

Chapter 4

Augmented Reality (AR) Applications in Science Education

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1. Introduction

In recent years, science education has undergone a significant transformation alongside rapidly developing digital technologies. The increasing integration of digital technologies into learning environments has diversified the ways in which pupils interact with scientific concepts and opened up new possibilities in the design of teaching processes (Abdullah et al., 2022). Among these technologies, augmented reality (AR) stands out as an innovative technology that enables abstract concepts in science to become more visible, interactive and experiential (Cankaya & Girgin, 2018). Research in the literature indicates that the integration of AR can have positive effects on students' motivation to learn and their attitudes towards the subject, and can support conceptual learning under appropriate pedagogical conditions (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018; Radu, 2014).

The integration of technological innovations into education systems does not merely entail the digitisation of teaching materials; it also offers new learning opportunities that can support students in developing their scientific process skills through hands-on, discovery-based and interactive methods. As science education is, by its very nature, a field encompassing processes such as experimentation, observation, modelling and problem-solving, the visual and interactive possibilities offered by technology largely align with the pedagogical requirements of this field. Consequently, digital tools have become a key component in creating learning environments that support students' understanding of complex scientific concepts. Within this transformation, AR has emerged as one of the leading technologies in science education, thanks to its structure that enables students to experience the real world and digital content simultaneously (Onbaşılı, 2018).

Augmented reality offers an experience created by integrating digital information, objects or animations onto the image perceived by users in their physical environment (Papadopoulos et al., 2021). This technology differs from traditional teaching tools in that it provides real-time interaction and engages the user with virtual content without disconnecting them from their physical environment. Students can examine molecular structures in three dimensions within AR environments, observe the functioning of the body's internal organs, and experience abstract physics concepts through interactive models. According to Azuma (1997), augmented reality is a system that combines real and virtual elements, enables real-time interaction, and is based on the three-dimensional alignment of virtual objects with the real environment. These features offer significant opportunities for concretising concepts and processes that are abstract, cannot be directly observed, or occur on different scales—issues frequently encountered in science education.

Research in science education indicates that AR applications can yield positive outcomes in terms of students' learning processes, motivation and various learning outcomes. For example, Sirakaya and Sirakaya (2018) found that in science lessons using augmented reality, students' motivation levels increased and that AR applications contributed to the development of positive attitudes towards the learning process. This finding should, however, be interpreted within the context of the relevant study; it should not be assumed that increased motivation necessarily translates into improved learning outcomes. Similarly, Sarioglu (2021) found that augmented reality training had a positive impact on science teachers' attitudes towards AR applications. These findings indicate

potential not only in terms of students' learning experiences but also in teachers' integration of innovative technologies into their teaching processes (Onbaşılı, 2018; Sarioglu, 2021).

Augmented reality possesses features that go beyond merely providing visual interaction in science education; it can also support the 'embodied learning' approach, which incorporates pupils' physical movements and interactions with their environment into the learning process. The embodied learning approach discussed by Abrahamson and Lindgren (2014) emphasises that learning is not merely a mental process; rather, bodily movements, gestures and spatial perception can form part of the learning process. Building on this theoretical framework, it can be argued that AR environments, in which students can explore digital objects through movement, position and interaction with the physical environment, hold potential for the design of multidimensional learning experiences that can engage both bodily and cognitive processes simultaneously. In this respect, AR can be regarded as a technology capable of contributing to the organisation of learning processes—particularly in science education—that require observation, modelling and interaction within a more experiential framework.

In summary, augmented reality technology is viewed as an innovative learning tool capable of making significant contributions to science education. This hybrid learning experience, which integrates real and virtual environments, may help students develop understanding of scientific concepts and apply scientific process skills when appropriately designed. This chapter comprehensively addresses the historical development and fundamental characteristics of augmented reality technology, its pedagogical contributions to science education, its areas of application, and the advantages and limitations reported in the literature. Furthermore, the opportunities that AR may offer for science teaching in the future, as well as its potential in terms of teacher training, are discussed. Thus, this chapter aims to provide a comprehensive framework regarding augmented reality-supported science education for researchers and practitioners.

2. The Historical Development of Augmented Reality in Science Education

2.1. The Emergence of Augmented Reality Technology

The historical development of augmented reality in science education began with early technological studies aimed at integrating computer-generated visuals with the physical environment in real time. In this context, the head-mounted display system developed by Sutherland (1968) is regarded as one of the pioneering systems enabling computer-generated three-dimensional visuals to be projected into the user's field of view. These early studies focused less on direct educational applications and more on technical problems that would form the basis for the subsequent development of AR technology, such as visualisation, tracking of user movements and the alignment of virtual objects with the physical environment.

One of the key milestones in the conceptual clarification of AR was the use of the term ‘augmented reality’ by Caudell and Mizell (1992) in the context of the head-mounted display system they developed for use in production processes at Boeing. This work made a significant contribution to the conceptualisation of the idea of enriching the physical working environment with computer-generated information. Subsequently, Milgram and Kishino (1994), by examining the relationships between real and virtual environments within the framework of the ‘reality–virtuality continuum’, contributed to clarifying the position of augmented reality within mixed reality. This approach has laid the theoretical groundwork for viewing AR as a technology that enriches the real environment with digital content, as distinct from virtual reality, which completely disconnects the user from the physical environment.

Azuma (1997), meanwhile, defined the distinctive characteristics of AR systems in a more systematic manner, thereby establishing an important reference point in the conceptual development of the field. Within this framework, AR is defined by the coexistence of real and virtual elements, the provision of real-time interaction, and the three-dimensional alignment of virtual objects with the real environment. These characteristics have also gained importance for subsequent educational research; in particular, the ability to link digital representations with real learning environments in real time has formed the basis for studies on the use of AR in education.

2.2. The Integration of Augmented Reality into Education and Science Education

Marker-based tracking systems developed in the late 1990s, along with the software tools supporting them, have played a significant role in making AR more feasible in educational settings. Research into the calibration of marker-based tracking and head-mounted display systems, conducted by Kato and Billinghurst (1999), contributed to the more stable integration of real and virtual objects. Such technical advancements and the emergence of tools such as ARToolKit facilitated the development of AR applications and enabled the creation of prototypes across various fields of application. From an educational perspective, these developments opened up new possibilities for representing three-dimensional spatial relationships, processes that cannot be directly observed, and phenomena occurring at different scales through interactive models.

One of the early examples in the context of science education is an AR application developed by Shelton and Hedley (2002) for teaching Earth–Sun relationships. The study addressed the representation via AR of phenomena that are difficult to observe directly and mentally model, such as the Earth’s movements and the spatial relationships between the Earth and the Sun. Such early applications are significant in that they demonstrate that AR can be used particularly in science and earth science topics that require three-dimensional spatial thinking. Thus, augmented reality has begun to feature in educational research as a tool for visualising scientific phenomena—including processes that cannot be directly observed and those occurring at different times and scales—within real learning environments.

However, early research has also shown that the use of AR on its own does not lead to higher levels of engagement or better learning outcomes. Kerawalla et al. (2006), having examined the use of augmented reality in primary school science teaching, highlighted the importance of pedagogical conditions—such as teacher guidance, clearly structured tasks, the management of pupils' attention and the appropriate organisation of classroom activities—for the effective integration of the technology into the classroom environment. This finding can be regarded as a significant turning point in the historical development of AR in science education: the ability of the visualisation and interaction opportunities offered by technology to translate into learning outcomes is linked not so much to the technology itself, but rather to the pedagogical aims for which it is used and how it is structured.

2.3. The Transition to Mobile AR and Evidence-Based Science Education Applications

From the 2010s onwards, the development of augmented reality in education has gained momentum along two main axes. The first of these is the advancement of mobile technologies and the cameras, sensors and location-tracking systems used in them; the second is the more systematic incorporation of instructional design principles derived from educational technology and the science of learning into AR applications (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). The widespread adoption of smartphones and tablets has contributed to AR applications moving beyond laboratory prototypes requiring specialised hardware to become more accessible in both classroom and out-of-school learning environments (Radu, 2014). In this process, AR has moved beyond being merely a visualisation technology for concepts and has begun to be regarded as an educational technology capable of supporting interaction, inquiry, problem-solving and context-based learning activities (Dunleavy et al., 2009).

For AR to be used effectively and sustainably in science education, it requires not only a technological infrastructure but also instructional design that is structured in a way that is sensitive to the classroom context. In this regard Cuendet et al. (2013) have highlighted the principles of integration, awareness, flexibility and minimalism in relation to AR design in the classroom, emphasising the importance of using the technology in a way that is compatible with existing teaching activities. When evaluated from the perspective of science education, this approach provides an important framework for integrating individual student interactions—particularly in laboratory and experimental activities—with the overall flow of classroom teaching. The teacher's ability to monitor the activities students carry out via AR and to make pedagogical interventions when necessary is crucial for maintaining a balance between technological interaction and instructional objectives.

With the widespread adoption of mobile AR technologies, the areas of application for augmented reality in science education have also diversified. In addition to three-dimensional modelling and experiment simulations, problem-solving, scientific inquiry, data collection and out-of-school learning activities have been incorporated into AR-supported learning environments. Applications developed particularly in the context of environmental education and fieldwork have enabled students to interact simultaneously with scientific data and digital content in real-world

environments (Dunleavy et al., 2009). Consequently, the role of AR in science education has expanded from the mere visual presentation of scientific concepts to supporting interactive and inquiry-based learning processes carried out in real-life contexts.

As the body of research on science education has grown, systematic reviews, meta-reviews and statistical meta-analyses synthesising the effects of AR applications on learning have also been published. Akcayir and Akcayir (2017), in a systematic review of the use of AR in education, reported various advantages in terms of learning outcomes, motivation and engagement, whilst also highlighting that technical issues and usability difficulties can limit implementation. Ibáñez and Delgado-Kloos (2018), in a systematic review focused on STEM learning, identified substantial use of AR for exploration and simulation and highlighted the importance of metacognitive scaffolding and experimental support. Radu (2014), in a meta-review and cross-media analysis, reported that the effects of AR on learning vary according to factors such as teaching method, learning context and student characteristics. Garzón and Acevedo (2019), in a statistical meta-analysis of quantitative studies, reported an overall medium effect of AR on students' learning gains. These findings should be interpreted with attention to methodological and contextual differences across the reviewed studies.

This body of research highlights two key implications for science education. Firstly, augmented reality offers significant pedagogical opportunities for representing scientific phenomena that are difficult to observe directly, occur at different scales, or are limited in traditional classroom settings, such as atomic and molecular processes, cellular structures, force fields and astronomical movements. Secondly, the impact of AR on learning cannot be explained solely by the technical characteristics of the technology used. Alignment with learning objectives, the nature of tasks, teacher guidance, classroom orchestration and how AR activities are integrated with laboratory, field or other learning environments are among the key factors determining the pedagogical quality of these applications (Cuendet et al., 2013; Kerawalla et al., 2006).

This historical and research-based development process demonstrates that the role of AR in science education has evolved beyond that of a mere technological innovation, diversifying in line with different learning objectives and teaching contexts. Accordingly, the following section examines the main areas of application for AR in science education.

3. Areas of Application for Augmented Reality in Science Education

In science curricula in Turkey, it is important for pupils to relate scientific knowledge and skills to everyday life, to participate actively in scientific processes, and to use their research, inquiry and problem-solving skills during the learning process (Ministry of National Education [MEB], 2018). In the Science Curriculum prepared within the framework of the Turkey Century Education Model (TYMM), science teaching is presented within a structure that holistically addresses conceptual skills, subject-specific skills, social-emotional learning skills, values and literacy skills (Ministry of National Education [MEB], 2024). When this programme approach is considered alongside the potential of augmented reality (AR) to incorporate interaction, visualisation, experience and real-life contexts into

the learning process, it can be said that AR is one of the technological tools capable of supporting the programme's objectives in science education.

3.1. Laboratory Applications and Experience-Based Learning

Scientific processes such as conducting experiments, making observations, identifying variables, collecting data and drawing conclusions are among the fundamental components of science education. Both the 2018 Science Curriculum and the Science Curriculum prepared under the TYMM framework place emphasis on learning experiences that support students' active participation in scientific processes, rather than merely acquiring scientific knowledge at a theoretical level (MEB, 2018, 2024). In this context, AR-supported laboratory activities can be regarded as complementary learning tools that, rather than replacing real experiments, support experimental processes and enable students to gain preliminary experience safely under specific conditions.

AR-based laboratory applications can enable students to examine processes prior to an experiment, observe the relationships between variables, and visualise certain processes that are difficult to observe directly during the experiment. Research in the literature indicates that AR applications can offer various advantages, particularly in terms of visualisation, interaction and the enrichment of the learning experience (Akçayır & Akçayır, 2017; Ibáñez & Delgado-Kloos, 2018). However, for these applications to be effective, it is important that AR activities are linked to the objectives of the experiment and that technological interaction does not replace real-world experimentation, observation and scientific inquiry. In this respect, AR can be used as a complementary technology that supports laboratory work and helps students make sense of experimental processes.

3.2. Three-Dimensional Modelling and Supporting Conceptual Learning

In science education, helping students make sense of concepts that are difficult to observe directly—such as cellular structures, atomic and molecular models, relationships between force and motion, and processes relating to the Earth and the universe—can present various challenges. The fact that conceptual skills and subject-specific skills in science are treated as key components of the learning process in the TYMM Science Curriculum necessitates that students not only acquire knowledge but also make sense of the relationships between scientific concepts and processes (MEB, 2024).

Augmented reality-supported three-dimensional models can enable students to examine scientific objects and processes from different angles, interact with the models, and relate visual representations of structures that cannot be directly observed to the real environment. Research indicates that AR-based visualisation applications hold significant potential, particularly in terms of understanding spatial relationships and supporting conceptual learning (Ibáñez & Delgado-Kloos, 2018; Radu, 2014). From this perspective, AR-supported three-dimensional modelling can be regarded as one of the tools capable of supporting the skill-based learning processes envisaged in TYMM.

3.3. Field Studies and Out-of-School Learning Environments

Linking science education to real life requires students to be able to use scientific knowledge not only in the classroom but also in understanding the events and problems they encounter in their daily lives and surroundings. The holistic structure of the TYMM Science Curriculum creates opportunities for learning experiences that support pupils in interacting with their environment and evaluating issues related to sustainability and the environment from a scientific perspective (MEB, 2024). In this context, out-of-school learning environments are one of the key learning areas where AR applications can be integrated with real-life contexts.

AR-based field applications can enable the physical environment in natural areas, botanical gardens, museums, science centres and similar out-of-school learning environments to be enriched with location- or object-sensitive digital content. For example, pupils can use AR to access additional information, three-dimensional models or guided inquiry tasks relating to a living organism, an ecosystem component or a natural formation they have observed in the real environment. Such applications can facilitate the establishment of links between observations made in the physical environment and digital information and representations. Studies conducted by Dunleavy et al. (2009) and Kamarainen et al. (2013) demonstrate that AR-supported contextual and field-based applications can be used to support scientific inquiry, problem-solving and environmental learning processes.

In this respect, augmented reality should be regarded not as a technology that replaces the physical environment in out-of-school science learning, but as a tool that supports pupils in relating the phenomena and processes, they observe in their surroundings to scientific knowledge. Such an approach can enable digital content to support the processes of observation, inquiry and interpretation whilst preserving pupils' direct interaction with the real environment.

When the Science Curriculum (MEB, 2018) is evaluated alongside the Science Curriculum (MEB, 2024) prepared within the framework of the Turkey Century Education Model, it can be said that augmented reality is a supportive technology that can be used for various purposes in science education. The visualisation of experimental processes in laboratory activities, the representation of structures and processes that cannot be directly observed through three-dimensional modelling, and the enrichment of the physical environment with digital content during fieldwork are among the primary areas of application.

However, the pedagogical value of AR in science education does not depend solely on the technical features of the technology. Alignment with learning objectives, student characteristics, teacher guidance, task design and how the technological activity is integrated with other learning experiences are among the key factors determining the quality of the application (Cuendet et al., 2013; Kerawalla et al., 2006). For this reason, when linking AR applications to the TYMM, it would be more appropriate to treat technology not as an end in itself but as a pedagogical tool that can support the development of the knowledge, skills and values envisaged in the curriculum.

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The examples presented in Tables 1, 2 and 3 provide a pedagogical framework for how augmented reality can be structured, taking into account the developmental characteristics and science learning needs of pupils at different year groups. This framework does not represent the AR activities directly included in the curriculum; rather, it illustrates example application areas developed in line with the skills- and values-focused approach of the Turkey Century Education Model Science Curriculum (MEB, 2024).

Upon examination of the proposed framework, it is evident that AR applications at Years 3–4 can support processes of observation, curiosity and basic discovery; at Years 5–6, they can contribute to the establishment of conceptual relationships, scientific inquiry and data interpretation; whilst in Years 7–8, they can be structured to facilitate more complex problem-solving, modelling, critical thinking and the assessment of environmental issues. Such a developmental approach could contribute to the use of AR in science education not merely as an engaging technology, but as a learning tool planned in line with pupils' year group, learning objectives and pedagogical requirements.

Table 1.

Areas of Application for Augmented Reality in Science Education for Years 3–4 (Science Curriculum of the Turkey Century Education Model, 2024)

AR application area	Learning objective	Skills and tendencies that can be supported	Values that can be linked	Example topic/activity
3D modelling	Recognising fundamental concepts through concrete experiences	Skills: Observation, making connections Tendencies: Curiosity, discovery	Sensitivity to nature, aesthetic sensitivity	Examination of plant parts using AR-supported 3D models
Laboratory applications	Pre-examination and familiarisation with experimental processes	Skills: Process monitoring, observation, drawing simple conclusions Tendencies: —	Responsibility, behaving safely	Visualisation of phase changes in substances using AR
Fieldwork	Exploring the immediate environment through scientific observation	Skills: Observation, asking questions, classification Tendencies: Curiosity	Environmental awareness and respect	AR-supported examination of living and non-living things in the school playground

Note: The examples of AR use, together with the associated skills, tendencies and values, were developed by the authors based on the MEB (2024) Science Curriculum; they are not taken directly from the curriculum.

Table 2.

Areas of Application for Augmented Reality in Science Education for Years 5–6 (Science Curriculum of the Turkey Century Education Model, 2024)

AR application area	Learning objective	Skills and tendencies that can be supported	Values that can be linked to	Example topic/activity
3D modelling	Understanding abstract structures and concepts	Skills: Establishing conceptual relationships, spatial thinking, using models Tendencies: Curiosity, openness to learning	—	Examining cells and organelles using AR-supported 3D models
Laboratory practicals	Investigating relationships between variables	Skills: Scientific inquiry, problem-solving, data interpretation Tendencies: —	Responsibility, scientific integrity	AR-assisted modelling of the effect of friction on different surfaces
Fieldwork	Establishing links between science and everyday life	Skills: Observation, inquiry, data collection and interpretation Tendencies: —	Environmental awareness, responsibility	Examining ecosystem components through AR-supported field observation

Note: The examples of AR use, together with the associated skills, tendencies and values, were developed by the authors based on the MEB (2024) Science Curriculum; they are not taken directly from the curriculum.

4. Advantages and Limitations of Augmented Reality Applications

Whilst the literature on the use of AR in science education reports various positive outcomes, these results do not imply that AR produces similar learning outcomes in every situation and every learning environment. The pedagogical value of AR applications depends on numerous interrelated variables, such as learning objectives, instructional design, student characteristics, teacher guidance and technological infrastructure (Akçayır & Akçayır, 2017; Cuendet et al., 2013; Radu, 2014). Therefore, the potential of AR in science education must be assessed by taking into account both the advantages it offers and the limitations it entails.

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Table 3.

Areas of Application for Augmented Reality in Science Education for Years 7–8 (Science Curriculum of the Turkey Century Education Model, 2024)

AR application area	Learning objective	Skills and tendencies that can be supported	Values that can be linked to	Example topic/activity
3D modelling	Establishing links between scientific models and concepts	Skills: Analytical thinking, modelling, evaluating system relationships Tendencies: Curiosity	Scientific integrity	Examining the historical development of atomic models using AR-supported models
Laboratory practicals	Investigating factors affecting the rate of dissolution (FB.7.5.3.2)	Skills: Critical thinking, problem-solving, self-regulation Tendencies: —	Responsibility, safe behaviour, scientific integrity	AR-supported investigation of factors affecting the rate of dissolution
Fieldwork	Conducting evidence-based assessments of environmental issues	Skills: Decision-making, collaboration, data interpretation Tendencies: —	Environmental awareness, responsibility	Investigating a local environmental issue as part of an AR-supported field activity

Note: The examples of AR use, together with the associated skills, tendencies and values, were developed by the authors based on the MEB (2024) Science Curriculum; they are not taken directly from the curriculum.

4.1. The Advantages of Augmented Reality in Science Education

Support for conceptual learning and visualisation

One of the key advantages of AR in science education is that it enables the examination of scientific structures and processes—which are difficult to observe directly—through three-dimensional and interactive representations. The visualisation of phenomena occurring at different scales, such as atomic and molecular structures, cellular processes and astronomical movements, can facilitate students' exploration of the spatial and conceptual relationships between these phenomena. Systematic reviews and meta-analyses demonstrate that AR, particularly through its visualisation and interaction capabilities, can support conceptual learning (Ibáñez & Delgado-Kloos, 2018; Radu, 2014). However, it should be borne in mind that a three-dimensional representation alone does not guarantee conceptual learning; the representation must be linked to learning objectives, and students' attention must be directed towards conceptually important features.

Supporting experience-based learning

AR applications can support the creation of experience-based learning environments where students can interact with scientific phenomena and processes. In particular, the visualisation of processes that are difficult to observe directly, or the prior examination of specific experimental scenarios, can enable students to form an understanding of the process before conducting the actual experiment (Akçayır & Akçayır, 2017). From this perspective, AR-supported applications can be regarded not as an alternative to laboratory activities, but as complementary tools that support real-world experimental and observational processes.

This complementary function of AR is significant from the perspective of science education. Rather than students merely interacting with digital representations, AR can enable them to compare the knowledge they acquire through AR with the results of real observations, measurements and experiments. Such a design can help prevent technological interaction from taking precedence over the scientific inquiry process, whilst allowing students to benefit from the visualisation capabilities of AR.

Supporting out-of-school and context-based learning

AR's ability to overlay digital information and representations onto the physical environment makes this technology significant for science learning outside the school setting as well. In settings such as natural environments, museums, science centres and environmental fieldwork, pupils can relate the physical objects and phenomena they observe to location- or object-sensitive digital content. This facilitates the exploration of scientific knowledge within real-life contexts.

Studies conducted by Dunleavy et al. (2009) and Kamarainen et al. (2013) demonstrate that AR-supported contextual and field applications can integrate students' interactions with the physical environment with scientific tasks and knowledge. Particularly from the perspective of environmental education, AR can contribute to the pedagogical structuring of fieldwork by supporting students' observations in the environment with additional information, data or guided inquiry activities.

Motivation, interest and engagement in the learning process

One of the frequently reported advantages of AR in science education is its ability to support students' motivation and interest in the learning process. Interactive and visually rich learning environments enable students to engage with scientific concepts and processes in different ways. Sirakaya and Sirakaya (2018) found that the use of AR in science education had a positive impact on students' attitudes and motivation towards the subject. Similarly, systematic reviews also highlight motivation and engagement as key advantages of AR in educational settings (Akçayır & Akçayır, 2017; Radu, 2014).

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However, it is important to distinguish between students' interest in technology and their long-term learning outcomes. The fact that students find an AR application engaging does not, in itself, indicate that conceptual learning has taken place. Therefore, motivational effects must be assessed in conjunction with learning objectives and academic outcomes.

4.2. Limitations of Augmented Reality in Science Education

Risk of prioritising technology over pedagogical design

One of the key factors that may limit the effectiveness of AR applications is when technological features take precedence over pedagogical aims. Activities that are not sufficiently linked to learning objectives, or that focus solely on students' interaction with digital objects, may result in the technological innovation offered by AR becoming more prominent than its instructional function. Kerawalla et al. (2006) highlight the importance of pedagogical elements—such as teacher guidance, task design and the organisation of classroom implementation—for AR applications to be effective in the classroom. Similarly, Cuendet et al. (2013) consider the integration of AR applications with existing classroom activities and the teacher's ability to monitor the learning process to be fundamental conditions for effective classroom implementation.

Technical infrastructure and accessibility

The widespread adoption of AR applications in science education depends on infrastructure conditions such as hardware, software, internet connectivity and technical support. Differences in the technical capabilities of devices, software incompatibilities and technical issues that may arise during use can cause interruptions to the learning process. Akcayir and Akcayir (2017) identify technical issues and usability difficulties as significant limitations to the use of AR in education.

This situation must also be assessed in terms of access to education. Unequal access to the necessary technological tools by pupils or schools may lead to disparities in the opportunities to benefit from AR-supported learning experiences. Therefore, when planning AR applications, existing infrastructure, device access and technical sustainability must be taken into account alongside pedagogical suitability.

Teacher competencies and classroom orchestration

For AR to be used effectively in science education, teachers must not only be able to operate the technology but also determine for which learning objective, at which stage and using which teaching method it should be employed. It is important for the teacher to monitor pupils' interactions with the digital environment, provide guidance when necessary and integrate the AR activity into the overall flow of classroom teaching.

The classroom orchestration approach highlighted by Cuendet et al. (2013) brings the teacher's role into sharp focus at this point. The use of AR applications in the classroom may give rise to new responsibilities for guidance, observation and organisation, rather than diminishing the teacher's pedagogical role. For this reason, teachers' professional development processes relating to AR must focus not only on the technical use of the applications but also on AR-supported instructional design.

Cognitive load and attention management

In AR environments, the physical surroundings, digital objects, textual information, sounds and interactive tasks may all require the student's attention simultaneously. Failure to structure these multiple information sources appropriately may cause students to divide their attention between information crucial to learning and secondary visual or interactive elements. Radu (2014) reported that the effects of AR on learning can vary depending on the characteristics of the application and context, whilst Akcayir and Akcayir (2017) also report various difficulties related to usability and the learning process in the use of AR in education.

Therefore, it should not be assumed that increasing the number of visual or interactive elements in AR designs will always result in a higher-quality learning experience. It is important that digital content is directly related to learning objectives, that unnecessary elements are minimised, and that the learner's attention is directed towards scientifically significant information and processes.

The risk of replacing real-world experiences

One of the fundamental characteristics of science education is that pupils interact directly with real objects, materials, living organisms and natural processes. For this reason, the systematic use of digital models offered by AR as a substitute for real experiments, field observations or physical materials must be carefully evaluated from a pedagogical perspective. One of the most powerful applications of AR is to support real learning experiences by making information and processes that cannot be directly observed visible, rather than eliminating these experiences.

For example, an AR model of a plant may be useful for examining the plant's internal structure; however, it does not fully replicate the tactile, spatial and contextual experience provided by observing a real plant. Similarly, whilst an AR laboratory application may be used for pre-experiment preparation or to demonstrate processes that cannot be observed, it should not replace students' experience of using real laboratory equipment and collecting data. Consequently, the role of AR in science education should be regarded as a 'complementary' rather than a 'substitute' technology.

When the advantages and limitations of augmented reality in science education are considered together, it becomes apparent that the technology's pedagogical value stems not from the use of AR itself, but from the way it is used. Although AR offers significant opportunities in terms of visualisation, interaction, context-based learning and motivation, it may not always produce the expected learning outcomes due to inadequate instructional design, technical issues, disparities in access, teacher competencies and difficulties in managing attention.

Therefore, the fundamental question regarding the integration of AR into science education should be framed not as ‘Should AR be used?’, but rather as ‘For which learning objective, with which pupils, in which context, and how should AR be used?’. When evaluated in light of the holistic approach of the Turkey Century Education Model to skills, values and learning experiences (MEB, 2024), it appears more appropriate to position AR not merely as a technological innovation, but as a pedagogical tool capable of supporting curriculum-aligned learning experiences.

5. Future Perspectives and Recommendations

Developments in augmented reality technologies are transforming and diversifying the ways in which these technologies are used in science education. The increasing technical capacity of mobile devices, the growing accessibility of 3D content development tools, and the increasing use of artificial intelligence (AI) technologies in educational settings are opening up new possibilities for designing AR-supported science learning environments that are more interactive and adaptable in the future. However, it is expected that the educational value of these technological developments will be determined not merely by the addition of new technical features to learning environments, but by how these features are linked to pedagogical objectives.

5.1. Integration of AR and Artificial Intelligence

One of the key areas of development regarding the future of AR in science education is the combined use of augmented reality and artificial intelligence technologies. The potential for AI to analyse data derived from student interactions, monitor learning processes and structure feedback according to different student needs offers the potential to make AR-supported learning environments more adaptable (Holmes et al., 2019; Luckin & Holmes, 2016). This type of integration is one of the key areas for future research, particularly in terms of monitoring students’ interactions with complex scientific processes and identifying the support they require during the learning process.

For example, interaction data—such as how a student interacts with a three-dimensional molecular model in an AR environment, which components they examine for longer, or at which stages they encounter difficulties in an experiment simulation—can be analysed using appropriate analytical systems. Such a framework could enable the provision of additional explanations, hints or guidance to the student during the learning process. However, there is a need to develop empirical evidence regarding the effectiveness of such applications in science education. Consequently, AR–AI integration should be regarded, at present, not so much as an established teaching model, but rather as an important area of research and development in terms of personalised and adaptable science learning environments.

The combined use of AR and AI may also provide new opportunities for teachers to monitor learning processes. Presenting data on pupils' progress in AR activities, the difficulties they encounter and the interactions they engage in to the teacher in a meaningful way can support pedagogical decision-making during the teaching process. However, in the development of such data-driven systems, issues such as pupil privacy, data security, algorithmic transparency and the preservation of the teacher's role in pedagogical decision-making must also be taken into account.

5.2. Teacher Training and Professional Development

The future of AR in science education depends not only on the development of the technology itself, but also on teachers' capacity to use this technology in a pedagogically meaningful way. AR-supported teaching requires teachers to go beyond merely being able to use an application technically; it requires them to set appropriate learning objectives, structure the relationship between digital content and the physical learning environment, manage student interactions, and assess whether the technology is genuinely contributing to the learning process.

For this reason, it is important for teacher training programmes to prioritise experiences focused on the design of AR-supported lessons and activities, rather than merely on the technical use of AR. Enabling trainee teachers to explore different AR applications, design AR-supported activities for specific science learning outcomes, implement these activities, and evaluate them from a pedagogical perspective can contribute to the development of their competencies in technology integration. Similarly, in professional development programmes for practising science teachers, emphasis should be placed on which learning objectives AR is suitable for, in which situations its use is not necessary, and how it can be integrated with real experiments.

Studies examining science teachers' views on augmented reality and other current educational technologies indicate that, whilst teachers recognise the educational potential of these technologies, they may face various requirements relating to implementation, infrastructure and competence (Işık & Kose, 2024). This situation indicates that teachers' professional development regarding AR should not be limited solely to technological skills.

5.3. Future Perspectives within the Context of the Turkey Century Education Model

The Science Curriculum prepared within the framework of the Turkey Century Education Model addresses conceptual skills, subject-specific science skills, social-emotional learning skills, literacy skills and values within a holistic approach to learning (MEB, 2024). This structure necessitates that, when integrating digital technologies such as AR into the curriculum, consideration be given not so much to the technology itself but to how it can contribute to the development of students' knowledge, skills and values.

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From this perspective, the future of AR within the TYMM context should not be associated solely with the use of more digital content or three-dimensional models. The key criterion for evaluation should be how AR applications can help pupils investigate a scientific problem, gather evidence, construct models, observe environmental processes, or relate scientific knowledge to the contexts of everyday life. Such an approach can help ensure that technology does not take precedence over the curriculum, thereby facilitating the use of AR as a tool that supports the learning experiences envisaged in the curriculum.

In particular, the use of AR in conjunction with out-of-school learning environments can offer significant opportunities in science topics directly related to real life, such as sustainability, environmental issues and human–environment interaction. Supporting students' observations in the real environment with digital data, models or guided inquiry tasks can help to develop learning experiences that enable the application of scientific knowledge in everyday contexts. However, empirical research directly linked to the programme's objectives and learning outcomes is required to determine whether such applications are effective within the framework of the TYMM.

5.4. Access, Infrastructure and Education Policies

The sustainable and widespread adoption of AR applications in science education is a process too comprehensive to be left solely to the individual efforts of teachers or to initiatives carried out in specific schools. Technological infrastructure, access to devices, internet connectivity, technical support, the development of high-quality digital content and teachers' professional development are interrelated components of this process. The literature reports that technical issues and usability difficulties can limit the use of AR applications in educational settings (Akçayır & Akçayır, 2017).

It is therefore important that educational policies aimed at promoting the widespread use of AR in science education do not focus solely on the provision of hardware. In addition to the technological infrastructure, it is necessary to develop pedagogically sound and accessible content, provide teachers with ongoing professional support, and take into account the technological access opportunities of schools in different socio-economic circumstances. Otherwise, there is a risk that technological innovations may exacerbate existing access disparities rather than expanding learning opportunities.

Accessibility and inclusivity in the development of AR content are also issues that require greater attention in the future. To ensure that pupils with different learning needs can benefit from AR environments, it is important that visual, auditory and interactive features are designed in accordance with accessibility principles. In this way, AR can be supported in becoming not only a technologically advanced tool, but also an inclusive learning tool that facilitates the participation of different groups of pupils.

5.5. Recommendations for Future Research

In research on the future of AR in science education, it is important to move beyond short-term studies that merely examine students' attitudes towards or satisfaction with the technology. Future research should examine the effects of AR on various learning outcomes—such as conceptual learning, scientific process skills, problem-solving, spatial reasoning and the retention of knowledge—using long-term research designs that encompass different student groups. Systematic reviews and meta-analyses indicate that methodological differences and contextual variables across studies can complicate the interpretation of AR's effects on learning (Garzón & Acevedo, 2019; Ibáñez & Delgado-Kloos, 2018; Radu, 2014).

In this regard, future research should go beyond simply testing the effectiveness of AR at a general level and focus on explaining in which student groups, in which science topics, with which pedagogical approaches, and under which implementation conditions it yields more effective results. Examining the role of variables such as teacher guidance, student characteristics, task design, the type of AR used, and integration with real-world experiments on learning outcomes could contribute to building a more explanatory body of research in the field.

Adaptive learning environments that integrate AR with artificial intelligence, the use of learning analytics alongside AR activities, out-of-school AR applications, and teachers' competencies in designing AR-supported instruction are also important areas for future research. Furthermore, the development of AR applications directly linked to the objectives of the TYMM Science Curriculum in the Turkish context and their empirical evaluation across different year groups could make significant contributions to the national literature.

The future of augmented reality in science education does not depend solely on the emergence of more advanced hardware or more realistic digital content. The sustainable and pedagogically meaningful use of AR requires a holistic approach that addresses elements such as instructional design, teacher competencies, accessibility, technological infrastructure, ethics and data security. Whilst technologies such as artificial intelligence and learning analytics offer significant potential for making AR-supported learning environments more adaptable in the future, there is a need for empirical research to demonstrate the impact of this potential within the context of science education.

Therefore, the fundamental approach for the future should not be to place augmented reality at the centre of teaching, but rather to regard it as one of the tools that can be utilised under appropriate pedagogical conditions to support science learning. Designing technological innovations in a way that is aligned with learning objectives, supports teacher guidance, takes into account differences in access among pupils, and integrates with real-world science experiences will be among the key factors determining the long-term value of AR in science education.

6. Conclusion

Augmented reality is one of the key educational technologies in science education that brings together the physical environment and digital representations, enabling students to interact with scientific concepts and processes in different ways. In particular, the visualisation of scientific phenomena that are difficult to observe directly, occur on different scales, or require an understanding of three-dimensional relationships is among the fundamental contributions that AR can make to science teaching. Furthermore, supporting laboratory activities, enriching out-of-school learning environments with digital content, and helping students establish connections between scientific knowledge and real-life contexts are expanding the scope of AR's application in science education.

However, the research discussed throughout this chapter demonstrates that the pedagogical value of AR does not stem solely from the use of the technology itself. In applications where learning objectives are not aligned, teacher guidance is limited, or technological interaction takes precedence over pedagogical aims, it may be difficult for AR to deliver the expected learning benefits. Therefore, when evaluating the impact of AR in science education, consideration must be given not only to students' interest in and motivation towards the technology, but also to learning outcomes such as conceptual learning, scientific inquiry, problem-solving and the ability to apply knowledge in different contexts. AR-supported applications are therefore better positioned as complementary tools that visualise and extend real experiments, observations and fieldwork rather than replace them.

When assessed within the framework of the Turkey Century Education Model, the potential of AR is linked not so much to the technology itself as to its capacity to support the development of the knowledge, skills and values envisaged in the curriculum. The examples of AR usage presented in this chapter for different year groups constitute a pedagogical framework of recommendations developed in line with this understanding. Structuring areas of application—such as laboratory activities, three-dimensional modelling and fieldwork—in line with pupils' developmental levels and learning objectives can contribute to the meaningful integration of AR into the curriculum. However, for such integration to be sustainable, teachers must be supported in designing AR-enhanced teaching, the necessary technological infrastructure must be provided, and disparities in access among pupils must be taken into account.

In the future, AR environments integrated with artificial intelligence, learning analytics and advanced mobile technologies have the potential to make science learning more adaptable and interactive. However, technological advancement does not automatically imply an increase in pedagogical quality. In this context, the long-term value of augmented reality in science education will be determined not so much by how advanced the technology is, but by how meaningfully and consciously it is used in line with learning objectives. Consequently, AR should be regarded not as an end in itself in science teaching, but as a pedagogical tool that supports students' processes of observing, questioning, modelling and making sense of the scientific world.

References

- Abdullah, N., Baskaran, V. L., Mustafa, Z., Ali, S. R., & Zaini, S. H. (2022). Augmented reality: The effect on students' achievement, satisfaction and interest in science education. *International Journal of Learning, Teaching and Educational Research*, 21(5), 326–350. <https://doi.org/10.26803/ijlter.21.5.17>
- Abrahamson, D., & Lindgren, R. (2014). Embodiment and embodied design. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 358–376). Cambridge University Press. <https://doi.org/10.1017/CBO9781139519526.022>
- Akcayir, M., & Akcayir, G. (2017). Advantages and challenges associated with augmented reality for education: A systematic review of the literature. *Educational Research Review*, 20, 1–11.
- Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, 6(4), 355–385. <https://doi.org/10.1162/pres.1997.6.4.355>
- Caudell, T. P., & Mizell, D. W. (1992). *Augmented reality: An application of heads-up display technology to manual manufacturing processes*. In Proceedings of the Twenty-Fifth Hawaii International Conference on System Sciences (Vol. 2, pp. 659–669). IEEE. <https://doi.org/10.1109/HICSS.1992.183317>
- Cuendet, S., Bonnard, Q., Do-Lenh, S., & Dillenbourg, P. (2013). Designing augmented reality for the classroom. *Computers & Education*, 68, 557–569.
- Cankaya, B., & Girgin, S. (2018). The effect of augmented reality technology on academic achievement in science lessons. *International Journal of Social and Humanities Sciences Research (JSHSR)*, 5(30), 4283–4290. <https://doi.org/10.26450/jshsr.882>
- Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. *Journal of Science Education and Technology*, 18(1), 7–22. <https://doi.org/10.1007/s10956-008-9119-1>
- 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>
- Holmes, W., Bialik, M., & Fadel, C. (2019). *Artificial intelligence in education: Promises and implications for teaching and learning*. Center for Curriculum Redesign.
- Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education*, 123, 109–123. <https://doi.org/10.1016/j.compedu.2018.05.002>

Augmented Reality (AR) Applications in Science Education

- Işık, E., & Kose, M. (2024). An examination of science teachers' views on augmented reality, the metaverse, artificial intelligence and their applications in education. *Journal of Individual Differences in Education*, 6(2), 149–169. <https://doi.org/10.47156/jide.1587315>
- Kamarainen, A. M., Metcalf, S., Grotzer, T., Browne, A., Mazzuca, D., Tutwiler, M. S., & Dede, C. (2013). EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips. *Computers & Education*, 68, 545–556. <https://doi.org/10.1016/j.compedu.2013.02.018>
- Kato, H., & Billinghurst, M. (1999). *Marker tracking and HMD calibration for a video-based augmented reality conferencing system*. In Proceedings of the 2nd IEEE and ACM International Workshop on Augmented Reality (IWAR '99) (pp. 85–94). IEEE Computer Society. <https://doi.org/10.1109/IWAR.1999.803809>
- Kerawalla, L., Luckin, R., Seljeftot, S., & Woolard, A. (2006). “Making it real”: Exploring the potential of augmented reality for teaching primary school science. *Virtual Reality*, 10(3), 163–174. <https://doi.org/10.1007/s10055-006-0036-4>
- Luckin, R., Holmes, W., Griffiths, M., & Forcier, L. B. (2016). *Intelligence unleashed: An argument for AI in education*. Pearson.
- Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE Transactions on Information and Systems*, E77-D(12), 1321–1329.
- Ministry of National Education [MEB]. (2018). *Science curriculum*. <https://mufredat.meb.gov.tr/ProgramDetay.aspx?PID=325>
- Ministry of National Education [MEB]. (2024). *Science curriculum of the Turkey Century Education Model*. <https://tymm.meb.gov.tr/ogretim-programlari/ders/fen-bilimleri-dersi>
- Onbaşı, U. İ. (2018). The effect of augmented reality applications on primary school pupils' attitudes towards augmented reality applications and their motivation in science. *Ege Education Journal*, 19(1), 320–337. <https://doi.org/10.12984/eggefd.390018>
- Ovez, F. D., & Şeker, B. S. (2022). An augmented reality-supported interdisciplinary teaching application in primary education. *Journal of the Institute of Natural Sciences*, 24(1), 313–334. <https://doi.org/10.25092/baunfbcd.995624>
- Papadopoulos, T., Evangelidis, K., Kaskalis, T. H., Evangelidis, G., & Sylaiou, S. (2021). Interactions in augmented and mixed reality: An overview. *Applied Sciences*, 11(18), 8752. <https://doi.org/10.3390/app11188752>
- Radu, I. (2014). Augmented reality in education: A meta-review and cross-media analysis. *Personal and Ubiquitous Computing*, 18(6), 1533–1543. <https://doi.org/10.1007/s00779-013-0747-y>

- Sarioglu, S. (2021). The effect of augmented reality training on science teachers' attitudes towards augmented reality applications. *Journal of Science, Mathematics, Entrepreneurship and Technology Education*, 4(1), 16–28.
- Shelton, B. E., & Hedley, N. R. (2002). *Using augmented reality for teaching Earth–Sun relationships to undergraduate geography students*. In Proceedings of the First IEEE International Augmented Reality Toolkit Workshop (pp. 8–15). IEEE. <https://doi.org/10.1109/ART.2002.1106948>
- Sirakaya, M., & Sirakaya, D. A. (2018). The effect of using augmented reality in science education on attitudes and motivation. *Kastamonu Education Journal*, 26(3), 887–905. <https://doi.org/10.24106/kefdergi.415705>
- Sutherland, I. E. (1968). *A head-mounted three-dimensional display*. In *Proceedings of the December 9–11, 1968, Fall Joint Computer Conference, Part I* (pp. 757–764). ACM Press. <https://doi.org/10.1145/1476589.1476686>

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