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Effectiveness of computer simulation in teaching physics in higher education: a systematic review

Efectividad de la simulación computacional en la enseñanza de la física en educación superior: una revisión sistemática

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Abstract

This systematic review aims to analyze recent empirical evidence on the effectiveness of computational simulations in teaching physics at the higher education level. To this end, a qualitative, descriptive, and deductive approach was employed, following the PRISMA protocol, which ensured a rigorous, transparent, and replicable process. The literature search was conducted in academic databases such as ERIC, Scopus, Dialnet, Springer, and Google Scholar, using key terms and Boolean operators. A total of 74 studies were identified, of which, after applying inclusion and exclusion criteria, 16 relevant studies were selected for the final analysis. The results show that computational simulations offer significant pedagogical benefits: they facilitate the understanding of abstract concepts, stimulate active learning, and increase student interest. However, significant challenges were also identified, such as insufficient teacher training, technological limitations at institutions, and resistance to change in traditional teaching methodologies. In conclusion, it is determined that computational simulations are more effective than conventional methods, as they promote more dynamic student participation, improve academic performance, and strengthen key competencies such as critical thinking and problem-solving.

Keywords: active learning, university education, simulation.

Resumen

La presente revisión sistemática tiene como objetivo analizar la evidencia empírica reciente sobre la eficacia de la simulación computacional en la enseñanza de la Física a nivel superior. Para ello, se empleó un enfoque cualitativo, descriptivo y deductivo, siguiendo el protocolo PRISMA, lo que garantizó un proceso riguroso, transparente y replicable. La búsqueda bibliográfica se realizó en bases de datos académicas como ERIC, Scopus, Dialnet, Springer y Google Scholar, utilizando términos clave y operadores booleanos. En total, se identificaron 74 estudios, de los cuales, después de aplicar criterios de inclusión y exclusión, se seleccionaron 16 investigaciones pertinentes para el análisis final. Los resultados evidencian que las simulaciones computacionales ofrecen beneficios pedagógicos notables: facilitan la comprensión de conceptos abstractos, estimulan el aprendizaje activo y aumentan el interés de los estudiantes. No obstante, también se detectaron desafíos importantes, como la insuficiente formación docente, las limitaciones tecnológicas de las instituciones y la resistencia al cambio en las metodologías de enseñanza tradicionales. En conclusión, se determina que las simulaciones computacionales superan en efectividad a los métodos convencionales, ya que favorecen una participación estudiantil más dinámica, mejoran el rendimiento académico y fortalecen competencias clave, como el pensamiento crítico y la resolución de problemas.

Palabras clave: aprendizaje activo, educación universitaria, simulación.

Introduction

Can a simulation replace a real laboratory in the learning of Physics? This question, which may have once been considered controversial, is now particularly relevant in the context of rapid technological evolution and profound changes in education. The incorporation of emerging technologies has transformed teaching methodologies in higher education, especially in traditionally complex fields like Physics.

For a long time, the teaching of this discipline has faced significant challenges due to the abstraction of its concepts, the need for specific spaces, and the lack of adequate resources for experimentation (Rehman et al., 2021). In contexts where laboratories are limited or nonexistent, the predominance of conventional lecture-based methods has favored memorization over critical thinking, thereby affecting the development of analytical skills and a deep understanding of physical phenomena (Darko & Darko, 2021). Globally, Physics is often perceived as a difficult subject, leading to low motivation, high dropout rates, and poor academic performance, particularly during the first year of university (Tsvetkova et al., 2023).

In light of this situation, computer simulation has emerged as an innovative and effective alternative. These tools allow for the representation of complex physical phenomena in interactive digital environments, promoting active student participation and facilitating the visualization of processes that may be costly, dangerous, or impractical in traditional laboratories (Flegr et al., 2023). Various studies have demonstrated that interactive simulators can match or even surpass the learning outcomes obtained in physical laboratories by encouraging creativity, critical thinking, and autonomous experimentation (Álvarez et al., 2025; Banda & Nzabahimana, 2023). For instance, Yaipén et al. (2023) highlight how online simulators have expanded access to experimental practices in environments where physical equipment is insufficient.

From a theoretical perspective, these experiences are grounded in constructivism, which posits that knowledge is actively constructed through interaction with the environment. Simulators like those from PhET align with this model by allowing students to explore, manipulate variables, and formulate hypotheses, thereby solidifying their understanding of physical phenomena (Saudelli et al., 2021). Moreover, it is recognized in scientific education that computational simulation fosters the development of investigative skills by providing safe, continuous, and replicable access to experimentation (Maraza et al., 2023).

However, doubts remain regarding the effectiveness of computer simulations in different educational contexts, specific areas, and educational levels. Although numerous case studies exist, systematic reviews integrating the most recent empirical evidence are scarce. Thus, this study poses the following question: How effective is computational simulation in enhancing the teaching and learning of Physics in higher education?

Building on this question, the primary purpose of this systematic review is to examine the current empirical evidence regarding the effectiveness of computational simulation in university-level Physics education. It aims to identify the pedagogical benefits associated with its use, the barriers to its implementation—such as a lack of teacher training and technological limitations—and to evaluate its effectiveness compared to traditional methods, considering indicators such as conceptual understanding, student motivation, and academic performance.

From this analysis, we aim to provide a comprehensive perspective that supports pedagogical decision-making, particularly regarding the integration of technology into university curricula. The following sections present the methodological development of the review, the main findings, and a critical discussion of the most relevant results.

Methodology

This study adopted a qualitative approach, applied to a systematic review with a descriptive and deductive character. The primary objective was to analyze and synthesize the available evidence regarding the effectiveness of computer simulation in teaching Physics at the higher education level. To ensure a methodical, transparent, and replicable process, the review was conducted following the PRISMA model, which ensured the quality and reliability of the collected data.

The procedure was structured into the following stages:

1. Identification stage

In this initial phase, a comprehensive and systematic search was conducted across various recognized academic databases, including ERIC, Scopus, Dialnet, Springer, and Google Scholar. The search strategy was designed using selected key terms, including "computer simulation," "physics teaching," "higher education," "active learning," and "educational technologies." Additionally, Boolean operators—such as AND and OR—were employed to optimize the relevance and accuracy of the results obtained.

Table 1
Search strategy for the study

Database	Keywords with Boolean operators	Studies identified
ERIC	("computer simulation" OR "digital simulation") AND ("physics instruction" OR "physics education") AND "higher education"	14 studies
Scopus	("computer simulation" OR "interactive simulation") AND ("physics teaching" OR "physics learning") AND "higher education"	18 studies
Dialnet	("educational technology" OR "digital tools") AND ("physics simulation" OR "virtual experiments") AND ("university learning" OR "HE")	10 studies
Google Scholar	("use of simulators in physics" OR "simulation-based learning") AND ("active learning" OR "student engagement") AND "higher education"	20 studies
Springer	("computer simulation" OR "ICT in education") AND ("university-level physics instruction" OR "physics didactics") AND "pedagogical effectiveness"	12 studies

As a result, a total of 74 initial records were identified. After removing 16 duplicate studies, 58 articles remained for the selection stage.

2. Selection stage

To ensure the quality and relevance of the included studies, inclusion and exclusion criteria were applied in accordance with the PRISMA model. The inclusion criteria were as follows:

- Articles published between January 2020 and March 2025.
- Publications in Spanish or English.
- Studies focused on the use of computer simulation in Physics education.
- Research conducted in the context of higher education or related relevant contexts.

Conversely, the exclusion criteria included:

- Duplicate articles or those written in languages other than Spanish or English.
- Research focused on fields of knowledge other than Physics.
- Works without access to the full text or lacking methodological rigor.
- Opinion pieces, editorials, or essays that lack scientific grounding.

3. Eligibility stage

During this phase, a thorough review of the 58 studies was conducted based on their titles and abstracts, resulting in the exclusion of 28 studies that did not align with the research objective. From the remaining 30 studies, attempts were made to retrieve the full text; however, 5 were unavailable due to access restrictions. Subsequently, 9 additional articles were excluded after a complete evaluation due to factors related to:

- The relevance of the methodological approaches employed.

- The appropriateness of the educational context in which the simulations were applied.
- The results concerning improvements in learning, motivation, and understanding of physical concepts.

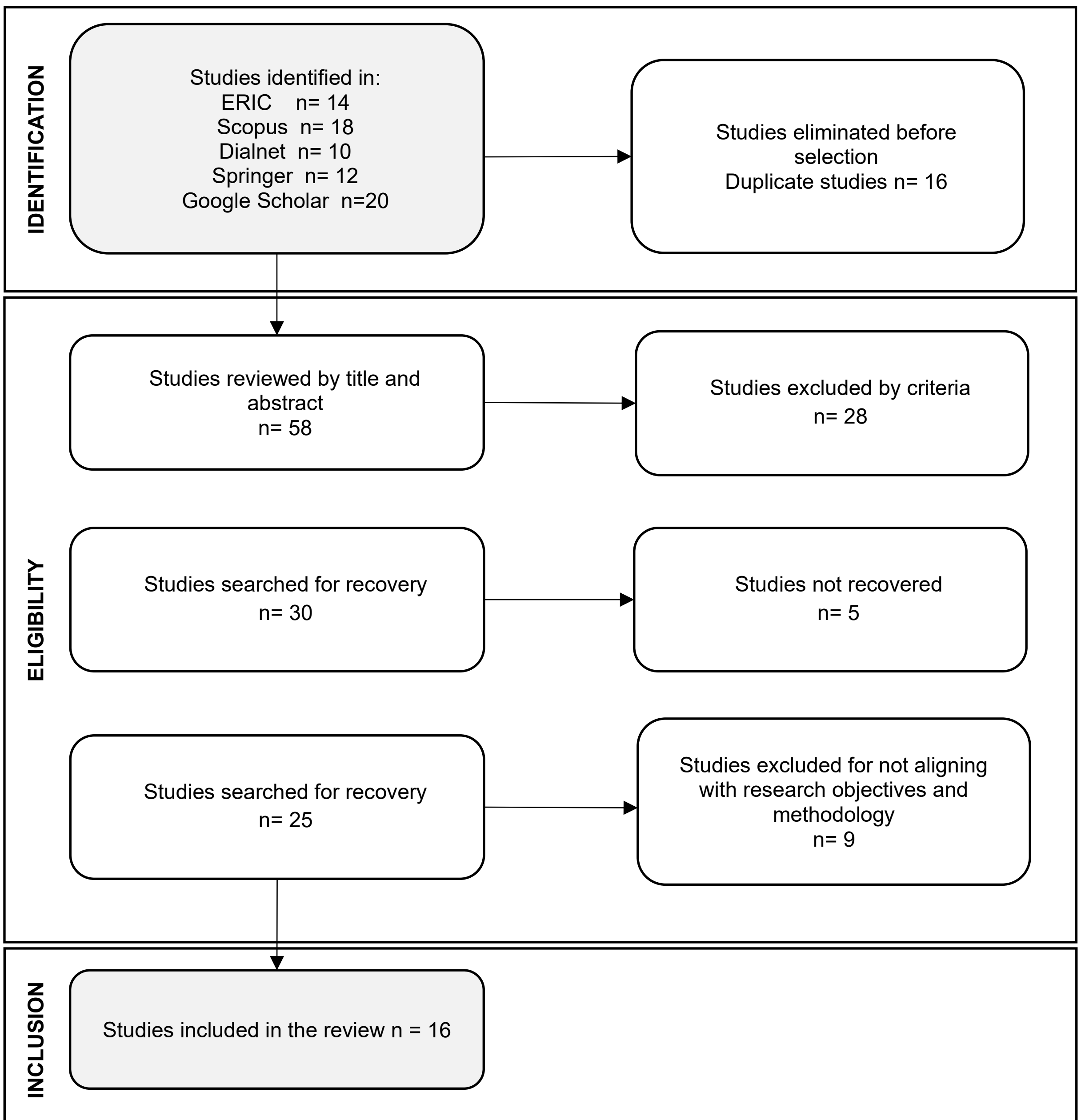
4. Inclusion and synthesis stage

Ultimately, 16 studies were included for the final analysis, all meeting the established criteria. These works underwent detailed analysis with the purpose of:

- Identifying the pedagogical benefits of using computer simulations in university-level Physics education.
- Detecting the barriers and challenges to implementing these technologies, such as a lack of teacher training and limitations in technological resources.
- Evaluating the effectiveness of simulations compared to traditional teaching methods.

Figure 1

PRISMA flow diagram



Results and discussion

Based on the review conducted of the 16 articles selected for this systematic review, the findings related to each of the proposed objectives are presented below in tabular format.

a) Pedagogical benefits of using computer simulations in university Physics education

First, the results obtained from various studies exploring the pedagogical impact of computer simulations on university-level Physics learning are highlighted. The table summarizes recent research evidencing how these tools enhance the development of key competencies, such as student motivation, conceptual understanding, and other relevant pedagogical aspects, thus contributing to a more meaningful and effective learning experience.

Table 2

Findings from the systematic review for specific objective 1 under PRISMA

No.	Authors/Year	Article Title	Study Type	Results
1	Maraza et al. (2023)	Towards the development of investigative skills in Physics students through the use of simulators: A case study	Qualitative Case Study	The use of simulators strengthened investigative skills such as hypothesis formulation, data analysis, and scientific reasoning. Students displayed greater initiative, critical reflection, and autonomy.
2	Yaipén et al. (2023)	Virtual simulators in the teaching-learning of Chemistry and Physics: A systematic review of the literature	Systematic Review	Pedagogical benefits such as improved understanding of abstract concepts, promotion of active learning, and student participation were evident. Advances in motivation and autonomy were also highlighted.
3	Babayekhorasani et al. (2024)	Blended learning: Enhancing student participation through simulation-based learning	Case Study / Experimental	The use of computer simulations and interactive tools such as MATLAB Live Scripts significantly increased participation and understanding of complex concepts. Key pedagogical benefits included active learning, immediate feedback, and the connection between theory and practice.
4	Rehman et al. (2021)	Teaching Physics with interactive computer simulation at the secondary level	Experimental Study	The use of interactive simulations significantly improved students' conceptual understanding, promoted autonomous learning, and enabled more effective problem-solving compared to traditional teaching methods. Students could visually interact with physical phenomena and develop critical thinking skills.
5	Darko & Darko (2021)	Enhancing students' learning of Physics concepts through simulation as a teaching tool of ICT	Qualitative Study Focused on PhET Simulations	PhET simulations improved conceptual understanding of physics, stimulated active student participation, and promoted critical thinking, demonstrating clear pedagogical benefits in learning complex concepts.

6	Saudelli et al. (2021)	PhET simulations in Undergraduate Physics: Constructivist learning theory in practice	Action Research	Pedagogical benefits of PhET simulations were identified as acting as a "more capable peer" according to Vygotsky's theory, facilitating conceptual understanding in university physics.
7	Poma et al. (2023)	Impact of using FISLAB on learning experimental Physics: A case study at Central University of Ecuador	Case Study Applied in Higher Education	It was confirmed that the use of computer simulations strengthens practical-theoretical learning, especially in contexts where access to physical laboratories is limited.

The studies consistently indicate that the use of computer simulations offers significant pedagogical benefits. These include strengthening practical-theoretical learning (Poma et al., 2023), improving conceptual understanding (Darko & Darko, 2021; Saudelli et al., 2021), and promoting the development of critical thinking skills (Maraza et al., 2023). In particular, the research by Poma et al. (2023) strongly supports these findings, evidencing that simulations through FISLAB effectively compensate for infrastructure limitations, favoring autonomous and interactive learning. Additionally, studies like that of Yaipén et al. (2023) confirm that virtual simulations stimulate active participation, autonomy, and student motivation. Consequently, the pedagogical benefits derived from the use of these tools are well-supported in the recent literature and manifest through various methodologies, ranging from qualitative to experimental approaches.

b) Barriers and challenges in the implementation of computer simulations

The following table summarizes findings from research that has identified the main obstacles to integrating computer simulations into university-level Physics education. Among the most common challenges are insufficient teacher training, technological limitations of institutions, and resistance to changes in pedagogical methodologies.

Table 2

Findings from the systematic review for specific objective 2 under PRISMA

No.	Authors/Year	Article Title	Study Type	Results
1	Kefalis et al. (2025)	Digital simulations in STEM Education: Perspectives from Recent Empirical Studies, A Systematic Review	Systematic Review of 31 Empirical Studies (2019–2024)	The review identifies challenges in implementing digital simulations in STEM education, including a lack of specific teacher training, technological resource limitations, and the need to adapt simulations to diverse educational contexts, which can hinder effective integration in Physics teaching.
2	López et al. (2024)	Fluidflow Simulator and Mathematical Assistant for Demonstrating the Existence of Miscible Fluids	Applied Study with Development and Use of Educational Simulator	The article highlights difficulties in integrating computer simulations in university contexts due to limited teacher training in digital technologies and scarce resources in public institutions. It also points to the need for greater technical and pedagogical support for teachers to incorporate these tools in Physics and Mathematics education.

3	Herrera (2024)	Development of Competencies through Prototypes and Simulators in an Interdisciplinary Physics-Mathematics Environment	Applied Research Focused on Educational Simulators and Prototypes	The article identifies key barriers and challenges in implementing computer simulations, such as a lack of teacher training in using these technologies, a shortage of adequate technological resources, and the need for continuous training for teachers. It also emphasizes that simulations and prototypes can improve conceptual understanding, but their effectiveness is limited by available infrastructure and teacher preparedness.
4	Sánchez & Mora (2020)	Simulation in Easy Java for the Poynting Field of a Circular Circuit	Development of Educational Simulation with Applicability Analysis	The study shows that while the simulation enhances understanding of complex concepts, barriers such as inadequate teacher training in tools like EJS and technological limitations in institutions exist. It also mentions resistance to methodological change, especially in environments dominated by traditional teaching.
5	Poma et al. (2023)	Impact of Using FISLAB on Learning Experimental Physics: A Case Study at Central University of Ecuador	Applied Case Study in Higher Education	Significant barriers were identified, including a lack of teacher training to manage FISLAB, limitations in students' access to adequate technological resources, and the need for greater digital infrastructure. Additionally, some institutional resistance to adopting innovative methodologies in traditional environments was noted.

The analyzed studies agree that, despite the evident benefits offered by simulations, their implementation faces both structural and human barriers. In particular, Kefalis et al. (2025) highlight that the lack of teacher training and adequate resources are frequent obstacles; this situation is corroborated by López et al. (2024) and Herrera (2024), who also emphasize the importance of technical and pedagogical support to facilitate the effective use of these tools.

This landscape reveals a significant gap between the available technological innovation and the preparation of the teaching staff, negatively impacting the effective adoption of simulations in education. Furthermore, Sánchez & Mora (2020) point out methodological resistance as a persistent cultural barrier within many traditional educational environments, thus limiting the incorporation of new practices. In this regard, Poma et al. (2023) reiterate that, although simulations possess high pedagogical potential, their effective utilization largely depends on the institutional context and the level of teacher training.

c) Effectiveness of simulations compared to traditional teaching methods

The following table presents results related to the comparison between traditional methods and the use of computer simulations in teaching Physics. It includes experimental and quasi-experimental studies that allow for assessing the effects of these methodologies on learning, motivation, and academic performance.

Table 3

Findings from the systematic review for specific objective 3 under PRISMA

No.	Authors/Year	Article Title	Study Type	Results

1	Álvarez et al. (2025)	Simulators as an Innovative Strategy in the Teaching of Physics in Higher Education	Quasi-experimental, Quantitative	The experimental group using PhET simulators showed a significant increase in motivation according to the RIMMS scale, compared to the control group that performed traditional practices. No significant differences in self-efficacy were found between the groups.
2	Flegr, Kuhn & Scheiter (2023)	When the Whole is Greater Than the Sum of Its Parts: Combining Real and Virtual Experiments in Science Education	Quasi-experimental, Quantitative	Students participating in combinations of real and virtual experiments obtained significantly higher scores in conceptual understanding (59.7% on average) compared to those who conducted only real experiments (53.5%). The sequence of experiments (real-virtual or virtual-real) did not affect the results, indicating that the combination of methods is more effective than exclusive use of traditional experiments.
3	Banda & Nzabahimana (2023)	The Impact of Interactive Simulation-Based Learning Using PhET on Motivation and Academic Performance among Physics Students in Malawi	Quantitative, Quasi-experimental Design	The experimental group using PhET simulations showed significantly superior academic performance compared to the control group ($p < 0.05$). Additionally, an increase in intrinsic motivation and interest in learning Physics was observed, demonstrating the effectiveness of simulations over traditional methods.
4	Sari et al. (2021)	Viability of Computer Simulation for Learning Newton's Law	Feasibility Study	The study demonstrates that computer simulations are effective in improving students' conceptual understanding of Newton's law, facilitating autonomous learning and better problem-solving compared to traditional methods.
5	Tsvetkova et al. (2023)	Development and Implementation of Virtual Physics Laboratory Simulations to Enhance Learning Experience in Higher Education	Implementation Study	Results indicate that virtual laboratory simulations improved student participation and understanding of physics concepts. Greater effectiveness in understanding complex principles was observed, especially when simulations were implemented in the classroom as a complement to traditional teaching methods. Additionally, students showed increased interest and motivation in learning Physics.
6	Poma et al. (2023)	Impact of Using FISLAB on Learning Experimental Physics: A Case Study at Central University of Ecuador	Applied Case Study in Higher Education	The simulations not only complement but can surpass the effectiveness of traditional methods in certain aspects of learning experimental Physics.

The findings reinforce the idea that computer simulations are as effective, if not more so, than traditional methods, particularly in developing conceptual understanding. For example, Banda & Nzabahimana (2023) and Sari et al. (2021) show significant improvements in academic performance and student autonomy, key aspects for deep and meaningful learning. Furthermore, Flegr et al. (2023) highlight that combining traditional methods with simulations yields better outcomes than the exclusive application of in-person practices, aligning with a hybrid perspective of the educational process.

On the other hand, Tsvetkova et al. (2023) and Álvarez et al. (2025) note that while these tools increase student participation and motivation, they do not always lead to significant changes in self-efficacy perception. Lastly, Poma et al. (2023) reaffirm that in contexts with limited resources, simulations can surpass conventional methods in effectiveness, thus demonstrating their potential to democratize access and educational quality.

Conclusions

Upon completion of the research, it is concluded that, regarding the first objective, the analyzed studies demonstrate that computer simulations provide significant pedagogical advantages for university-level Physics education. These tools not only facilitate the visualization and interaction with abstract phenomena, enhancing the understanding of theoretical concepts, but also promote the development of higher-order cognitive skills, such as critical thinking, problem-solving, and analysis. Consequently, they contribute to a more enriching and autonomous learning experience for students. Thus, the use of simulations is established as an innovative educational alternative, aligned with the current demands of scientific education in digital environments.

Regarding the second objective, various limitations have been identified that hinder the effective implementation of computer simulations in the university context. Among the most notable barriers are insufficient teacher training in the use of these technologies, resistance to methodological change, and limitations in the technological infrastructure of some educational institutions. While these challenges can be overcome, they require prioritization from academic authorities and educational policy makers, as they restrict the transformative impact of ICT on the teaching of exact sciences. Overcoming these barriers necessitates investment in teacher training, technological improvements, and curricular adjustments to enable a more equitable and sustainable adoption of simulations.

Finally, concerning the third objective, the comparison between traditional methods and computer simulations reveals that the latter can be as effective, and even superior, to traditional lectures, particularly regarding learning outcomes. Most of the reviewed studies indicate improvements in academic performance, greater retention of knowledge, and a notable increase in student motivation when using simulated environments. These results suggest that simulation not only complements but, in many cases, surpasses conventional approaches, highlighting its value in contexts where access to physical laboratories is limited. Therefore, its strategic incorporation into university curricula represents a tangible opportunity to innovate in the teaching of Physics, supported by scientific evidence.

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