Utilization of PhET Simulation to Understand Atomic Structure and Stability in Chemistry Learning

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Abstract

Chemistry learning, especially about atomic structure, is often considered difficult because it is abstract and difficult to visualize. The lack of interactive media causes low conceptual understanding of students related to protons, neutrons, electrons, and atomic stability. This research uses qualitative with case study method to explore the utilization of PhET Simulation in learning chemistry, especially on the material of atomic structure and stability. The results showed that students in the experimental class experienced a significant increase in understanding of atomic structure, the ability to identify stability based on electron configuration, and higher learning motivation than the control class. The use of PhET facilitates interactive visualization that makes abstract concepts more concrete, while improving 21st century skills such as critical thinking and collaboration. These findings indicate that the integration of PhET supports technology-based learning and experiential learning, in line with the direction of 21st century education transformation. Technical barriers such as device limitations and teacher readiness need to be overcome through training and provision of facilities. Thus, the utilization of PhET Simulation is effective in improving the understanding of atomic concepts and can be used as a long-term innovative strategy to strengthen chemistry learning in the digital era.

Keywords: PhET Simulation, atomic structure, chemistry learning

Introduction

The development of digital-based educational technology and virtual simulation has opened up new opportunities to improve the quality of science learning, especially chemistry, to be more interactive and visual (Fiandini et al., 2025). The abstract concept of atoms and subatomic structures is often an obstacle for students in understanding the material, especially regarding atomic stability and the components of protons, neutrons, and electrons (Viario et al., 2025). This difficulty makes students' conceptual understanding still limited when only learning through conventional methods (Banda & Nzabahimana, 2021). In Indonesia, most secondary schools still apply a chemistry learning approach that emphasizes memorization of theories and teacher explanations in class, so student engagement is low and their ability to internalize abstract atomic concepts is not optimal (Ahmad et al., 2023). This demands innovation in learning media that can present a more concrete, interactive learning experience, and in accordance with the characteristics of the 21st century generation.

PhET Simulation is a digital-based interactive learning platform designed to visualize science concepts in a real and exploratory way (Ndagijimana et al., 2025). In the context of chemistry, this simulation allows students to virtually build atoms, observe the number of protons, neutrons and electrons, and understand how the configuration of subatomic particles affects the stability of atoms (Al-Mansoori & Benitez, 2024). The use of PhET has been widely implemented in various countries as a strategy to improve students' conceptual understanding and student engagement in science learning (Salame & Makki, 2021). In contrast to conventional methods that tend to be passive, PhET encourages students to learn experientially, explore various possible atomic structures, try out combinations of subatomic particles, and directly see the consequences of any changes to atomic stability (Sa'diyah & Lutfi, 2023). This approach not only makes abstract chemical concepts more concrete and easy to understand, but also improves students' critical thinking, problem solving, and creativity. Lebih jauh, The integration of interactive simulations such as PhET is in line with 21st century education principles that emphasize active learning, digital literacy, and the simultaneous development of cognitive and affective skills (Dy et al., 2024), thus providing a more holistic learning experience that is relevant to the needs of today's digital generation.

Students often face difficulties in understanding the concepts of atomic structure, atomic symbols, and atomic stability because this material is very abstract and cannot be observed directly (Erlina et al., 2022). Conventional chemistry learning that emphasizes theory explanation and memorization makes student engagement tend to be low, especially when learning complex material such as atomic theory, isotopes, and electron configuration (Mhlongo, 2025). In addition, the lack of learning media that allows students to see the interaction between protons, neutrons, and electrons in real time causes their conceptual understanding to remain limited (Romero et al., 2025). This condition has an impact on students' low ability to relate theory to real phenomena, as well as reducing learning motivation, so that interactive simulation-based learning innovations are needed that can make atomic concepts more concrete, interesting, and easy to understand.

The integration of PhET simulation in chemistry learning has a high urgency because it can increase student engagement and learning motivation through visual, interactive, and hands-on learning experiences (Lahlali et al., 2023). By utilizing this simulation, students can directly understand the relationship between the number of protons, neutrons, and electrons with atomic stability, so that previously abstract concepts become more concrete and easy to understand. This approach also encourages students to learn exploratively, trying various combinations of subatomic particles, and observing their impact on atomic properties, so that students' critical thinking, creativity, and problem-solving skills increase significantly. Furthermore, the use of PhET is in line with the principles of 21st century education, which emphasizes cognitive, affective, and digital skills (21st century skills), and supports technology-based learning that is relevant to the needs of today's digital generation, making the learning process more effective and contextual (Yani & Widiyatmoko, 2023).

Although a number of studies have explored the use of PhET Simulations in chemistry learning in general, studies that specifically examine the utilization of PhET to construct atoms and analyze their stability are still very limited. Most of the previous studies emphasize more on basic chemical concepts or chemical reaction phenomena, without highlighting how students can understand atomic structure visually and interactively. In Indonesia, in particular, there are still few studies that evaluate the effect of PhET on students' conceptual understanding of atomic stability, including their ability to relate the number of protons, neutrons, and electrons to atomic stability. This condition shows an important research gap to be filled, given the need for innovative learning media that can visualize abstract material, increase student engagement, and foster critical and analytical thinking skills in the context of modern chemistry learning.

Based on the phenomena, problems, and research gaps that have been identified, this study aims to analyze the effectiveness of using PhET Simulation in learning chemistry, especially in understanding atomic structure. This study also assesses the extent to which the use of simulations can help students understand atomic stability and the relationship between protons, neutrons, and electrons conceptually and visually. In addition, this research is expected to provide recommendations related to the development of interactive and explorative simulation-based chemistry learning media, so as to increase student engagement and strengthen their conceptual understanding of abstract material.

Method

This research uses a qualitative approach with a case study method to explore the utilization of PhET Simulation in learning chemistry, especially on the material of atomic structure and stability. The research subjects consisted of high school students who participated in chemistry learning using PhET Simulation, as well as teachers who acted as learning facilitators. Data collection was conducted through several techniques: first, participatory observation in the classroom to directly see students' interactions with the simulation, including how they build atoms, observe protons, neutrons, and electrons, and analyze atomic stability; second, in-depth interviews with students and teachers to explore experiences, perceptions, difficulties, and learning strategies applied during the use of the simulation; third, documentation of student activities, such as observation notes, simulation screenshots, and results of atom building exercises and virtual experiments. Data analysis was conducted thematically, with a coding stage to identify patterns, categories, and inter-thematic relationships relating to atomic concept understanding, student engagement, learning motivation, and interactive learning experiences. This approach allowed the research to not only assess the effectiveness of PhET simulation in visualizing abstract atomic concepts, but also highlight technical and pedagogical challenges, teacher learning strategy innovations, as well as the potential for developing technology-based chemistry learning media to improve 21st century skills, such as critical, creative, and collaborative thinking.

Result and Discussion

Learning Design and Implementation with PhET

In this study, teachers designed chemistry learning by utilizing PhET Simulation to build atoms virtually, allowing students to directly see the number of protons, neutrons, and electrons and modify atomic configurations to observe their stability. This activity emphasizes exploration, experimentation, and collaboration between students, so that the learning process becomes more interactive and hands-on compared to conventional methods that are passive. Observations show that students actively try various combinations of subatomic particles, discuss with friends to understand changes in atomic stability, and record their observations systematically. This approach is in line with the principles of experiential learning that emphasizes direct student involvement in the learning process, as well as active learning that encourages the development of critical thinking, problem solving, and collaborative skills. By using PhET, the abstract concept of atomic structure becomes more concrete and visual, so that students are able to understand the relationship between subatomic particles and its implications for atomic stability in a real way.

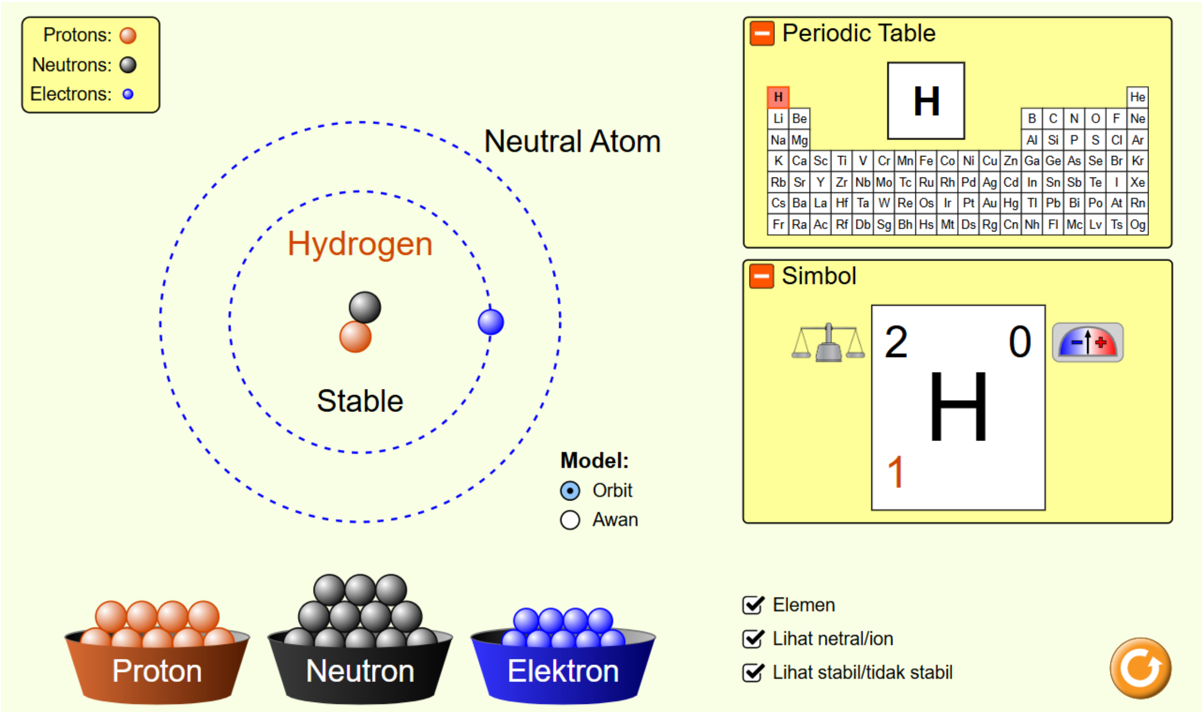

Figure 1. PhET view Simulation of building an atom, showing protons, neutrons and electrons

Figure 1 shows the display of PhET Simulation when students virtually build a hydrogen atom. In this simulation, the number of protons, neutrons, and electrons are clearly displayed with different colors, protons (red), neutrons (gray), and electrons (blue) so that students can easily recognize subatomic particles and their position in the atom. The simulation also displays the atomic symbol, mass number, and atomic number, as well as the stability status of the atom (stable or unstable), so students can immediately see the relationship between the configuration of subatomic particles and the stability of the atom. This visual feature allows students to interactively observe how changes in the number of protons, neutrons or electrons affect atomic balance, while strengthening their conceptual understanding of atomic structure and stability principles. In this way, the PhET simulation bridges abstract atomic concepts into a visual, immersive and exploratory learning experience.

Student Engagement

The observation shows that students' engagement in learning using PhET simulation occurs in three main dimensions: cognitive, affective, and social. Cognitively, students not only observed, but also analyzed changes in atomic configuration and drew conclusions regarding atomic stability, which was seen in the difference between stable and unstable atoms. Affective engagement is reflected in the high sense of enthusiasm and curiosity when students experiment with various combinations of protons, neutrons, and electrons, which creates intrinsic motivation to learn further without external pressure. Social engagement emerges through group discussions that allow students to exchange ideas, correct each other's electron configurations and build complex atoms collaboratively. This discussion presents novelty because, in addition to confirming previous research findings regarding the effectiveness of interactive simulations over conventional methods, these data suggest that the PhET immersive experience can enhance understanding of the concept of atomic stability more explicitly.

Understanding Atomic Concepts and Stability

The results showed that students were able to explain atomic structure better after using PhET Simulation. They were not only able to mention the number of protons, neutrons, and electrons, but also able to determine the stability of the atom based on its electron configuration. Some students can even connect the results of exploration through simulation with the concept of atomic theory, atomic symbols in the periodic table, and the phenomenon of isotopes. This indicates that simulation-based learning experiences not only improve basic skills in recognizing subatomic particles, but also expand students' understanding of more complex conceptual aspects. This finding reinforces the literature on the effectiveness of visual-based and interactive learning, which emphasizes that concrete representations of abstract concepts can facilitate students in building deeper conceptual understanding. In other words, PhET acts as a bridge between abstract theories of atomic structure and real understanding that can be observed directly, so that students more easily understand the relationship between the configuration of subatomic particles and atomic stability. Images of examples of stable versus unstable atoms or correct/wrong electron configurations reinforce this finding, as they visualize the direct consequences of electron configuration on atomic stability, allowing students to see the connection between theory and virtual experiment simultaneously. This approach emphasizes the importance of interactive visualization as a tool to deepen students' multi-dimensional engagement while stimulating critical and collaborative reasoning.

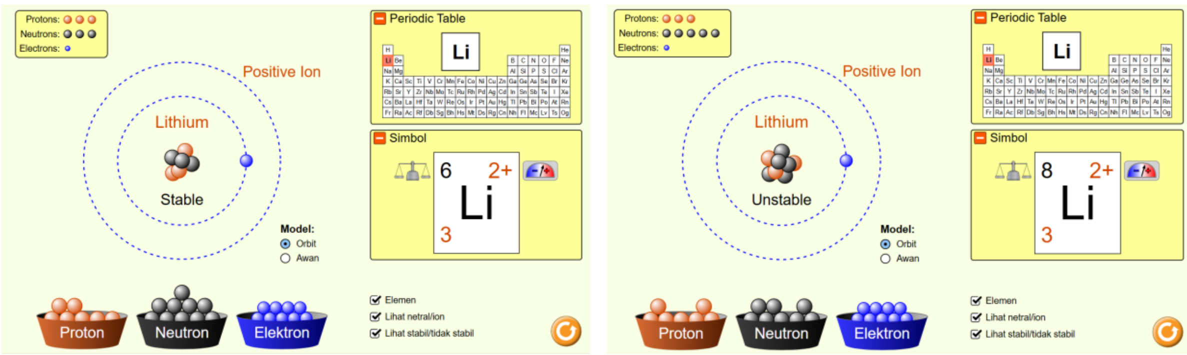

Figure 2. Examples of stable vs. unstable atoms or incorrect/incorrect electron configurations

Figure 2 displays a comparison between stable and unstable lithium atoms through the configuration of protons, neutrons and electrons. In stable atoms, the number of electrons matches the number of protons thus creating a charge balance, resulting in a stable atom. In contrast, unstable atoms show a mismatch in the number of electrons, leading to a charge imbalance and higher potential for reactivity. This visualization makes it easier for students to understand the concept of atomic stability concretely, as they can see first-hand how electron configuration affects atomic stability. In the context of learning, this simulation increases students' overall engagement: cognitive engagement through analyzing and comparing atomic structures, affective engagement through curiosity and enthusiasm when trying to modify electron configurations, and social engagement through discussion and collaboration with peers to compare stable and unstable atoms. Thus, this image not only strengthens students' theoretical understanding, but also facilitates an interactive, explorative learning experience and encourages active participation in the learning process.

Challenges and Obstacles

The results show that the challenges in implementing PhET Simulation are not only technical, but also involve more complex pedagogical and environmental aspects. Technical barriers such as limited computer devices or gadgets, as well as the uneven quality of internet connections, indicate a gap in educational infrastructure that can hinder equitable learning experiences. In some cases, these limitations result in students having to share devices, which indirectly reduces the intensity of their interaction with the simulation. From the perspective of TPACK (Technological Pedagogical Content Knowledge) theory, this condition confirms that the success of technology integration is not only determined by the sophistication of the media, but also the availability of technical support that allows its optimal use. Meanwhile, pedagogical obstacles arise due to differences in teacher readiness in utilizing PhET as a learning tool. Teachers who are accustomed to conventional methods tend to face difficulties in designing simulation-based activities that emphasize exploration and discovery. This has implications for less than optimal knowledge transfer, as digital media that should facilitate conceptual understanding becomes an additional burden if not integrated appropriately.

In addition, environmental factors show the important role of the education ecosystem in determining the successful use of technology-based media. The varying support from schools, both in terms of facilities and internal policies, reflects the disparity in the implementation of learning innovations. Schools with adequate facilities and visionary leadership are more able to encourage teachers and students to utilize PhET consistently, while schools with limited resources tend to lag behind in this innovation. The role of parents is also a significant element, especially in the context of hybrid or out-of-school learning, where support for device access and supervision of learning affects the sustainability of student exploration. This analysis shows that the barriers that arise are not just momentary technical problems, but are closely related to the readiness of the education system as a whole in adopting 21st century learning approaches. Therefore, solution strategies need to be more targeted, such as strengthening teacher training based on real practices, expanding access to devices through collaboration with external parties, and designing PhET integration into the curriculum as part of official school policies. Thus, the utilization of PhET is not only a short-term technological intervention, but also part of a more systematic and sustainable educational transformation.

Implications for Learning Innovation

The results show that the use of PhET Simulation in chemistry learning has significant positive implications for learning innovation. Students not only gain a more interactive learning experience, but are also encouraged to conduct independent exploration of abstract concepts such as atomic structure and stability. The visualization of subatomic particles provided by PhET allows students to observe the relationship between the number of protons, neutrons and electrons directly, thus reducing the cognitive difficulties that usually arise in text-based and lecture-based learning. Furthermore, this experience not only improves conceptual understanding, but also strengthens learning motivation as students feel more actively involved in the learning process. In line with this, the application of PhET contributes to the development of 21st century skills, such as critical thinking in analyzing atomic stability, creativity in constructing different atomic configurations, and collaboration through group discussions to solve problems.

This discussion confirms that the integration of PhET Simulation is a strategic step in supporting the digital transformation of education, especially in chemistry subjects that are often seen as difficult and abstract. By utilizing a technology-based approach, learning becomes more contextual, in accordance with the characteristics of the digital generation that requires a visual and interactive learning experience. This implication also signifies that PhET can be used as a long-term strategy in learning innovation, not only to increase student engagement, but also to strengthen conceptual understanding in depth. When systematically integrated into the curriculum, PhET can be an important tool in building a chemistry learning ecosystem that is more adaptive to the demands of the 21st century, while reducing the gap between abstract theory and concrete learning experiences. Thus, the application of PhET is not just an alternative learning media, but a real representation of educational modernization efforts oriented towards the quality of understanding and competitiveness of students in the digital era.

Conclusion

The conclusion of this study confirms that the utilization of PhET Simulation in chemistry learning is effective to improve the understanding of the concept of atomic structure and stability, while strengthening 21st century skills such as critical thinking, creativity, and collaboration. Interactive visualization helps students understand the relationship between protons, neutrons, and electrons with atomic stability concretely, different from conventional learning that tends to be abstract. Despite technical and pedagogical barriers, with the right tools, teacher training, and curriculum integration, PhET can be a long-term innovative strategy in the digital transformation of chemistry learning in the modern era.

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