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A SYSTEMATIC REVIEW OF SCIENCE TEACHERS' USE, PERCEPTIONS AND CHALLENGES OF TECHNOLOGY-ENHANCED SIMULATIONS

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Abstract

Technology-enhanced simulations (TES) have gained significance in science education because they can facilitate inquiry learning, represent abstract science concepts visually, and offer interactive learning opportunities. Although science teachers are increasingly incorporating TES into their lessons, they still face a few challenges that affect their effective integration of TES into their lessons. Despite the progressive use, science teachers still experienced some challenges that affect the effective incorporation of TES into the lesson. This systematic review aims to compile empirical studies from 2020 to 2026 that look at the use, problems, and perceptions of science teachers with technology-integrated simulations in science education. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework guided the review of peer-reviewed qualitative, quantitative and mixed methods studies retrieved from Google Scholar. The results show that science teachers frequently resort to TES to facilitate conceptual understanding, inquiry learning, testing of hypothesis and substitution of lab in limited physical resources. Overall, teachers believe that simulations are effective in improving student visualization, their active learning, and their engagement. However, several issues hinder effective implementation, including a lack of infrastructure, inadequate professional development, unreliable internet access, limited institutional support, and difficulty aligning simulations with curriculum standards. In addition, the review points to new trends like the use of virtual reality (VR), AI-driven simulations, and gamified learning settings, especially in pre-service teacher training. The results indicate that TES have high pedagogical potential, but the integration of TES into the system should be coordinated in terms of investment in teacher training, infrastructure, curriculum alignment and institutional support systems. This review provides an aggregated evidence base, which can be used for informing current educational policies, teacher preparation, and future research on science teaching through simulation.

Keywords: science education, science teachers, simulation-based learning, technology-enhanced simulations, technology integration

INTRODUCTION

Digital technologies are a rapidly developing tool that has changed the way of teaching and learning in many subject areas, including science education. Technology enhanced simulations (TES) are among the most encouraging innovations, interactive computer-mediated simulation environments that enable students to visualize, manipulate, and explore abstract scientific phenomena that are not easily observed in real settings in the classroom (Rutten et al., 2021; Wieman et al., 2020). Virtual laboratories, computer-based modelling platforms and tools like PhET Interactive Simulations have been widely used in K-12 and higher education settings as dynamic representations of concepts in biology, chemistry, physics and earth sciences (Adams, W.K., et al., 2020; Olympiou & Zacharia, 2022).

Science teachers position play an important role in the effective integration of TES in the teaching and learning process. They make decisions about when, how and why of the deployment of simulations, based on a combination of technological competence, pedagogical beliefs, institutional support and perceived utility (Bray & Tangney, 2022; Tondeur et al., 2021). Although the literature on the significant advantages of simulation-based learning—higher levels of student engagement, conceptual understanding, and inquiry skills—continually grows, there are a number of barriers. These include poor infrastructure, lack of professional development, and lack of congruence between simulation content and curriculum standards (Merchant et al, 2021; Psycharis, 2022). It is therefore crucial to understand how science teachers use these affordances and constraints, to inform policy and practice.

In the past, teachers' attitudes and utilization of specific simulation platforms have been investigated case by case, but there is a lack of a thorough overview of the literature. Previous work has largely been directed towards student outcomes or towards larger-scale educational technology integration, with teachers' experiences and outcomes as a secondary concern (Merchant et al., 2021; Rutten et al., 2021). Furthermore, the evidence available prior to the significant increase in digital and blended learning that has been brought about by the COVID-19 pandemic, which completely changed the way teachers interact with educational technologies (Bray & Tangney, 2022; Tondeur et al., 2021). So a timely and necessary comprehensive and up to date synthesis, both teacher centered and student oriented, is needed.

This systematic review aims to fill this gap by compiling peer-reviewed empirical studies published between 2020 and 2026 that investigated the use, perceptions and challenges by science teachers with technology-enhanced simulations. The aim of this review is to provide answers to four main science research questions as outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, namely: (1) How do science teachers use technology-enhancing simulations in teaching? (2) How do science teachers perceive the effectiveness of these simulations that utilize technology (3) What are some of the difficulties science teachers face in adopting technology enhanced simulations? and (4) What are the themes or trends that appear in the discussed studies? This review seeks to offer educators, curriculum developers and policy makers an aggregated set of evidence to inform decisions when implementing simulation-based tools for helping to implement and maintain their use within a science curriculum.

METHODOLOGY

The method for this study was systematic literature review (SLR) to discuss the use, problems, and attitudes of teachers on technology-enhanced simulation. The review process was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Page, 2021). Four major stages of the PRISMA flowchart were followed to select the articles: identification, screening, eligibility and final inclusion. In the identification stage, relevant literature was identified from the search engine Google Scholar using the search terms “science teacher”, “STEM teacher”, “biology teacher”, “physics teacher”, “chemistry teacher”, “simulation-based learning”, “virtual simulations”, “digital simulations”, “computer simulations”, “PhET simulations”, “perceptions”, “attitudes”, “beliefs”, “experiences”, “barriers”, “difficulties”, “limitations”, “implementation”, “integration”, and “utilization”. The identified relevant literature was screened in the screening stage by selecting the year of publication (2020-2026) of the journal articles. At the eligibility stage, selected articles from the journals were once again screened to exclude articles that addressed topics other than science, articles with only student participants and not teacher participants, non-peer-reviewed articles (blog, editorial), duplicate articles, and articles that were not specifically about technology-enhanced simulations. Since the inclusion stage, articles published between 2020-2026, which involved science teachers as participants, discussed technology-enhanced simulations in science education, and were written in English and had a full text were included in the study, with the exception of those with full text that were not found in English. Selected content analysis was used for the analysis of studies that fulfilled the inclusion criteria.

LITERATURE REVIEW

Technology-enhanced simulations (TES) as tools for teaching science have become increasingly common in the last decade, and there has been a growing body of research on TES. TES refers to interactive computer mediated environments where the learner can manipulate variables, observe phenomena, and participate in scientific enquiry in a virtual environment (Makamu & Ramnarain, 2022). Within this space have emerged various platforms, including dynamic representations of concepts such as PhET Interactive Simulations, virtual laboratories and computer-based modeling tools, allowing for dynamic visualization of concepts in the fields of biological, chemical and physical sciences (Ben Ouahi et al., 2022). A recent empirical study by Drigas et al. (2025) revealed that digital simulations were effective across a range of empirical studies in STEM education in improving conceptual understanding, engagement, and problem-solving skills for learners and identified the areas that needed more research in primary and special education settings. Likewise, a systematic review by Wörner et al., (2022) that included 42 experimental studies revealed that, overall real and virtual experiments were most effective at promoting conceptual understanding as compared to a single type of experiment, although no sequence was found that was generally superior.

The theory of simulation-based learning is mostly based upon constructivism and cognitive learning theory. Learners who engage with simulations build meaning by exploring, hypothesizing, and receiving instant feedback from the simulations, which allows them to better engage with abstract scientific phenomena than when they are taught passively (Batamuliza et al., 2024). Nandani

and Raturi (2024) examined the design of Fiji science teachers' simulations and found that Cognitive Theory of Multimedia Learning (CTML) provides further support for the design of simulations that align visual and verbal channels of information to reduce the extraneous cognitive load. These theoretical foundations highlight why simulations have been placed on the shoulders of not only as additional digital resources but also as epistemologically valid pedagogical tools.

Empirical studies have reported different patterns of science teachers' use of TES in their instruction. When surveyed, 114 middle and high school science teachers in Morocco were asked about their use of PhET simulations; those teachers who used PhET simulations tended to use them mostly at the investigative stage of their lessons to illustrate abstract phenomena and to scaffold their conceptual understanding (Ben Ouahi et al., 2022). This study identified certain characteristics of teachers who most frequently use simulations in their teaching: 1) technologically competent, 2) having institutional support. Makamu and Ramnarain (2022) examined three physical sciences teachers in grade 10 in South Africa that utilized the 5E inquiry-based teaching model to teach using simulations. The qualitative results indicated that simulations allowed teachers to provide opportunities for hands-on inquiry, particularly for hypothesis testing, for providing evidence-based explanations, and for decreasing their reliance on the teacher to provide answers or explanations, in ways consistent with the Engage, Explore, Explain, Elaborate, and Evaluate cycle.

Research also shows that teachers are using simulations for more than just exploratory/explanatory use, but to replace dangerous or resource-intensive lab experiments. Batamuliza et al. (2024) matched with eight lower secondary chemistry teachers in Rwanda, reported that interactive computer-based learning systems (ICBLS) were appreciated because it allows for experimentation in safe and controlled environment, in particular, for chemical reactions that may be dangerous in physical laboratories. In the Philippines, Paje et al. (2021) also reported the use of computer-based technology such as simulating tools to overcome the limitation of resources in under-equipped schools in the Philippines. The results of this study indicate that pedagogical practices in the use of TES are not only determined by teachers' pedagogy but also by circumstances of the material environment within which they work.

Furthermore, Almasri (2022), in her study on the relations between the use of simulation, student engagement, self-confidence and learning styles, remarked that teachers who used simulations in science lessons found differentiated benefits for students with different cognitive preferences, specifically for kinesthetic and visual learning orientations. The work highlights the importance of teachers' mediation and how they need to consider the needs of the students they are working with and how this might affect the choice and use of TES tools in the classroom.

The prevailing pattern across the literature is one of favorable teacher perceptions toward the effectiveness of TES in science instruction. Ben Ouahi et al. (2022) reported that the majority of surveyed science teachers viewed interactive simulations as highly effective for both teaching and learning, particularly for visualizing abstract concepts, increasing student motivation, and supporting investigative approaches to science. These positive perceptions were more pronounced among teachers who had received dedicated training and had longer experience using simulation platforms.

Batamuliza et al. (2024) similarly found that chemistry teachers perceived ICBLS as beneficial for safety, collaboration, and active learning, framing them as instruments that democratize access to experimental science in schools with limited physical laboratory resources. In Fiji, Nandani and Raturi (2024) reported that teacher readiness to use digital simulations improved markedly following an intervention combining training in cognitive strategies and practical simulation use, suggesting that perceptions of effectiveness are not static but can be cultivated through targeted professional learning. Palacios et al. (2024), developing and validating a 27-item questionnaire administered to 783 secondary teachers in Spain, identified five attitudinal factors shaping teacher dispositions toward virtual simulations; their findings indicated that prior training and positive classroom experiences were the strongest predictors of favorable attitudes, reinforcing the relationship between professional competence and perceived effectiveness.

The relationship between teacher perceptions and actual use is further mediated by broader pedagogical beliefs. Teachers who hold constructivist views of learning tend to perceive TES as well-aligned with inquiry-oriented science teaching, while those with more transmission-oriented pedagogies may struggle to identify appropriate integration points (Makamu & Ramnarain, 2022). Research on TPACK—Technological Pedagogical Content Knowledge provides a useful framework: teachers who possess robust content knowledge, pedagogical flexibility, and technological familiarity are better positioned not only to perceive simulations favorably but to deploy them in ways that generate meaningful learning outcomes (Mishra & Koehler, as cited in Jiménez Sierra et al., 2023). This body of evidence suggests that perception alone is insufficient; sustained, pedagogically informed engagement with TES is required to translate positive attitudes into effective instructional practice.

The COVID-19 pandemic constituted a pivotal moment for TES adoption, as the sudden shift to remote and hybrid learning compelled teachers to engage with digital platforms including simulations at an unprecedented scale and pace. Research conducted in the immediate post-pandemic period documents both accelerated uptake and heightened awareness of the limitations of simulation-based instruction when delivered without adequate scaffolding or student support (Drigas et al., 2025). A systematic review by Sun et al. (2022) examining guidance-designed simulation-based inquiry learning in science education over the prior decade found that while guidance consistently produced positive effects on learning outcomes, the design of that guidance and particularly its alignment with students' cognitive engagement was more consequential than the simulation platform itself.

A distinct trend in recent literature concerns the heterogeneity of TES contexts. Earlier reviews tended to focus disproportionately on student outcomes in higher education settings, often in Western contexts, while teacher experiences and K–12 implementation in the Global South received comparatively less attention (Batamuliza et al., 2024; Nandani & Raturi, 2024). More recent empirical work is beginning to address this imbalance, contributing evidence from African, Pacific Island, Southeast Asian, and Middle Eastern educational settings. This geographic diversification of the research base reflects a growing recognition that the affordances and constraints of TES are shaped by local infrastructure, curriculum policy, and cultural context—factors that earlier, predominantly Western-oriented syntheses were poorly positioned to capture.

While there are known benefits of TES it is clear there are significant barriers to the effective use of TES. In a mixed methods study with 609 STEM teachers in secondary schools, Pozuelo-Muñoz et al. (2025) reported that the use of virtual simulations was hampered by three primary factors: logistical problems related to school resources, limited availability of appropriate virtual simulations to match curriculum topics, and inadequate time and training to create pedagogically viable simulations-based lessons. Not all of these barriers were experienced equally: teachers in the schools with better ICT infrastructure and administrative support reported significantly lower constraints.

One of the most consistently mentioned barriers from literature is professional development. Even among the chemistry teachers who had positive perceptions about ICBLs, Batamuliza et al., (2024) reported that the lack of adequate professional training was still a big hurdle for teachers who were not confident in using simulations in a pedagogical way beyond the technical level. This resonates with the existing research on technology integration: A systematic review commissioned by Tran et al. (2025) of teacher professional development and the use of digital tools for digital instruction revealed that more than 40% of teachers across the globe reported a lack of training in digital pedagogy, and only 30% reported using digital tools frequently to support their instruction. The review also pointed out that gaps in access to professional development, institutional support, and digital infrastructure exacerbated challenges to implementation, especially in lower-resource school settings.

A related barrier is infrastructure deficits. A lack of devices and a lack of internet connectivity was found to be a major constraint on science teachers' ability to implement digital simulations in Fiji (Nandani and Raturi, 2024). This concern has been reported in various geographic settings ranging from Morocco (Ben Ouahi et

al., 2022) to Rwanda (Batamuliza et al., 2024) and thus is not only a regional issue. In other education technology (EdTech) adoption-related research, it is also reported that persistent barriers such as assets, funding, suitable infrastructure, and access to internet connections in the classroom continue to hinder the use of technology. (Zekioglu et al., 2024 as cited by Starks & Reich, 2024)

Additional challenges relate to the alignment of simulation content with national curriculum standards, teachers' concerns about student distraction when treating simulations as entertainment, and the cognitive demand placed on students who lack sufficient prior theoretical knowledge to interpret simulation outputs meaningfully (Pozuelo-Muñoz et al., 2025). Together, these barriers reveal that effective TES integration requires coordinated action at multiple levels from classroom pedagogy to institutional policy and resource allocation.

Collectively, the literature reviewed points toward a convergent set of themes: teachers generally perceive TES as effective and valuable, yet their actual use remains constrained by professional development gaps, infrastructure deficits, and curriculum alignment challenges. Addressing these barriers requires not only investment in technology provision but equally in the pedagogical preparation of teachers to integrate simulations with intentionality and disciplinary coherence.

RESULTS AND DISCUSSION

This section presents the findings of the systematic review, synthesizing empirical evidence drawn from eleven peer-reviewed studies published between 2020 and 2026. The studies collectively examine science teachers' use, perceptions and challenges of technology-enhanced simulations (TES) across diverse geographic and educational contexts.

Table 1: Review of literature on the Teachers’ Use, Perceptions and Challenges of Technology-Enhanced Simulations

Author/s (Year)	Country / Location / Setting	Field of Study (Level)	Method	Key Findings
Ben Ouahi, Lamri, Hassouni, & Al Ibrahmi (2022)	Morocco (middle and high schools)	Physics-chemistry; life and earth sciences (secondary)	Quantitative (survey; n = 114)	Most teachers viewed PhET simulations as effective for visualizing abstract phenomena and supporting inquiry; use was concentrated in the investigative phase of lessons; technological competence and institutional support were associated with higher frequency of use; infrastructure limitations and insufficient training were the principal obstacles.
Nandani & Raturi (2024)	Fiji (Year-11 classrooms)	Science (secondary)	Mixed methods (TAM + CTML framework; intervention design)	Teacher readiness and perceptions of digital simulations as both useful and easy to use improved meaningfully following targeted training; cognitive knowledge and practical skills increased post-intervention; inadequate device access and unreliable internet remained significant barriers to consistent deployment.
Penn & Mavuru (2020)	South Africa	Life sciences (pre-service / teacher education)	Quantitative / mixed methods	Pre-service life sciences teachers held generally favorable attitudes toward

				virtual laboratory simulations; reception was positive across most dimensions, though some participants expressed uncertainty regarding pedagogical alignment with curriculum requirements.
Ogegbo & Ramnarain (2022)	Rural South Africa (Grade 11 classrooms)	Physics (secondary)	Mixed methods (quasi-experimental + qualitative)	Interactive simulation technology (IST) proved effective as a guided-inquiry approach in a rural school context; simulations supported hypothesis testing, evidence-based reasoning, and reduced reliance on teacher-centered instruction; contextual and infrastructural constraints required adaptive implementation strategies.
Al Breiki, Al Abri, Al Moosawi, & Alburaiqi (2023)	Oman	Science (secondary; n = 171)	Quantitative (structural equation modeling; Diffusion of Innovation + Theory of Planned Behaviour)	Attitude toward virtual reality was the strongest predictor of adoption intention; subjective norms and perceived behavioral control also contributed significantly; perceived skills readiness moderated the relationship between social influence and adoption intention.
Ates & Kolemen (2024)	Turkey	Science (secondary)	Quantitative (TPB + Protection Motivation Theory model)	Perceived threats, anticipated benefits, attitudes, and cognitive-motivational factors collectively shaped science teachers' intentions to adopt gamified virtual reality; threat appraisal processes functioned as both motivators and inhibitors of adoption depending on perceived coping efficacy.
Govender & Nzabahimana (2025)	Mozambique	Science (secondary)	Qualitative (multiple-case study)	Teachers held broadly positive beliefs about the role of simulations in inquiry-based science teaching; however, systemic barriers—including inadequate infrastructure, restrictive curriculum policies, and limited institutional support—constrained practical integration in under-resourced school settings.
Penn & Matome (2025)	Eastern Cape, South Africa (rural schools; n = 186)	Life sciences (secondary)	Sequential explanatory mixed methods (Technology Acceptance Model)	Teachers demonstrated positive perceptions of virtual laboratories, reporting high perceived usefulness and ease of use; despite favorable attitudes and stated intentions, the study found that intent alone did not reliably predict actual adoption, suggesting that access conditions and support structures mediate behavioral follow-through.
Batamuliza et al. (2026)	Secondary schools (sub-Saharan African context)	Science (secondary)	Quantitative	Barriers to virtual simulation use included indirect obstacles originating from educational policy bodies, inadequate training provisions, and institutional inertia; years of teaching experience significantly influenced the frequency with which simulations were deployed, with more experienced

				teachers using them less often.
Morales et al. (2024)	South Africa (n = 83)	Science (pre-service / microteaching)	Quantitative (survey; regression analysis)	Pre-service science teachers demonstrated a high level of acceptance and strong intention to integrate virtual reality classrooms into future teaching practice; positive attitudes were reinforced by microteaching experiences with VR tools.
Zhang et al. (2025)	International (pre-service contexts)	Science and mathematics (pre-service / teacher education)	Qualitative	Pre-service teachers reported meaningful perceptions and learning experiences when using AI-powered virtual reality simulations for dialogic teaching practice; key challenges included difficulty adapting to simulation-based pedagogical environments, managing AI-generated interactions, and bridging the gap between simulated and real classroom dynamics.

Patterns of Technology-Enhanced Simulation Use in Science Teaching

There is significant variation in the studies regarding the use of technology-enhanced simulations (TES) by science teachers, which is attributed to pedagogical orientations, institutional contexts and platforms. Some of the main findings of Ben Ouahi et al. (2022) indicated that the Moroccan science teachers used the PhET simulations mostly to showcase abstract phenomena and guide the construction of conceptual understanding, instead of using them as complete teaching units themselves. This supplementary pattern is in line with global meta-analysis findings that simulations are used most often in conjunction with traditional instruction and that they have the greatest impact when incorporated into the design of lessons (Rutten et al., 2012).

Simulations can play a more central role in guided-inquiry settings. The use of interactive simulation technology (IST) allowed for hypothesis testing, evidence-based explanation, and reduced teacher dependence, characteristics of the 5E inquiry model found in a parallel study in South Africa by Makamu and Ramnarain (2022). The use of simulations was also reported in low-resourced environments, with Govender and Nzabahimana (2025) and Penn and Matome (2025) documenting this practice in Rwandan chemistry teaching; similarly, Batamuliza et al. (2024) reported that Rwandan chemistry teachers appreciated simulation platforms for conducting safe experiments with chemical reactions that are hazardous or resource demanding in real laboratory contexts.

A third pattern of pre-service contexts of use is related to the development of pedagogical competency itself, as seen in simulations using AI-powered virtual reality (VR) environments as means for not only teaching scientific content, but also for developing pedagogical competency. The pre-service science and mathematics teachers engaged in the dialogic teaching skills in qualitatively different application of pre-service teaching students: using virtual reality (VR) with the support of generative artificial intelligence (AI) as a rehearsal space for teaching. Likewise, Morales et al. (2024) reported that microteaching experiences in VR classrooms positively affected the attitudes of pre-service teachers, and their attitudes towards VR tools in their future professional lives, indicating that early exposure to VR during

teacher preparation might be an important factor in supporting its long-term use.

Science Teachers' Perceptions Regarding the Effectiveness of Technology-Enhanced Simulations

One major finding from the studies reviewed is that science teachers generally have positive views of TES. For Moroccan teachers, the interactive simulations are extremely effective in both teaching and learning processes, especially in enhancing their students' motivation and facilitating the visualization of abstract scientific concepts, as Ouahi et al. (2022) have revealed. In Fiji, Nandani and Raturi (2024) found similar positive perceptions, with readiness and perceived ease of use significantly improving after training. However, Penn and Matome (2025) found that teachers in the life sciences field in South African schools had high perceived usefulness and ease of use, which was in line with the prediction of the Technology Acceptance Model (TAM). The results support Palacios et al. (2024) validation of teacher attitudes questionnaire (TAQ) for 783 secondary school teachers in Spain, where prior training and positive experiences in the classroom emerged as the most significant factors in the development of positive attitudes toward virtual simulations, further supporting the idea that attitudes are not dispositional but rather a result of experiences.

Theory-driven adoption studies offer a finer-grained understanding of what accounts for these attitudes. In the case of the Omani science teachers, Al Breiki et al. (2023) concluded that attitude towards VR was the most powerful predictor of behavioral intention to use VR alone, better than the other factors (SEMs). Combining the Theory of Planned Behaviour and Protection Motivation Theory, Ateş and Kölemen (2024) also found that teachers' intentions to adopt were higher when they believed their threats were high and coping efficacy was high, indicating that the professional development of teachers might be effectively leveraged to engage teachers rather than reduce the apprehensions associated with emerging simulation tools.

A key qualification to the overall favorable perceptions noted by researchers in a number of studies is the difference between intent and actual usage. Penn and Matome (2025) found that positive intentions were not consistently translated into the actual adoption, while Batamuliza et al. (2024) identified institutional and policy

issues that dampened the correlation between having a positive attitude and classroom practice. This gap in implementation is well documented in the broader technology integration literature; according to Tondeur et al. (2017), pedagogical beliefs are necessary but not sufficient factors in the technology integration process, and institutional context (institutional climate, access to support, and resources) moderate the attitude–behavior relationship. Concerns about alignment with curriculum might dampen adoption for future use in the classroom.

Emerging Themes and Trends in the Reviewed Studies

From synthesis of the reviewed literature several overarching themes and trends emerge. The persistent reporting of the intention-behaviour gap in Morocco, South Africa, Fiji and Rwanda and the fact that it has not been fully addressed by research literature highlights the need to first acknowledge that having a favourable attitude is a necessary but not sufficient condition for sustained TES integration, (Penn & Matome, 2025; Batamuliza et al., 2024). Institutional mechanisms such as administrative encouragement, communities of practice, and explicit accommodation of simulation-based inquiry in the curriculum seem necessary to fill this void.

Second, the field is seeing a qualitative change with increased scope and sophistication of TES, including VR and gamified simulation technology powered by AI. Pre-service teachers appreciated the use of AI powered VR simulations as pedagogical tools for rehearsing complex dialogic teaching strategies without risk of failure—a tool that could not be replicated on traditional platforms. There also were significant challenges that participants experienced with the use of AI-generated student interactions, including the issue of adapting to representational conventions and the transfer of skills to real classroom contexts. The design of instructional guidance was shown to be more important than the simulation platform, with even more profound impact on learning outcomes than complex interactional environments of AI-enabled VR (Sun et al., 2022).

Third, Ateş and Kölemen's (2024) use of Protection Motivation Theory suggests a shift toward more theoretically integrative models that can account for the more ambiguous and morally laden adoption decisions stimulated by immersive AI environments. Gamification features were correlated with greater perceived value in terms of engagement but also elicited concerns around pedagogical trivialization and curricular alignment, some of those concerns that are not captured appropriately by existing frameworks like TAM.

Fourthly, we found that the pre-service teacher education environment is a crucial but unexploited factor in the promotion of TES. In a study by Morales et al. (2024), microteaching experiences in VR classrooms achieved high acceptance and positive intentions which can be transferred to early career practicum. The findings are in line with the notion that technology integration must be integrated in an authentic way, not just as technology modules during practicum (Jiménez Sierra et al., 2023). A key temporal dimension in the process of adoption which can be added to the DOT framework used by Al Breiki et al. (2023) is that of the stages of adoption, which include awareness, interest, evaluation, trial, and adoption, and that pre-service learning exposure can help to speed up the process.

Last, the longstanding infrastructure and professional development deficit recorded throughout sub-Saharan Africa, the Pacific Islands

and North Africa highlight a systemic inequity issue. Ensuring access to TES while excluding or incentivizing its adoption may actually exacerbate rather than reduce educational inequities. Research and policy should consider TES not as a stand-alone solution, but when combined with a variety of other instructional strategies, such as physical experiments and teacher-led discussion, to determine the circumstances under which simulation-based learning is successful. An investigation of which conditions are successful for TES should be combined with other instructional strategies, such as physical experiments and teacher-led discussion (Wörner et al., 2022).

Challenges Encountered by Science Teachers in Using Technology-Enhanced Simulations

All reviewed studies confirm that barriers to the integration of TES continue to exist even among teachers with positive perceptions and definite intentions to adopt TES. These barriers exist at individual, institutional, and systemic levels and are context specific.

Infrastructure gaps are the most common problem reported in all geographic areas. Positive science teachers' attitudes towards simulation were not translated into regular use of the devices and internet access, as reported by Nandani and Raturi (2024). Similar restrictions have been reported in Morocco by Ben Ouahi et al. (2022) and among the most intractable barriers in Mozambique by Govender and Nzabahimana (2025) for systemic infrastructure barriers. The results indicate that infrastructure problems are not exclusive to any specific region but rather are more widespread.

The need for professional development gaps was identified as another key constraint. Batamuliza et al. (2024) showed that the frequency of using simulation was significantly reduced due to training that was inadequate and having restrictive institutional policies. In a similar study, Tran et al. (2025) found that over 40% of teachers worldwide felt ill-prepared for digital pedagogy, and they only reported using digital tools frequently in teaching and learning in 30% of cases, with access to professional development exacerbating implementation difficulties in lower-resourced systems. Most importantly, in an intervention study, Nandani and Raturi (2024) found that these deficits are not set in stone: After providing a mix of cognitive strategy instruction and simulation-based practice, teacher readiness and perceived ease of use increased significantly.

The third type of barrier relates to curriculum and policy alignment. According to Govender and Nzabahimana (2025), there was a lack of policy support for simulation-based inquiry in the curriculum in Mozambique, despite the presence of an institutional strategy for adapting curriculum. Govender and Nzabahimana (2025) noted that the policy did not sufficiently support simulation-based inquiry in the curriculum, despite the implementation of an institutional strategy for adapting curriculum in Mozambique. Similarly, Batamuliza et al. (2024) found that policy-level barriers were also significant barriers, as institutional inertia may impact individual teachers' integration efforts regardless of positive attitudes and skills. These systemic barriers are similar to the multilevel approach put forward by Bray and Tangney (2017) which suggested that integration of sustainable technology needed to occur at all three levels: classroom, school, and policy. It is interesting to note that teachers with more experience employed simulations less than those with less experience, indicating that such cognitive inertia may occur as a result of more time spent on

traditional pedagogical practices, another implication for career-stage-differentiated professional development design.

CONCLUSION

This systematic review examined science teachers' use, perceptions and challenges of technology-enhanced simulations across diverse educational and geographic contexts. The findings demonstrate that TES have become important pedagogical tools in science education, supporting inquiry-based instruction, conceptual visualization, experimentation, and learner engagement. Teachers employ simulations in varied ways depending on contextual conditions, instructional goals, and available technological resources. In many cases, TES serve not only as supplementary instructional tools but also as practical alternatives to resource-intensive or hazardous laboratory activities.

The review further reveals that science teachers generally hold positive perceptions regarding the effectiveness of simulations in improving teaching and learning outcomes. Positive attitudes toward TES are strongly associated with perceived usefulness, prior training, technological competence, and successful classroom experiences. Emerging technologies such as virtual reality and AI-powered simulations also indicate an expanding scope for simulation-based instruction and teacher preparation.

Despite these benefits, significant barriers continue to constrain TES integration. Infrastructure limitations, inadequate internet connectivity, insufficient professional development, limited institutional support, and curriculum alignment challenges remain persistent concerns across multiple contexts. The review also highlights the gap between teachers' positive intentions and their actual classroom implementation of TES, suggesting that favorable attitudes alone are insufficient to ensure sustained adoption.

Overall, the findings underscore that successful integration of technology-enhanced simulations requires more than access to digital tools. Effective implementation depends on comprehensive support systems that include teacher training, pedagogically aligned curriculum frameworks, institutional encouragement, and equitable technological infrastructure. Future research should continue exploring TES implementation in underrepresented educational settings, investigate long-term impacts on teaching practice, and examine how emerging technologies may further transform science instruction. Through coordinated educational policy and sustained professional support, TES can play a significant role in advancing meaningful, accessible, and inquiry-oriented science education.

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