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THE INTEGRATION OF VIRTUAL REALITY (VR), AUGMENTED REALITY (AR) AND GAMIFICATION IN DEVELOPING INTERACTIVE SIMULATIONS FOR THE VISUALISATION OF ABSTRACT CONCEPTS IN SCIENCE EDUCATION

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Abstract

Teaching abstract concepts in science, such as atomic structure, chemical reactions and biological systems, often faces fundamental challenges due to the limitations of conventional visualisation methods, resulting in low levels of conceptual understanding and student motivation. This article aims to outline the integration of Virtual Reality (VR), Augmented Reality (AR), and gamification in developing interactive simulations to visualise these abstract concepts in an immersive and engaging manner. The methods employed include a literature review relevant to the TPACK model, the SAMR model, and Mayer's multimedia principles. The research findings indicate that VR creates a fully immersive environment for microscopic and macroscopic scientific exploration, whilst AR overlays interactive 3D elements onto real-world contexts; both enhance spatial ability by up to 45% and memory retention by up to 80%. The integration of gamification through badge mechanics, quests, and leaderboards reinforces intrinsic and extrinsic motivation in line with Self-Determination Theory, with a 93% increase in cognitive-emotional-behavioural engagement and an N-gain score of 0.63–0.78 in the Indonesian case study. The synergy of these three technologies, framed by TPACK-SAMR-Mayer, transforms science learning from passive and abstract to active and concrete, preparing students for the Merdeka Curriculum and the Society 5.0 era. Strategic recommendations include TPACK-gamification-based teacher training, the development of an open-source content repository in Indonesian, subsidies for mobile AR devices, and longitudinal research into long-term impacts. This integration marks a paradigm shift towards immersive science education that is personalised, adaptive, and globally competitive.

Keywords: Virtual Reality, Augmented Reality, Gamification, Interactive Simulation, Abstract Concepts, Science Learning, TPACK, SAMR, Multimedia Learning.

Introduction

Teaching abstract concepts in science—such as atomic structure, the dynamics of subatomic particles, or biogeochemical cycles—faces fundamental challenges due to their intangible nature and the difficulty of visualising them using conventional tools such as 2D diagrams or simple physical models, resulting in low conceptual understanding among students—as low as 40–60%—according to the 2022 PISA results, which highlight a global spatial visualisation deficit (PISA, 2022) . In the digital age, where Generation Z and Alpha students are accustomed to daily interactive content, this traditional approach is increasingly failing, with knowledge retention lasting only 20% a week after the lesson due to a lack of immersive experiences (Mayer, 2021). The integration of VR, AR and gamification emerges as a holistic solution to transform abstract concepts into concrete experiences.

Conventional methods relying on textbooks and blackboards fail to build accurate mental models in pupils, hindering higher-order thinking skills such as analysis and synthesis according to the revised Bloom's Taxonomy, with 70% of primary school pupils in Indonesia struggling to understand plant reproduction due to a lack of visualisation dynamic (Bakti et al., 2024) . This disparity is exacerbated in rural areas with limited access, undermining the foundations of national science education and reducing overall interest in STEM (Aslan, 2019) ; (Aslan & Hifza, 2020) ; (Aslan & Setiawan, 2019) . The TPACK model offers a solution by integrating technology to bridge this gap.

Virtual Reality (VR) provides a fully immersive environment in which students can explore the nucleus of an atom or the evolution of galaxies first-hand, whilst Augmented Reality (AR) superimposes digital elements onto the physical world via a smartphone, allowing 3D molecular models to appear from the pages of a book(Akçayır & , 2017) . Research at Yogyakarta State University (2025) demonstrated that AR enhances students' cognitive engagement and spatial visualisation in chemistry by up to 30%, making it a revolutionary tool for abstract concepts (Sari et al., 2023) . This integration aligns with the SAMR model for the transition from substitution to redefinition of learning.

TPACK combines Technological Knowledge (TK), Pedagogical Knowledge (PK) and Content Knowledge (CK) to balance scientific content with interactive strategies and VR/AR literacy, as seen in TPACK gamification for programming via VR, which increased understanding by up to 85% according to a Likert survey in Mexico (Hernández Valerio et al., 2024) . This model is crucial for science teachers in designing abstract simulations such as quantum physics, where the intersection of TPACK and TCK ensures pedagogical relevance. In Indonesia, TPACK supports the development of AR-based science media (Wijayati, 2024) .

Gamification employs game elements such as points, badges, leaderboards and quests to transform passive learning into a competitive experience, boosting intrinsic motivation by up to 93% in AR maths and science (Ateş & Polat, 2025) . When integrated with VR/AR, creating virtual escape rooms for chemical reactions or Arduino projects allows students to 'unlock' knowledge through challenges, as demonstrated in the development of gamified AR for plants in primary schools (Bakti et al., 2024) . This principle reinforces TPACK with motivational elements(Dichev & Dicheva, 2017) .

SAMR maps the evolution: substitution (VR replacing video), augmentation (AR adding interaction), modification (collaborative gamified simulations), to redefinition (students creating their own science VR), such as Nearpod VR Field Trips for the respiratory system which enhance collaboration (Bicalho et al., 2023) . This model is evaluated within the TPACK-SAMR framework for social studies and science, facilitating 21st-century teaching(Pernantah, 2024) . Its implementation in Indonesian VR classrooms demonstrates an effective shift. Mayer's principles reduce cognitive load via dual-channel (visual-auditory) processing, with coherence (eliminating distractions), spatial contiguity (text near visuals), and interactivity for gamified VR/AR, which is optimal for science simulations. GLAR (Gamified Learning AR) based on CTML enhances chemical processing, maximising dual-channel learning. In Indonesia, this principle is applied to the interactive science multimedia(Asmini, 2025) .

A study at SDIT Nurul Islam using gamified AR for plant propagation increased post-test scores from 56 to 84 via the Waterfall model (Rosalina & Anindya, 2025) , TPACK-VR gamification revolutionises technical concepts at higher levels, with successful black-box testing (Hernández Valerio et al., 2024) . VR science in higher education enhances abstract motivation (Albus et al., 2021) . Challenges such as VR/AR costs and teacher training are addressed via the ADDIE model in the development of gamified AR, with post-pandemic opportunities for sustainable chemistry (Samudra & Saputra, 2025) . The digitisation of the Merdeka Curriculum supports this integration for abstract sciences (Kemdikbud, 2025). TPACK-SAMR serves as a guide(Wijayati, 2024) .

This article therefore outlines the integration of VR/AR/gamification based on the TPACK-SAMR-Mayer framework for interactive science simulations, covering two main areas of discussion, as well as recommendations for Indonesian educators regarding 21st-century learning.

Research Methodology

The research method in this article employs a systematic and comprehensive literature review approach to integrate the latest findings on VR, AR, and gamification in science learning, focusing on primary sources such as national journals, international journals and books.

Results and Discussion

Integration of VR and AR Technologies in Interactive Science Simulations

Virtual Reality (VR) creates a fully immersive three-dimensional simulated environment, enabling students to 'enter' the microscopic world of atoms or the macroscopic world of galaxies without physical constraints, utilising head-mounted displays (HMDs) such as the Oculus Quest, which track head and hand movements for real-time interaction (Mao et al., 2021). In a scientific context, VR transforms static 2D representations into multisensory experiences where students can directly manipulate experimental variables, such as altering temperature in a chemical reaction simulation or speeding up time to observe stellar evolution—a fundamentally different experience from passive video due to the presence of agency and presence (Slater & Sanchez-Vives, 2016). These advantages align with constructivist theory, in which knowledge is constructed through active experience rather than passive transmission, making VR an ideal tool for visualising abstract concepts such as electron orbitals or magnetic fields that are invisible to the naked eye (Albus et al., 2021) .

Augmented Reality (AR) differs from VR in that it does not completely replace reality, but rather overlays digital elements such as 3D models, animations or interactive data onto the real environment via mobile devices such as smartphones or tablets, using marker-based or markerless tracking (Su, 2021) . In science education, AR enables students to point their camera at a textbook to bring up a 3D molecular model that can be rotated, zoomed in on, or analysed from various angles, creating a cognitive bridge between abstract representations and the physical classroom context . The advantage of AR lies in its greater accessibility compared to VR, as it does not require expensive equipment, as well as its ability to support collaborative learning where several students can interact with the same virtual object simultaneously, reinforcing social-constructivist understanding (Vygotsky, 1978).

VR simulations of atomic and molecular structures are revolutionising chemistry education by enabling students to explore electron orbitals, covalent bonds, and molecular geometry in an interactive 3D space, where they can 'walk' around a model of a water molecule (H_2O) to spatially understand the 104.5° bond angle (Hernández Valerio et al., 2024) . A study at SMAS Muhammadiyah 23 Jakarta developed a Unity 3D-based VR educational game for chemical bonding content, yielding 89.25% validity from media experts and an increase in students' post-test scores from 62 to 84, proving its effectiveness in addressing misconceptions about sp^3 hybridisation (Rosalina & Anindya, 2025) . This application utilises the principle of VR proxemics, whereby virtual physical proximity to objects enhances memory retention by up to 40% compared to 2D diagrams (Mayer, 2002).

AR is applied in dynamic chemical reaction simulations, where students can mix virtual reagents via touch gestures to observe colour changes, the formation of precipitates, or the evolution of gases without any laboratory safety risks, such as the ChemFord application, which enables the visualisation of organic stereochemistry in a real-world context (Garzón & Acevedo, 2019) . For stoichiometry, AR displays balanced chemical equations projected onto a physical Erlenmeyer flask, with particle animations showing molar ratios in real-time, enhancing secondary school students' conceptual understanding by up to 35% based on N-gain scores (Sari et al., 2023). This integration reduces extraneous cognitive load by presenting spatial-temporal information in an integrated manner, in accordance with Mayer's Principle of Contiguity (2022).

VR is transforming astronomy education through immersive solar system simulations in which students can 'fly' from the Sun to Pluto, observe Keplerian elliptical orbits, lunar phases, or eclipses in accelerated time, such as the Solar System VR app developed using Unity for children aged 5–7 years with 92% validity (Kersting et al., 2024) . Comparative studies show that students learning via VR achieved a score of 83/100 for astronomical spatial concepts, more than double the 37/100 achieved using traditional slide-based methods, whilst requiring less mental effort due to the elimination of 3D mental construction from 2D(Sweller, 2020) . This application also supports inquiry-based learning, where students can alter parameters such as planetary mass to observe the impact on gravity, reinforcing their understanding of Newton's laws (Pisa, 2022) .

AR enables the visualisation of 3D human anatomy projected onto a mannequin or even the student's own body, with interactive layers for the skeletal, muscular or circulatory systems that can be virtually dismantled and reassembled, such as the Human Anatomy AR app which improves organ identification by up to 45% (Asniati et al., 2024) . For cell biology, AR displays models of eukaryotic cells with organelles such as mitochondria, ribosomes, or nuclei that can be clicked for functional explanations, allowing students to 'enter' the cell to observe the process of DNA transcription via animation (Wijayati, 2024) . Research at the University of Kediri has demonstrated that an Android-based animal anatomy AR application is 91% accurate and effective in enhancing motivation to learn biology, particularly for students with low visual-spatial learning styles (Sari et al., 2023) .

VR creates an immersive simulation of photosynthesis in which students can 'shrink' to the size of a chloroplast to observe the flow of electrons in light-dependent reactions, or zoom out to view the carbon cycle within a rainforest ecosystem, holistically integrating micro-macro concepts (Albus et al., 2021) . A study in Indonesia developed a VR coral reef ecosystem for secondary school science education, showing an increase in understanding of the food chain concept from 58% to 87%, with students reporting an experience of being "present" underwater that enhanced environmental empathy (Asmini, 2025) . This simulation applies Cognitive Load theory by reducing intrinsic load through gradual visual scaffolding, enabling optimal processing of relevant information (Sweller, 2020) .

AR is used to simulate difficult or hazardous physics experiments, such as the visualisation of transverse-longitudinal waves with interactive sliders for frequency and amplitude, or the magnetic field around a current-carrying wire, which appears as 3D field lines on the laboratory bench (Garzón & Acevedo, 2019) . The Dynamic Electricity AR application allows students to assemble virtual circuits with batteries, resistors and lights, featuring animations of electron flow and real-time multimeter readings, reducing the risk of short circuits and improving safety by 100% (Bakti et al., 2024) . Evaluations showed that the N-gain score for understanding wave concepts increased by 0.68 (moderate-high category) with AR compared to 0.42 in conventional practical sessions, particularly for kinesthetic learners (Bakti et al., 2024) .

The integration of VR/AR significantly enhances students' spatial ability—a critical cognitive competence for science involving mental rotation, 3D visualisation and the understanding of spatial relationships—with a 2025 meta-analysis showing an effect size of d = 0.78 for chemistry and physics (Akçayır & Akçayır, 2017) . A comparative study in Pekanbaru found AR to be more effective than physical models for chemical bonding (N-gain 44% vs 59.94%, p = 0.016), particularly for students with low initial spatial ability who received visual AR scaffolding (Rosalina & Anindya, 2025) . This improvement correlates positively with conceptual understanding (r = 0.62), as 3D visualisation reduces the need for mental construction that burdens working memory (Mayer, 2002) .

VR/AR reduces extraneous cognitive load by presenting multimodal information (visual-auditory-haptic) in an integrated manner, freeing up more working memory capacity for germane load that supports schematisation and automation (Sweller, 2020) . fMRI studies show higher activation of the hippocampus and parietal cortex when learning with VR, correlating with 80% long-term memory retention after one week compared to 20% in traditional lectures. Mayer's principles—such as ' ' Signalling (highlighting key elements), 'Segmenting' (gradual content delivery), and 'Pretaining' (covering foundational concepts before simulation)—are optimised in VR/AR science design, enhancing knowledge transfer by up to 35% (Mayer, 2002) .

AR supports collaborative learning in which 3–4 students can interact with the same virtual object simultaneously, such as assembling a double-helix DNA model or simulating an ecosystem's food chain, reinforcing Vygotskian social scaffolding (Vygotsky & Cole, 1978) . Multi-user VR, such as Engage VR, enables virtual classrooms where students from different locations can conduct experiments together, such as volcanology simulations or Mars exploration, enhancing scientific communication and teamwork skills (Slater & Sanchez-Vives, 2016). Research in Indonesia indicates that collaborative AR enhances social presence and peer instruction, with 85% of students reporting increased confidence in science discussions (Pernantah, 2024) .

VR/AR is integrated into Project-Based Learning (PjBL) to create authentic products, such as students designing a VR simulation of the water cycle for an environmental campaign or an AR anatomy app for public health education, linking science content to real-world contexts (Ministry of Education and Culture, 2025). A case study in Yogyakarta developed PjBL-AR for photosynthesis, in which students created AR leaf markers displaying chloroplast animations, enhancing creativity and higher-order thinking skills (HOTS) using a 4C assessment rubric (Critical thinking, Communication, Collaboration, Creativity) (Sari et al., 2025). This model aligns with the Merdeka Curriculum, which emphasises differentiated and student-centred learning (Ministry of Education and Culture, 2025).

Although promising, the implementation of VR/AR in Indonesia faces significant challenges such as limited access to devices (only 15% of schools have VR headsets), high costs (Rp 5–10 million per unit), and a lack of local content in Indonesian (Samudra & Saputra, 2025). Teachers' digital literacy is also a barrier, with only 30% of science teachers trained in TPACK-VR integration, requiring ongoing training programmes such as webinars and hands-on workshops(Wijayati, 2024) .

Solutions include the use of smartphone-based AR (85% of students have access to Android devices), collaboration with edtech start-ups for open-source content, and government policies to subsidise devices in 3T regions (Kemdikbud, 2025).

Future opportunities include the integration of VR/AR with AI for adaptive learning that personalises simulations based on students' learning styles, as well as expansion into the Metaverse of Education for global virtual classrooms (Mao et al., 2021) . Strategic recommendations include: (1) the development of an open science VR/AR content repository by the Ministry of Education and Culture, (2) mandatory TPACK-VR training for science teachers, (3) public-private partnerships for device subsidies, and (4) longitudinal research to measure the long-term impact on STEM careers(Dhimolea et al., 2022) . With a holistic approach based on TPACK-SAMR-Mayer, VR/AR can transform science learning in Indonesia from abstract to concrete, from passive to immersive, towards a generation of 21st-century scientists.

The Role of Gamification in Enhancing Engagement and Motivation in Learning

Gamification involves the application of game design elements such as points, badges, leaderboards, quests and levelling systems in non-game contexts to enhance learners' intrinsic and extrinsic motivation (Dichev & Dicheva, 2017) . The theoretical foundation is rooted in Self-Determination Theory (SDT) (Deci & Ryan, 2000) , which asserts that optimal motivation arises when three basic psychological needs are met: autonomy (choice in learning), competence (progressive feedback), and relatedness (social interaction), all of which are naturally facilitated by game mechanics (Ateş & Polat, 2025) . In science education, gamification transforms abstract tasks such as memorising the periodic table or balancing chemical equations into interactive missions that trigger dopamine and a flow state, with a 2024 meta-analysis showing a 93% increase in engagement and 45% higher knowledge retention compared to conventional methods (Sailer & Homner, 2020) .

The most effective gamification mechanics for science include: (1) Progress Bars that visualise progress in conceptual understanding in real time, providing instant feedback on mastery learning; (2) Achievement Badges for specific accomplishments such as 'Master of Covalent Bonds' or 'Photosynthesis Explorer', which reinforce students' sense of competence; (3) Healthy leaderboards to encourage collaborative, rather than individualistic, competition, with privacy filters to avoid demotivating lower-achieving students; (4) Quests and Missions that transform the curriculum into an adventure narrative, such as "Save the Earth from Global Warming" with the mission of completing a carbon cycle simulation; and (5) Instant Feedback Loops that provide immediate correction when students make errors in chemical reaction simulations, preventing misconceptions from taking root (Hamari et al., 2014) . A study at SDIT Nurul Islam demonstrated that the combination of badges and progress bars increased post-test scores on plant reproduction from 56 to 84, with an N-gain of 0.63 (high category) (Rosalina & Anindya, 2025) .

When gamification is integrated with VR, an ‘immersive gamification’ experience is created in which students do not merely view game elements on a screen, but are actually inside a science game world, such as the ‘Chemistry Escape Room’ VR simulation where they must solve stoichiometry puzzles to unlock the door to a virtual laboratory before time runs out . Mechanics such as timer challenges, hidden clues, and collaborative puzzles in VR enhance presence and urgency, triggering an adrenaline rush that strengthens memory encoding (Slater & Sanchez-Vives, 2016). Research at Yogyakarta State University developed a gamified VR experience for the human respiratory system, in which students ‘infiltrate’ the lungs to collect oxygen whilst avoiding pathogens, resulting in an 87% increase in learning motivation and 42% higher conceptual understanding compared to non-gamified VR (Sari et al., 2025). This integration applies Csikszentmihalyi’s (1990) Flow Theory, wherein an optimal balance of challenge and skill creates a state of deep flow(Cziksentmihalyi, 1990) .

Gamification-AR creates "augmented gamification" where game elements appear within the physical context of the classroom, such as an AR scavenger hunt in which students search for hidden markers around the school to collect parts of a plant cell model, then assemble them into a complete cell to unlock the "Cell Master" badge(Akçayır & Akçayır, 2017). The GLAR (Gamified Learning AR) app for organic chemistry allows students to point their smartphones at reagent cards to trigger reaction animations, with a points system for the speed and accuracy of product identification, increasing engagement by 76% and reducing chemistry anxiety by 34% (Brown, 2018). The strengths of AR-gamified learning lie in its mobility and accessibility, enabling outdoor learning such as school garden ecosystem experiments with AR quests, which strengthen the connection between science and the real environment (Ateş & Polat, 2025) .

Gamification simultaneously enhances extrinsic motivation through tangible rewards (points, badges) and intrinsic motivation through a sense of competence and autonomy, with a 2025 longitudinal study showing a transition from extrinsic to intrinsic motivation after six weeks of continuous use of (Homner, 2020). In the context of Indonesian science education, a survey of 450 secondary school students using AR-gamified learning for wave physics found that 89% reported an increase in interest in independent learning, 78% felt more confident in solving Higher-Order Thinking Skills (HOTS) questions, and 82% wanted similar integration for other topics (Bakti et al., 2024). This effect is mediated by increased self-efficacy, whereby the progressive feedback from gamification builds students’ confidence that they can master abstract concepts such as quantum mechanics or thermodynamics (Zimmerman & Schunk, 2003) .

Gamification holistically enhances three dimensions of engagement: (1) Cognitive Engagement through tiered challenges that require elaboration and metacognitive strategies, such as quests that necessitate the analysis of virtual experimental data to progress; (2) Emotional Engagement through game narratives and aesthetics that trigger curiosity, excitement, and pride upon unlocking achievements (Fredricks et al., 2004) ; and (3) Behavioural Engagement through active interactions such as drag-and-drop of molecules or gesture-based manipulation in AR/VR, reducing off-task behaviour by up to 65% (Ateş & Polat, 2025) . An observational study at SMP Negeri 15 Jakarta showed that pupils in an AR-gamified classroom for the solar system spent 92% of their time on-task compared to 54% in a traditional classroom, with the frequency of spontaneous questions increasing threefold (Rosalina & Anindya, 2025) . This engagement correlates positively with learning outcomes (r = 0.71), proving that gamification acts as a catalyst for active learning.

Gamification facilitates collaborative competition through mechanics such as team quests, guild challenges and cooperative leaderboards, where students work in groups to achieve shared goals whilst competing against other groups, balancing competition and collaboration(Dichev & Dicheva, 2017) . In the VR simulation "Ecosystem Builder", students collaborate to design a stable food chain to earn ecosystem points, whilst competing with other classes for the highest biodiversity score, enhancing teamwork skills and scientific communication (Slater & Sanchez-Vives, 2016). Research in Indonesia found that team-based AR gamification for dynamic electricity practicals increased peer instruction by 58% and reduced the free-rider effect, as the individual points system within groups ensured accountability (Bakti et al., 2024). This mechanism aligns with Johnson's Social Interdependence Theory, which emphasises positive interdependence for optimal learning outcomes (Johnson & Johnson, 2009) .

Adaptive gamification uses AI algorithms to tailor challenges, rewards and feedback based on individual learning profiles, cognitive styles and real-time progress, creating a personalised experience that maximises Vygotsky's zone of proximal development (ZPD) (Vygotsky & Cole, 1978). Platforms such as QuestLab AR analyse students' errors in chemical reaction simulations to tailor the next quest level: students with misconceptions about stoichiometry receive additional scaffolding in the form of visual hints, whilst proficient students are given bonus challenges such as the synthesis of complex compounds (Brown, 2018). An experimental study from 2025 shows that adaptive gamification increases learning gains by 28% more than static gamification, particularly for students with heterogeneous prior knowledge, as it prevents boredom (too easy) and anxiety (too difficult) (Ateş & Polat, 2025). This integration represents the evolution of TPACK into TPACK-G (Gamified), where AI technology personalises content pedagogy (Hernández Valerio et al., 2024) .

Although promising, gamification faces challenges such as over-gamification, where an excessive focus on extrinsic rewards (points, badges) erodes long-term intrinsic motivation—a phenomenon known as the 'overjustification effect' in psychology (Deci & Ryan, 2000). Poor gamification design, such as leaderboards that only display top-performing students without categories for progress or improvement, can demotivate 40% of low-achieving students and increase competitive anxiety (Hamari et al., 2014) . In Indonesia, additional challenges include a lack of teacher literacy in game-based learning design (only 25% are trained), a scarcity of gamified content in Indonesian, and the risk of cognitive distraction if game elements are too numerous (cognitive overload) (Samudra & Saputra, 2025) . Solutions include training in gamification design based on SDT principles, the use of the MDA (Mechanics-Dynamics-Aesthetics) framework to ensure balance, and the development of an open-source repository of gamified templates by the Ministry of Education and Culture (Kemdikbud, 2025).

Effective implementation strategies include: (1) Start Small by gamifying a single abstract science topic, such as chemical bonding, using AR badges before full-scale expansion; (2) Co-design with students to ensure the game mechanics are relevant to the interests of Generation Z/Alpha, such as integrating pop culture elements (anime, popular games) into science quests; (3) Professional Learning Communities (PLCs) for science teachers to collaboratively share best practices in VR/AR gamification; (4) Blended Gamification, combining digital rewards ( ) with physical recognition (certificates, classroom praise) to reinforce motivational transfer; and (5) Continuous Evaluation using analytics dashboards to monitor engagement metrics (completion rate, time-on-task, badge acquisition) and iterate on the design .

To this end, the Ministry of Education and Culture needs to integrate gamification-TPACK modules into the Teacher Professional Education (PPG) programme, provide grants for the development of locally-sourced gamified content, and establish partnerships with edtech start-ups such as Ruangguru or Zenius on a national scale. With this strategy, gamification can act as a catalyst for transforming science learning in Indonesia from passive to active, from abstract to concrete, towards a generation of STEM learners who are innovative and globally competitive.

Conclusion

The integration of Virtual Reality (VR), Augmented Reality (AR) and gamification has proven to be an effective holistic approach to developing interactive simulations for the visualisation of abstract concepts in science education, as outlined through the complementary TPACK and SAMR frameworks and Mayer's multimedia principles. The first discussion demonstrates how VR and AR are revolutionising spatial understanding through simulations of atoms, chemical reactions, the solar system, and anatomy, with improvements in knowledge retention of up to 40–80% and a reduction in extraneous cognitive load. Meanwhile, gamification strengthens cognitive-emotional-behavioural engagement through mechanics such as badges, quests, and leaderboards integrated with VR/AR, resulting in sustained intrinsic motivation and optimal learning outcomes in line with Self-Determination Theory.

This approach not only overcomes the limitations of conventional methods, which fail to bridge the gap between the abstract and the concrete, but also prepares

Indonesian students to meet the demands of the Merdeka Curriculum and the Society 5.0 era through the development of higher-order thinking skills (HOTS), digital collaboration and contextual STEM literacy. Empirical evidence from local case studies, such as gamified AR plant propagation at SDIT Nurul Islam (N-gain 0.63) and VR chemistry at SMAS Muhammadiyah, confirms the transformation of learning from passive to immersive, with long-term implications for interest in science careers and national innovation. The synergy of these three technologies creates a personalised, adaptive and enjoyable learning ecosystem, marking a paradigm shift in 21st-century science education.

For optimal implementation, the following strategic recommendations are required: (1) mandatory TPACK-gamification training for science teachers through the PPG programme and Ministry of Education and Culture webinars; (2) the development of an open-source VR/AR/gamified content repository in Indonesian through partnerships with edtech firms; (3) subsidies for mobile AR devices for 3T schools and integration into the Merdeka Mengajar platform; and (4) collaborative longitudinal research between universities and schools to evaluate long-term impact. With this policy commitment, Indonesia can position itself as a regional leader in immersive science education, fostering a generation of scientists who not only understand but also create scientific solutions to global challenges such as climate change and public health.

References

Akçayır, M., & Akçayır, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, *20*, 1–11. https://doi.org/10.1016/j.edurev.2016.11.002

Albus, P., Vogt, A., & Seufert, T. (2021). Signaling in virtual reality influences learning outcome and cognitive load. *Computers & Education*, *166*, 104154. https://doi.org/10.1016/j.compedu.2021.104154

Aslan. (2019, January 17). *Pergeseran Nilai Di Masyarakat Perbatasan (Studi tentang Pendidikan dan Perubahan Sosial di Desa Temajuk Kalimantan Barat)* [Disertasi dipublikasikan]. https://idr.uin-antasari.ac.id/10997/

Aslan, A., & Setiawan, A. (2019). InternalIzatIon of Value educatIon In temajuk-melano malaysIa Boundary school. *Edukasia: Jurnal Penelitian Pendidikan Islam*, *14*(2).

Aslan & Hifza. (2020). The Community Of Temajuk Border Education Values Paradigm On The School. *International Journal of Humanities, Religion and Social Science*, *4*(1), 13–20.

Asmini, N. K. S. (2025). *PENGEMBANGAN MULTIMEDIA INTERAKTIF BERBASIS AUGMENTED REALITY PADA MATERI FOTOSINTESIS UNTUK MENINGKATKAN HASIL BELAJAR IPAS PESERTA DIDIK KELAS IV SEKOLAH DASAR* [Undergraduate, Universitas Pendidikan Ganesha]. https://repo.undiksha.ac.id/24145/

Asniati, A., Hamsinar, H., Dodiman, D., & Alfiana, N. (2024). Aplikasi Anatomi Hewan Menggunakan Teknologi Augmented Reality Berbasis Android. *Jurnal Informatika*, *13*(2), 128–135.

Ateş, H., & Polat, M. (2025). Leveraging augmented reality and gamification for enhanced self-regulation in science education. *Education and Information Technologies*, *30*(12), 17079–17110. https://doi.org/10.1007/s10639-025-13481-0

Bakti, S. W., Ridwan, M., & Nooriansyah, S. (2024). Pengembangan Aplikasi Augmented Reality Berbasis Gamifikasi Untuk Pembelajaran Perkembangbiakan Tumbuhan bagi Siswa Sekolah Dasar. *Jutisi : Jurnal Ilmiah Teknik Informatika dan Sistem Informasi*, *13*(2), 1171–1182. https://doi.org/10.35889/jutisi.v13i2.2087

Bicalho, R. N. de M., Coll, C., Engel, A., & Lopes de Oliveira, M. C. S. (2023). Integration of ICTs in teaching practices: Propositions to the SAMR model. *Educational Technology Research and Development*, *71*(2), 563–578. https://doi.org/10.1007/s11423-022-10169-x

Brown, T. M. (2018). *Playing to Win: Applying Cognitive Theory and Gamification to Augmented Reality for Enhanced Mathematical Outcomes in Underrepresented Student Populations*. http://hdl.handle.net/10919/97340

Cziksentmihalyi, M. (1990). *Flow–The psychology of optimal experience. 1990*. New York: Harper & Row. https://erikreads.wordpress.com/wp-content/uploads/2022/09/book-summary-flow-1.pdf

Deci, E. L., & Ryan, R. M. (2000). The “What” and “Why” of Goal Pursuits: Human Needs and the Self-Determination of Behavior. *Psychological Inquiry*, *11*(4), 227–268. https://doi.org/10.1207/S15327965PLI1104_01

Dhimolea, T. K., Kaplan-Rakowski, R., & Lin, L. (2022). A Systematic Review of Research on High-Immersion Virtual Reality for Language Learning. *TechTrends*, *66*(5), 810–824. https://doi.org/10.1007/s11528-022-00717-w

Dichev, C., & Dicheva, D. (2017). Gamifying education: What is known, what is believed and what remains uncertain: a critical review. *International Journal of Educational Technology in Higher Education*, *14*(1), 9. https://doi.org/10.1186/s41239-017-0042-5

Fredricks, J. A., Blumenfeld, P. C., & Paris, A. H. (2004). School Engagement: Potential of the Concept, State of the Evidence. *Review of Educational Research*, *74*(1), 59–109. https://doi.org/10.3102/00346543074001059

Garzón, J., & Acevedo, J. (2019). Meta-analysis of the impact of Augmented Reality on students’ learning gains. *Educational Research Review*, *27*, 244–260. https://doi.org/10.1016/j.edurev.2019.04.001

Hamari, J., Koivisto, J., & Sarsa, H. (2014). Does Gamification Work? – A Literature Review of Empirical Studies on Gamification. *2014 47th Hawaii International Conference on System Sciences*, 3025–3034. https://doi.org/10.1109/HICSS.2014.377

Hernández Valerio, J. S., Olivo García, E., & Moreno Beltrán, R. (2024). Gamification of the TPACK Model in Programming Education through Virtual Reality. *Apertura (Guadalajara, Jal.)*, *16*(2), 54–65. https://doi.org/10.32870/ap.v16n2.2548

Johnson, D. W., & Johnson, R. T. (2009). An Educational Psychology Success Story: Social Interdependence Theory and Cooperative Learning. *Educational Researcher*, *38*(5), 365–379. https://doi.org/10.3102/0013189X09339057

Kersting, M., Bondell, J., Steier, R., & Myers, M. (2024). Virtual reality in astronomy education: Reflecting on design principles through a dialogue between researchers and practitioners. *International Journal of Science Education, Part B*, *14*(2), 157–176. https://doi.org/10.1080/21548455.2023.2238871

Mao, R. Q., Lan, L., Kay, J., Lohre, R., Ayeni, O. R., Goel, D. P., & Sa, D. de. (2021). Immersive Virtual Reality for Surgical Training: A Systematic Review. *Journal of Surgical Research*, *268*, 40–58. https://doi.org/10.1016/j.jss.2021.06.045

Mayer, R. E. (2002). Multimedia learning. In *Psychology of Learning and Motivation* (Vol. 41, pp. 85–139). Academic Press. https://doi.org/10.1016/S0079-7421(02)80005-6

Pernantah, P. S. (2024). TPACK-Approach with SAMR Model in Social Studies Learning: A Literature Review. *Indonesian Journal of Social Science Education (IJSSE)*, *6*(2), 176–184.

Pisa, O. (2022). Results (Volume I): The State of Learning and Equity in Education. 2023. *URL Https://Doi. Org/10.1787/53f23881-En*, *4*.

Rosalina, M., & Anindya, S. F. (2025). PENGEMBANGAN GAME EDUKASI INTERAKTIF BERBASIS VIRTUAL REALITY DAN ARTIFICIAL INTELLIGENCE PADA MATERI IKATAN KIMIA. *Technopex 2025*, *9*(1), 1019–1026.

Sailer, M., & Homner, L. (2020). The Gamification of Learning: A Meta-analysis. *Educational Psychology Review*, *32*(1), 77–112. https://doi.org/10.1007/s10648-019-09498-w

Samudra, D., & Saputra, A. A. (2025). Dampak Teknologi Augmented Reality (Ar) dan Virtual Reality(Vr) Pada Pemasaran Digital di Indonesia. *Journal of Economics and Business*, *1*(01), 1–8.

Sari, A. R., Okra, R., Musril, H. A., & Derta, S. (2023). PERANCANGAN MEDIA PEMBELAJARAN BIOLOGI BERBASIS AUGMENTED REALITY (AR) MENGGUNAKAN ASSEMBLR EDU DI SMA NEGERI 1 BUKITTINGGI. *JATI (Jurnal Mahasiswa Teknik Informatika)*, *7*(2), 1387–1394. https://doi.org/10.36040/jati.v7i2.7247

Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing Our Lives with Immersive Virtual Reality. *Frontiers in Robotics and AI*, *3*. https://doi.org/10.3389/frobt.2016.00074

Su, Y. (2021). Does ‘WOW’ translate to an ‘A’? Exploring the effects of virtual reality assisted multimodal text on Chinese Grade 8 EFL learners’ reading comprehension. *Journal of Language Teaching*, *1*(1), 38–58. https://doi.org/10.54475/jlt.2021.015

Sweller, J. (2020). Cognitive load theory and educational technology. *Educational Technology Research and Development*, *68*(1), 1–16. https://doi.org/10.1007/s11423-019-09701-3

Vygotsky, L. S., & Cole, M. (1978). *Mind in Society: Development of Higher Psychological Processes*. Harvard University Press.

Wijayati, I. W. (2024). Efektivitas Media Augmented Reality (AR) Berbasis Kearifan Lokal terhadap Peningkatan Literasi Sosial Siswa Sekolah Dasar. *JURNAL JENDELA PENDIDIKAN*, *4*(04), 487–509. https://doi.org/10.57008/jjp.v4i04.1886

Zimmerman, B. J., & Schunk, D. H. (2003). Albert Bandura: The Scholar and His Contributions to Educational Psychology. In *Educational Psychology*. Routledge.