findings of the PhET study by the American Journal of Education and Technology (2025), which reported an overall Likert weighted mean of 4.731 for student perceptions across parameters of ease of access, physical features, ease of manipulation, and relevance. The present study's perception data confirm that students appreciate the intuitive, self-paced, and exploratory nature of ICT tools, which aligns with constructivist learning principles (Jonassen, 1999).

The finding that 79% of students preferred ICT tools but also valued traditional methods supports the emerging consensus on blended learning approaches. Studies by IAFOR (2023) and El Kharki et al. (2021) have similarly advocated for a blended laboratory approach that combines the strengths of virtual tools with the tangible, hands-on experience of physical laboratories. This blended model is particularly relevant for government colleges in India, where physical laboratory resources are limited but cannot be entirely replaced.

5.1 Implications for NEP 2020 Implementation

The findings of this study directly support the NEP 2020's call for technology-enabled, learner-centred education. The policy's provisions for digital infrastructure, virtual classrooms, and simulation-based learning are empirically validated by the present results. Specifically, the study demonstrates that freely available ICT tools such as PhET simulations and government-funded virtual labs (Amrita, Olabs) can produce large learning gains even in resource-constrained government college settings. This is significant because over 70% of India's undergraduate students are enrolled in government-affiliated institutions (AISHE, 2022), and these institutions often lack the advanced laboratory equipment available at premier institutions.

For effective implementation, the study underscores the need for: (a) faculty development programs focused on digital pedagogy and simulation-based instruction, (b) provision of reliable internet connectivity and computer labs in government colleges, (c) curriculum redesign to integrate ICT activities with learning outcomes, and (d) institutional policies that incentivize ICT adoption in teaching.

6. Conclusion

This study provides empirical evidence that ICT tools—specifically PhET simulations, virtual laboratories, and physics animations—significantly enhance the conceptual understanding of B.Sc Physics students compared to conventional instruction. The experimental group demonstrated statistically significant and practically meaningful improvements across all four physics domains (mechanics, electromagnetism, optics, and modern physics), with an overall normalized gain of 0.58 (medium-high) and a large effect size (Cohen's $d = 1.52$). Student perceptions were highly favourable, with 87% reporting improved visualization and engagement.

The findings advocate for the systematic integration of ICT tools into undergraduate physics curricula, particularly in government colleges across India, in alignment with the vision of NEP 2020. A blended instructional approach—combining the dynamic visualization capabilities of simulations and virtual labs with the experiential value of physical laboratories and guided mathematical problem-solving—appears to be the most effective strategy for maximizing learning outcomes.

6.1 Limitations

The study was limited to two government colleges in Kurnool district, which may affect generalizability. The quasi-experimental design, while practical, does not provide the same level of internal validity as a true experimental design. The 8-week intervention period may not capture long-term retention effects. Future longitudinal studies with larger, multi-state samples and randomized controlled trial designs are recommended.

6.2 Recommendations for Future Research

- (i) Investigate the long-term retention of conceptual understanding through delayed post-tests at 3-month and 6-month intervals.
- (ii) Explore the differential effectiveness of specific ICT tools (PhET vs. virtual labs vs. animations) through factorial designs.
- (iii) Examine the role of faculty training and digital readiness as moderating variables in ICT-enhanced instruction.
- (iv) Extend the study to include M.Sc Physics students and interdisciplinary science courses.

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