



Harnessing PhET Simulations for Sustainable Physics Education: Turning Digital Innovation into Improved Learning Outcomes

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Abstract

The fast pace of digital technology has continued to change educational practices throughout the world, bringing with it new chances for improving teaching and learning processes. One of the big developments in Physics education is the use of Physics Education Technology (PhET) simulations to create interactive, learner-centred virtual environments in which to explore scientific subjects. PhET simulations are helpful tools for educational institutions to improve learning results in a sustainable manner, facing problems such as complex concepts, lack of laboratory resources, and waning student interest in science courses. In this study, we discuss the possibility of PhET simulations as a sustainable digital innovation that has the ability to improve Physics education. It covers the ideas of sustainable education, digital innovation and PhET simulations, and their importance for today's teaching and learning. The paper also analyses the importance of PhET simulations in enhancing conceptual understanding, critical thinking, problem-solving skills, student engagement, and academic accomplishment. In addition, it addresses the issues that can prevent their successful deployment and offers concrete advice for enhancing the instructional usefulness of these tools. The research suggests that effective integration of PhET simulations in Physics classrooms can greatly improve learning results, while serving the broader goal of sustainable education in the twenty-first century.

Keywords: PhET Simulations, Physics Education, Digital Innovation, Sustainability, Learning Outcomes.

Introduction

Education has always changed to meet the needs of society, technology and developing human needs. Over the last few decades, the world has seen an unparalleled boom in digital technologies that has brought major changes to almost every sector, including education. The importance of integrating technology into teaching and learning is increasing as educators look for new and inventive ways to improve instructional effectiveness, promote learner engagement, and prepare students for participation in a technology-driven world. Thus, digital innovation is not considered an optional add-on to educational practice, but rather as a fundamental component of effective teaching and learning in the twenty-first century. Physics is one of the several sciences taught in schools and occupies a unique place because of its vital role in the explanation of natural phenomena as well as in the support of scientific and technological progress. Physics is the foundation for many of the sciences and technologies such as engineering, medicine, telecommunications, IT and energy development.

Physics is a very important subject, but many students find studying it quite challenging. This view is typically related to the abstract character of many Physics ideas, the mathematical demands of the discipline and the limited opportunity

for actual experimentation in many educational environments (Hake, 1998). Traditionally, Physics instruction has often relied on teacher-centred practices of lectures, note-taking, and memorisation of formulas. Although these strategies may help in passing on knowledge, they are usually not very useful in developing a deeper conceptual understanding or meaningful engagement with scientific principles. Therefore, students may memorise definitions and equations without truly grasping the principles behind them or their real-world implications. These experiences can lead to poor achievement, low memory, and decreasing interest in Physics (Finkelstein et al., 2005).

The rising need for quality science education has therefore encouraged educators, researchers, and policymakers to investigate creative teaching practices that can make Physics more accessible, engaging and relevant to learners. One of the most promising breakthroughs in this respect is the use of digital simulations. Educational simulations offer students the opportunity to visualise scientific phenomena, change variables, test hypotheses, and see effects in ways that might not be achievable through traditional classroom learning. Simulations create interactive learning environments that facilitate active learning and motivate students to generate knowledge through exploration and discovery. Among the most extensively used instructional simulations are the PhET (Physics Education Technology) simulations produced by academics at the University of Colorado Boulder. PhET simulations are interactive computer programs grounded in research, aimed at assisting learners in grasping scientific and mathematical concepts through visual representations and virtual experiments (Perkins et al., 2006). PhET simulations allow students to immediately interact with topics, investigate cause-and-effect linkages and get rapid feedback on their activities, unlike traditional instructional resources. These aspects make learning more interesting and meaningful and promote deeper conceptual understanding.

The increasing use of PhET simulations is strongly connected with current concerns about sustainable education. Sustainable education refers to the creation of learning systems that are accessible, inclusive, adaptive and able to address existing educational demands without jeopardising prospects. It aims to ensure access to quality education for all learners, irrespective of social, economic or geographical barriers (UNESCO, 2020). In Nigeria and many other developing nations, schools are faced with issues such as a lack of suitable laboratory facilities, instructional materials, overcrowded classrooms, and inadequate budgets. These constraints typically limit students' opportunity to engage in hands-on scientific activity. Many of these difficulties are addressed with the use of PhET simulations, which provide a practical and inexpensive solution. Virtual laboratories allow students to carry out experiments, explore scientific concepts and gain hands-on experience without the need for costly laboratory equipment or consumables. Furthermore, simulations are reusable, easily modifiable and accessible via desktops, tablets and cellphones. These traits are particularly important in enabling equal access to quality Physics education and supporting the goals of educational sustainability through PhET simulations.

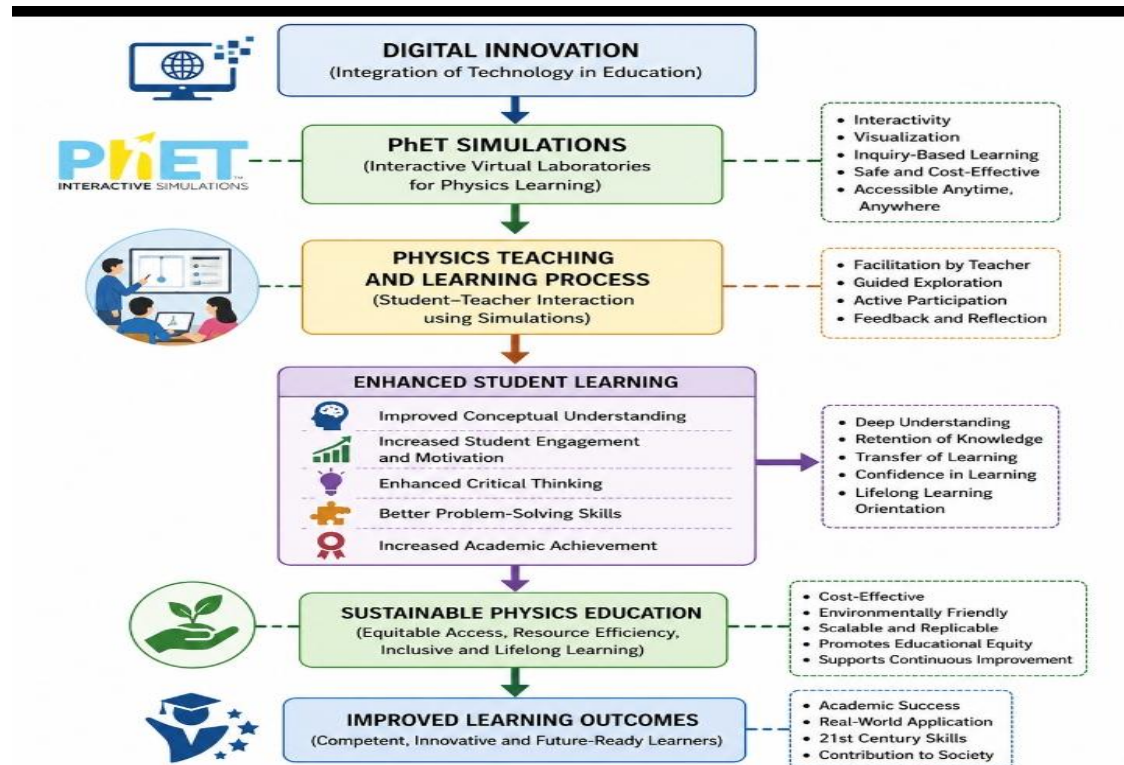
Furthermore, the use of PhET simulations is consistent with contemporary educational philosophies that emphasise learner-centred instruction and active knowledge building. Constructivist theorists claim that learners learn best when they actively participate in the learning process rather than passively receiving information from teachers (Piaget, 1972). Likewise, experiential learning theory proposes that meaningful learning happens when learners directly interact with situations, reflect on the experiences, and use the newly learned knowledge to solve problems (Kolb, 1984). PhET simulations promote these theoretical viewpoints by giving chances for exploration, experimentation, and inquiry-based learning. The use of PhET simulations in science teaching has been connected with beneficial outcomes, as demonstrated in multiple studies in recent years. Research findings show that students who learn through simulations often show better conceptual understanding, more motivation, better problem-solving skills, and better academic accomplishment than those who are taught only using traditional techniques (Wieman et al., 2008). These findings imply that PhET simulations have great promise for transforming Physics teaching and improving learning outcomes.

With the increased adoption of digital transformation in educational institutions, there is an increasing need to understand how innovative technologies may be effectively used to enhance teaching and learning. Harnessing PhET simulations for sustainable Physics education is a key step toward tackling persisting issues in physics education, while preparing learners with the information, skills and competences required in a continuously changing environment. It is against this context that this paper discusses the importance of PhET simulations in fostering sustainable Physics education and enhancing learning outcomes among learners.

The main objective of this paper is to examine how PhET simulations can be harnessed to promote sustainable Physics education and improve learning outcomes among students. Specifically, the paper seeks to:

1. Examine the concept of PhET simulations and their role in Physics education.
2. Explain the relationship between digital innovation and sustainable education.
1. Discuss the relevance of PhET simulations in contemporary Physics teaching and learning.
2. Explore the various applications of PhET simulations in Physics education.
3. Highlight the benefits of PhET simulations in enhancing students' learning outcomes.
4. Identify the challenges associated with the integration of PhET simulations into Physics instruction.
5. Examine the implications of PhET simulations for sustainable Physics education.
6. Suggest practical strategies for effective implementation of PhET simulations in schools.

Conceptual Framework



Explanation of the Conceptual Framework

The conceptual framework shows how PhET simulations as digital innovation may enhance the teaching and learning of Physics and eventually improve learning outcomes. The framework starts with Digital Innovation, which is the use of current technology in teaching and learning. One great example of such innovation is PhET Simulations, which offers interactive virtual laboratories to visualise scientific concepts, do experiments and actively participate in learning. The use of PhET simulations makes the Physics teaching and learning process more learner-centred, interactive and inquiry-driven. Students can explore concepts, receive fast feedback and actively participate in class activities. Therefore, we have good learning outcomes such as: better conceptual grasp of Physics subjects, higher student engagement and motivation, improved critical thinking abilities, better problem-solving skills and improved academic performance. These benefits together promote Sustainable Physics Education, which focuses on equal access to excellent learning, efficient use of educational resources, inclusivity and lifelong learning.

In the end, sustainable Physics education leads to Improved Learning Outcomes, developing competent, innovative and future-ready learners who can apply scientific knowledge effectively in real-world circumstances and contribute meaningfully to the growth of society. Source: Researcher's Conceptualisation from Literature Review (2026).

Conceptual Clarifications

A good comprehension of the main topics related to this work is necessary to appreciate the importance of PhET simulations in fostering sustainable Physics education. In this section, we explore ideas such as Physics education, sustainable education, digital innovation, PhET simulations, and theoretical frameworks that promote the use of PhET simulations in teaching and learning.

Physics Education

Physics Education is the process of teaching and understanding the concepts, theories, laws and applications of Physics. This includes the teaching methods, learning activities, evaluation methods, and educational materials used to help students learn about physical phenomena and their interaction with the natural environment. Physics is often considered to be one of the most fundamental fields of science in that it explains the behaviour of matter, energy, motion, force, electricity, magnetism, and many other phenomena that affect everyday life. The understanding developed by physics provides the basis for progress in engineering, medicine, telecommunications, transportation, space exploration, and information technology.

Physics is a very important subject, but it is still a difficult subject for many learners. Students often have difficulties in understanding abstract concepts such as electromagnetic fields, wave motion, quantum phenomena and atomic structures. These problems are typically exacerbated by poor laboratory facilities, lack of instructional materials and teaching strategies that emphasise memorisation rather than conceptual understanding. Therefore, modern Physics teaching aims at shifting from conventional teacher-centred approaches to learner-centred approaches that promote active engagement, inquiry, experimentation and problem solving. The incorporation of digital technology, including simulations, virtual laboratories, and interactive multimedia materials, has become more and more critical in achieving these aims.

Effective Physics education should not simply be about helping students pass examinations. Instead, it should cultivate scientific literacy, critical thinking, creativity and the capacity to use scientific knowledge to address real-world challenges. These educational results are vital for national growth and for global competitiveness in an increasingly technology-driven society.

Sustainable Education

The idea of sustainable education stems from the larger concept of sustainable development, which is based on the idea of fulfilling the requirements of the present without jeopardising the capacity of future generations to fulfil their own needs. In education, sustainability is about building learning systems that are accessible, inclusive, flexible, resource-efficient and able to sustain ongoing development over time. According to UNESCO (2020), sustainable education is an education that educates students with the knowledge, skills, values and attitudes essential to help build a more sustainable society. It emphasises lifelong learning, social responsibility, environmental awareness and economic viability. In practical terms, sustainable education is concerned with making sure that all learners are able to access quality learning opportunities regardless of their geographical location, economic background, gender or physical ability. It also encourages educational institutions to make optimal utilisation of resources with high standards of teaching and learning.

The importance of sustainable education in Physics teaching cannot be overestimated. Traditional laboratory-based instruction frequently involves costly equipment, consumable materials and specialist facilities. In many of the developing countries, these resources are either inadequate or not available. This means students may finish their studies with little practical experience, although they have learned the scientific ideas. Digital technologies like the PhET simulations provide sustainable options that may be revisited and revisited without incurring major recurrent costs. These technologies allow learners to engage in meaningful scientific investigations with limited resources. Hence, sustainable education has become an educational and economic need in modern society.

Digital Innovation in Education

Digital innovation is the application of digital technologies to produce new or enhanced ways, processes, goods and services to boost effectiveness and efficiency. Digital innovation in education is the use of electronic devices to enhance teaching, learning, communication, assessment, and educational management. Digital innovation has turned traditional classrooms into dynamic learning environments. Students can access knowledge, engage with classmates, conduct online experiments and get immediate feedback on their learning progress.

Examples of digital innovations in education include:

E-learning platforms, Virtual Laboratories, Educational Simulations, Artificial Intelligence Tools, Interactive Whiteboards, Mobile Learning Applications, Educational Games, Learning Management Systems. Digital innovation is particularly relevant now, because today's learners grow up in a technology-rich world. These students tend to do better with interactive, technology-based instructional approaches than with traditional approaches.

Digital innovation helps to overcome some of the restrictions that are connected with traditional classroom learning in physics education. Static diagrams and verbal descriptions may not always be sufficient to explain complicated ideas, and simulations and animations can be used to visually present them dynamically. This helps pupils comprehend and helps them to gain a deeper grasp of concepts. In addition, digital innovation affords flexible learning where students are able to learn at their own pace, review concepts as needed and do self-directed learning activities. Such features make digital technology a useful tool to improve the quality and sustainability of education.

PhET Simulations:

PhET stands for Physics Education Technology and is a set of free interactive simulations created by the University of Colorado Boulder. Created for the teaching of Physics, the project now includes simulations for Chemistry, Biology, Earth Science and Mathematics. PhET simulations are based on educational research and are designed to support active learning by encouraging exploration, experimentation, and inquiry. The simulations allow visualisations of scientific concepts that are typically unseen or difficult to see in the real world. For example, students could use a PhET simulation to watch electrons pass through an electrical circuit, explore interactions between atoms and molecules, evaluate wave behaviour, or see what happens when different forces are applied to moving objects. Such encounters allow learners to relate theory to observed outcomes. A distinctive strength of PhET simulations is their participatory aspect. The students alter variables, test predictions, analyse data and conclude, rather than just observe demonstrations. This kind of active interaction leads to better comprehension and stimulates scientific thinking.

PhET simulations possess several important features, including:

Interactivity: Students actively interact with the learning materials, adjusting factors and witnessing the results.

Visualisation: Abstract scientific topics become apparent and easy to grasp.

Instant Feedback: Learners get immediate feedback from their actions, allowing them to self-correct and learn better.

Accessibility: The simulations are freely available and can be accessed on many digital devices.

Inquiry-Based Learning: Students learn through inquiry and investigation instead of the passive receipt of knowledge. These properties make the PhET simulations powerful instruments for increasing teaching and learning in physics education.

Theoretical Foundations of PhET Simulations

The effectiveness of PhET simulations is supported by several educational theories that emphasise active learning and learner engagement.

Constructivist Learning Theory

The Constructivist Learning Theory is mostly linked to Jean Piaget (1972), who claimed that learners actively construct knowledge through interactions with their environment. The theory argues that learning happens when people create new understanding on the basis of earlier experiences and existing knowledge structures. Constructivism denies the notion of knowledge as a commodity to be transferred from teacher to student. Rather, learners need to be active participants in the learning process, investigating, questioning, experimenting, and reflecting.

PhET simulations are powerful tools for supporting constructivist principles, allowing students to:

1. Investigate scientific phenomena on their own.
2. Change some factors and see what happens.
3. Test hypotheses.
4. Promote understanding through discovery.
5. Connect existing knowledge to fresh experience. As learners engage with simulations, they become active participants, not passive users of information, thereby improving conceptual understanding and knowledge retention.

Experiential Learning Theory

Kolb (1984) established the Experiential Learning Theory, which emphasises learning through experience. The theory states that effective learning occurs through a continuous cycle of concrete experience, reflective observation, abstract conceptualisation, and active experimentation. PhET simulations are interactive virtual environments where students can experience science first-hand. This understanding is significant. It is based on experiences in experimentation and observation. For example, a student working with a PhET simulation of electricity can alter the voltage settings, see how the current changes, think about what is happening, create an explanation, and test new ideas. This process is similar to the cycle of experiential learning and facilitates greater understanding.

Cognitive Theory of Multimedia Learning

The Cognitive Theory of Multimedia Learning by Mayer (2009) states that learners grasp information better when presented in visual and spoken forms. The theory emphasises that meaningful learning happens as learners actively pick, organise and integrate information from numerous sources. PhET simulations include visualisations, animations, interactive controls, and explanations. Such qualities allow learners to digest information more effectively by engaging several cognitive pathways at the same time. So the theory provides additional support for the use of simulations in Physics education, especially when handling abstract issues that are hard to understand using text only.

Linking the Concepts Together

The above concepts are strongly related to each other. The goal of physics education is to build scientific literacy and problem-solving skills in learners. Sustainable education is about providing opportunities for quality learning that may continue to be available and effective throughout time. Digital innovation offers the technological instruments to improve educational practices, and PhET simulations are a real example of this innovation applied to Physics classrooms.

Collectively, these themes highlight how technology can be used to tackle longstanding issues in science teaching. The integration of the three concepts of sustainability, innovation and learner-centred instruction embedded in PhET simulations provides a potential route for the improvement of learning outcomes and the enhancement of Physics education in the twenty-first century.

Discussion

Applications of PhET Simulations in Physics Education

The integration of technology in education is rapidly expanding the options for teaching and studying Physics. PhET simulations have become well known among the plethora of digital resources accessible, due to their capacity to make abstract scientific concepts engaging learning experiences. They are versatile and can be used in many areas of Physics. They are great educational materials for teachers and students. PhET simulations are very powerful in that they can be used to supplement classroom teaching in online settings in which students can investigate concepts that are hard to witness directly. Students do not sit passively to watch these simulations, but they become active participants in the learning process. They can control variables, investigate, test ideas, and see the results of what they do in real time. This stimulates curiosity, scientific inquiry and meaningful learning.

Application of PhET Simulations in Mechanics

Mechanics is frequently one of the first branches of Physics that students encounter. It includes subjects like motion, force, velocity, acceleration, momentum and energy. Many students fail to grasp these concepts because they entail interactions between variables that are not always obvious in our everyday experience. PhET simulations solve this difficulty by enabling students to visualise and interact with physical systems. Virtual exercises allow learners to analyse the effects of changing force on motion, the effects of changing mass on acceleration and witness the effects

of friction on moving objects. For example, students can learn about Newton's laws of motion by using simulations, where they can apply different pressures to objects in a virtual environment and see their movements. Such experiences make the theoretical notions more real and understandable.

Application in Electricity and Magnetism

Many of the processes involved are not readily observable, which makes electricity and magnetism some of the most abstract parts of Physics. Students have difficulty visualising electric current, magnetic fields, voltage and resistance. PhET simulations give us a visual picture of these invisible processes. Learners may monitor the path of electrons in electrical circuits, discover how resistance influences the flow of current and examine the interaction between magnetic fields and charged particles. PhET simulations allow students to build and operate virtual circuits to grasp concepts that would otherwise be quite abstract. These experiences help lessen the risks connected with working with electrical equipment, especially for those who are new to it.

Application in Waves and Sound

Waves and sound are studied in terms of wavelength, frequency, amplitude, resonance and propagation of waves. Students typically have a hard time grasping these concepts, since it is difficult to visualise wave motion. PhET simulations provide dynamic visualisations of wave behaviour and allow learners to visualise the propagation of waves via different media and how changes in frequency or amplitude impact the properties of waves. Through interactive activities, students can analyse sound waves, musical instruments and resonance. Such experiences increase knowledge and allow the learner to relate theoretical ideas to phenomena encountered in everyday life.

Application in Thermodynamics

Thermodynamics deals with heat, temperature, energy transmission, and matter's behaviour. Many thermodynamic processes are at the molecular scale and cannot be seen directly. PhET simulations show students molecular mobility and how temperature affects the behaviour of particles. They may see how heat is shared between objects, learn about the states of matter and look at energy changes. These simulations close the gap between tiny processes and macroscopic data and make thermodynamic ideas easier to understand.

Application in Modern Physics

Modern Physics covers challenging topics such as atomic structure, quantum mechanics, nuclear processes and radioactivity. These issues are typically seen as hard precisely because they include events that we do not directly observe. PhET simulations allow students to explore atomic models, look into radioactive decay, and study the behaviour of subatomic particles in interactive virtual environments. Simulations play a key role in conceptual understanding and learner confidence by making these abstract concepts visible and engaging.

Application in Laboratory Activities

Laboratory work is an important part of Physics education. It allows for practical learning and scientific study. Many schools, however, confront problems that include poor laboratory facilities, lack of equipment and insufficient budget. PhET simulations are virtual labs that allow students to experiment, even when resources are limited. In addition, learners can collect data, interpret results, test hypotheses, and develop conclusions in methods that are very similar to real laboratory experiences. Virtual laboratories are not a complete replacement for physical experiments, but can give good alternatives when laboratory resources are limited or unavailable.

Benefits of PhET Simulations in Physics Education

The increasing popularity of PhET simulations in science education can be attributed to the numerous benefits they offer learners, teachers, and educational institutions. These benefits extend beyond academic achievement to include enhanced engagement, improved accessibility, and greater sustainability.

Improved Conceptual Understanding

One of the most significant benefits of PhET simulations is their ability to improve students' conceptual understanding of Physics. Many scientific concepts are difficult to explain using words alone because they involve invisible processes or abstract relationships. Through interactive visualisations, learners can observe scientific phenomena, explore cause-

and-effect relationships, and develop a deeper understanding of concepts that might otherwise remain confusing. Rather than memorising formulas, students gain meaningful insights into the principles underlying physical phenomena.

Increased Student Engagement and Motivation

Student participation is an essential element of effective learning. Traditional lecture-based teaching may sometimes not be able to catch the interest of learners, especially when dealing with complex scientific subjects. PhET simulations provide dynamic and entertaining learning experiences that spark curiosity and promote inquiry. Students are not just passive recipients of knowledge but active participants in the learning process. This enhanced engagement frequently results in increased motivation and a more positive attitude about Physics.

Enhancement of Critical Thinking Skills

Scientific learning requires learners to think critically, analyse information, evaluate evidence, and make informed decisions. PhET simulations provide opportunities for students to develop these skills through inquiry-based learning activities. As students manipulate variables and observe outcomes, they learn to identify patterns, formulate explanations, test hypotheses, and draw conclusions based on evidence. Such experiences contribute to the development of higher-order thinking skills that are valuable beyond the Physics classroom.

Promotion of Problem-Solving Abilities

Problem-solving is one of the most essential aims of Physics teaching. Students experience circumstances through simulations where they must use scientific ideas to obtain certain goals. They get to explore, make mistakes, and see the repercussions right away, which helps learners build confidence in their problem-solving skills. They learn that science is not only about finding the right answers but comprehending processes and linkages.

Improved Academic Achievement

Some studies have found beneficial correlations between the use of instructional simulators and student academic achievement. Improvements in achievement often follow when learners grasp topics better and are actively involved in learning activities. PhET simulations are often used by students, and they show superior performance in exams, retention of knowledge and conceptual understanding compared with students taught with standard instructional approaches.

Accessibility and Inclusiveness

PhET simulations are also a major benefit in that they are accessible. Simulations are free to use on desktops, tablets and smartphones. This flexibility means that learners can access educational resources from anywhere. Furthermore, the simulations are visual and interactive, therefore catering to different learning styles. Simulation-based training can be useful to visual, auditory, and kinaesthetic learners.

Cost-Effectiveness

Physics labs can be expensive to start and to keep going. Schools confront problems in getting laboratory equipment, replacing damaged materials and purchasing consumable supplies. The PhET simulations are low-cost options as they provide virtual environments where experiments can be performed several times without incurring additional costs. This makes quality Physics education more inexpensive and sustainable, especially in resource-constrained situations.

Safe Learning Environment

Some Physics experiments can be potentially dangerous. These include electrical shocks, exposure to radiation, and the use of fragile equipment. Virtual simulations remove these hazards, yet still allow students to experiment with scientific topics. Learners can experience potentially dangerous situations without fear of injury, therefore boosting confidence and experimentation.

Encouragement of Independent Learning

PhET simulations offer students self-directed learning by letting them master concepts at their own speed. Activities can be repeated, challenging themes reviewed and investigations performed independently by learners. This autonomy creates habits of lifelong learning and accountability for one's own educational progress.

Contribution to Sustainable Education

One of the greatest benefits of PhET simulations is perhaps their contribution to sustainable education. Simulations help establish successful and sustainable education systems by reducing the need for physical resources, lowering operating costs and increasing access to quality learning opportunities. Their capacity to offer meaningful learning experiences while saving resources is in line with the objectives of sustainable development and modern educational reform.

Challenges of Integrating PhET Simulations into Physics Education

The use of PhET simulations in Physics teaching has many advantages; however, there are various problems that may prevent the proper implementation. This is especially true in developing nations where educational institutions are often limited by infrastructure, finance and technology.

Inadequate Technological Infrastructure: One of the most significant barriers to the successful integration of PhET sims is a lack of technical infrastructure. To make effective use of digital simulations, you need access to computers, tablets, cellphones, projectors and other technological equipment. Unfortunately, many schools, particularly in rural areas, do not have this basic equipment. Some institutions don't have enough computers to support huge numbers of students, making it impossible for all learners to have equal opportunities to learn. However, the full capabilities of the PhET simulations cannot be achieved without sufficient technological infrastructure.

Poor Internet Connectivity: Although many PhET simulations can be downloaded and used offline, an internet connection is still needed to receive updates, download new simulations and explore other learning resources. In many underdeveloped areas of the world, internet services are not available, not dependable, or too costly for educational institutions to maintain. Limited internet connection hampers both teachers and students from effectively capitalising on digital learning developments.

Unreliable Electricity Supply: Effective instructional technologies are highly dependent on a consistent electricity supply. Power outages are a big concern in many underdeveloped countries as they happen frequently. Electricity interruptions may interfere with lessons, damage technological equipment, and deter teachers from incorporating digital resources into classroom teaching. Technology-based teaching methods could be hard to maintain for long without a stable power source.

Limited Digital Competence among Teachers: "Any educational innovation can only be successful if teachers are part of it. However, some Physics teachers may not have the required knowledge and abilities for the integration of digital technology into their instructional practices. Many of the educators had been trained using traditional teaching approaches and may have had minimal exposure to simulation-based learning. Thus, individuals may be uncomfortable utilising technology tools or may not be able to use them efficiently. Hence, instructors need to be in regular professional development and continual training to build their digital skills.

Resistance to Educational Change: Humans tend to get comfortable with what they know, and education is no different. Resistance to the implementation of PhET simulations by certain instructors and administrators may arise from their familiarity with traditional instructional practices. This resistance may be a result of fear of technology or workload, doubt of efficacy or lack of faith in the use of digital devices. To address this situation, awareness must be raised, training provided, and institutional support given.

Digital Divide among Learners: Digital gap is the difference in access to technology resources among various categories of learners. Some pupils have personal computers, smartphones and internet connections, while some may not have these facilities. This imbalance can result in educational disadvantages, especially when simulation-based learning spreads outside the classroom. Providing equal opportunities for great education still requires bridging the digital gap.

Financial Constraints: PhET simulations are free to use, but implementation may involve investment in hardware, software, internet connectivity, maintenance and teacher training. Many educational institutions are operating under tight financial constraints, and it is not easy to acquire and sustain the needed technology resources. This necessitates sustainable funding arrangements to support long-term implementation.

Risk of Overdependence on Technology: Technology can bring a lot of educational advantages, but relying too heavily on electronic devices might have unforeseen repercussions. Students still demand hands-on experimentation,

collaborative learning, and direct experience with real materials. PhET simulations should therefore complement and not replace the traditional laboratory experience and classroom interactions in their entirety.

Implications for Sustainable Physics Education: The integration of PhET simulations into Physics instruction has far-reaching implications for educational practice, policy, and student learning outcomes.

Enhanced Quality of Physics Instruction: Interactive simulations help teachers to clarify difficult ideas and make them more successful. This increases the quality of instruction and thus, more meaningful learning experiences. Teachers can utilise simulations to explain scientific principles which are otherwise difficult to explain by traditional teaching approaches.

Increased Student Achievement: When students are actively involved with learning materials, conceptual understanding rises considerably. Better understanding often means better academic accomplishment, better retention of knowledge and better examination performance. Hence, the broad use of PhET simulations can potentially contribute positively to educational outcomes.

Promotion of Scientific Literacy: Scientific literacy involves understanding scientific concepts and applying scientific reasoning to everyday situations. Through simulation-based learning, students develop inquiry skills, analytical thinking, and evidence-based decision-making abilities. These competencies are essential for functioning effectively in a rapidly changing technological society.

Advancement of Educational Equity: PhET simulations provide opportunities for students in resource-poor schools to experience virtual laboratory activities that might otherwise be unavailable. This contributes to reducing educational inequalities and promoting equitable access to quality science education. Consequently, learners from disadvantaged backgrounds can participate more fully in meaningful scientific learning experiences.

Strengthening Twenty-First Century Skills: Modern society requires individuals who can think critically, solve problems creatively, communicate effectively, and adapt to technological change. Simulation-based learning helps students develop many of these essential competencies. By promoting active learning and technological engagement, PhET simulations contribute to the preparation of learners for future educational and professional challenges.

Environmental Sustainability: Traditional laboratory activities often involve the use of consumable materials, chemicals, paper resources, and energy. Virtual simulations reduce the need for many of these resources, thereby contributing to environmental conservation. The adoption of simulation-based learning, therefore, aligns with broader sustainability goals aimed at reducing waste and promoting responsible resource utilisation.

Conclusion

The rapid growth of digital technology has created unprecedented opportunities for transforming educational practices and improving learning outcomes. Among the numerous innovations currently influencing science education, PhET simulations have emerged as powerful instructional tools capable of addressing many of the challenges traditionally associated with Physics teaching and learning. This paper has demonstrated that PhET simulations provide interactive, engaging, and learner-centred environments that promote conceptual understanding, critical thinking, problem-solving skills, and academic achievement. Through virtual experimentation and visualisation, students are able to explore complex scientific concepts in ways that are both meaningful and accessible. The discussion further revealed that PhET simulations contribute significantly to the goals of sustainable education by reducing dependence on costly laboratory resources, expanding access to quality learning experiences, and supporting inclusive educational practices. Although challenges such as inadequate infrastructure, financial limitations, poor electricity supply, and limited teacher competence may hinder effective implementation, these obstacles can be addressed through strategic planning, investment, and capacity building. Ultimately, harnessing PhET simulations for Physics education represents more than the adoption of a technological tool; it reflects a commitment to innovative, equitable, and sustainable learning. As educational institutions continue to embrace digital transformation, the effective integration of PhET simulations will remain an important strategy for improving educational quality and preparing learners for success in an increasingly technological world.

Suggestions

To maximise the educational benefits of PhET simulations and promote sustainable Physics education, the following suggestions are offered.

1. Governments should invest more heavily in educational technology infrastructure within schools.
2. Educational institutions should provide adequate computers, projectors, tablets, and related technological resources.
3. Reliable electricity supply should be prioritised to support technology-enhanced learning.
4. Schools should ensure consistent internet connectivity for teachers and students.
5. Regular professional development programmes should be organised to improve teachers' digital literacy and technological competence.
6. Teacher education institutions should incorporate simulation-based instructional strategies into their training programmes.
7. Curriculum developers should formally integrate PhET simulations into Physics curricula.
8. School administrators should encourage the use of learner-centred teaching approaches that incorporate educational technologies.
9. Public-private partnerships should be established to support the acquisition and maintenance of technological facilities.
10. Students should be encouraged to utilise PhET simulations for independent learning beyond classroom activities.
11. Educational policymakers should develop clear policies supporting digital innovation in science education.
12. Continuous monitoring and evaluation should be conducted to assess the effectiveness of simulation-based instruction.
13. Schools should combine virtual simulations with physical laboratory activities to provide balanced learning experiences.
14. Efforts should be made to bridge the digital divide by improving access to technological resources among disadvantaged learners.
15. Researchers should continue investigating innovative ways of utilising simulations to improve learning outcomes in Physics and other science disciplines.

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