

Research on the Application of AR Technology in Educational Materials, as Well as the Management Challenges and Corresponding Solutions

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Abstract: This study aims to systematically analyze the innovation in application models and accompanying managerial challenges arising from integrating augmented reality (AR) technology into educational materials, thereby establishing a practical response framework. Through comprehensive literature review, case studies, and empirical data analysis, the paper first clarifies the primary forms of AR-based teaching materials—integrated textbooks, mobile applications, and wearable devices—and their benefits for enhancing learning immersion. Data shows these materials improve knowledge retention rates by approximately 12% in STEM disciplines, though poor design may increase external cognitive load for learners by up to 30%. The research identifies three core management challenges: sustained investment pressures on technological infrastructure, deficiencies in content quality and ethical oversight, and uneven adoption due to inadequate teacher professional development. To address these issues, the study proposes an integrated management approach: establishing cross-departmental AR material standards for standardized development; designing tiered teacher empowerment systems to bridge the technological gap; and exploring sustainable operation and evaluation models leveraging open resources and subscription services. The conclusion emphasizes that the healthy development of AR educational materials requires moving beyond technical optimism toward building a comprehensive ecosystem that balances technological innovation, pedagogical adaptation, and robust governance, enabling this technology to evolve from experimental applications into a sustainable educational driver.

Keywords: AR Technology; Textbook Application; Management Challenges;

Learning Outcomes; Standardization System

1. Introduction

Augmented reality technology is revolutionizing knowledge presentation and interaction paradigms in education at an unprecedented level, with its integration into teaching materials having progressed from sporadic experiments to a critical phase of large-scale exploration. Global educational technology market analysis reveals that AR-based educational applications maintained a compound annual growth rate exceeding 28% between 2023 and 2025, with educational content products accounting for nearly 40% of this share—a clear testament to their robust evolution from auxiliary tools to core instructional platforms. The essence of this integration lies in transforming abstract, static symbolic systems into interactive, context-driven mixed-reality experiences that bridge theoretical frameworks with practical perception. Numerous empirical studies have demonstrated that well-designed AR teaching materials can enhance the comprehension efficiency of complex concepts by approximately 34%, while demonstrating significant advantages in motivating learning. However, beneath the technological allure, profound structural challenges are emerging as key bottlenecks hindering its transition from "useability" to "effective implementation." Current academic discussions predominantly focus on technical efficacy while largely overlooking the systemic impacts of integrating this technology into existing educational systems—including persistent financial pressures from rapidly evolving infrastructure, scientific and ethical risks associated with non-standardized content, and gaps in professional competence and acceptance amid teachers' role transformations. Therefore, this study aims to go beyond the superficial hype surrounding AR technology applications by systematically examining how AR educational materials deliver benefits in

specific use cases, comprehensively identifying the management challenges encountered during scaling implementation, and developing a holistic framework that integrates technological principles, pedagogical approaches, and managerial expertise. This effort seeks to provide theoretical foundations and practical pathways for advancing sustainable, high-quality educational empowerment through AR technology [1].

2. Current Status and Benefit Analysis of AR Technology Application in Teaching Materials

2.1 Main Forms and Typical Cases of AR Teaching Materials

Currently, AR educational materials have evolved from conceptual prototypes into various deployable formats, primarily categorized into three types: integrated AR books, mobile application-assisted versions, and wearable device-immersive solutions. Integrated AR books typically feature graphics-based markers directly printed on traditional pages; learners can scan these markers with their mobile devices to access overlay 3D animations or video explanations—a format widely adopted in science and geography education at the primary level [2]. For instance, a German publishing group's junior high school physics AR textbook displays dynamic simulations of electric charge flow and safety guidelines on screen when students scan circuit diagrams, visualizing abstract principles. Mobile application-assisted versions offer greater flexibility as standalone platforms linked to specific textbook chapters, providing not only 3D models but also interactive assessments and step-by-step guidance [3]. A prime example is the "Anatomy 4D" app for medical education, which enables students to examine human organ systems layer by layer on tablets and dissect muscle tissues to observe skeletal structures—significantly reducing reliance on traditional anatomical experiments. Wearable device-immersive solutions, such as professional training materials using head-mounted devices like HoloLens, are currently limited to higher-level skill development in higher education or vocational training due to cost constraints; for example, mechanical engineering students can learn assembly techniques by interacting with virtual engine components through gestures [4]. Although these approaches differ in technical implementation and cost, they

all signify a fundamental shift in textbooks—from static information carriers to dynamic interactive interfaces—with the core objective of creating a blended learning space that integrates symbolic cognition with perceptual experience.

2.2 Empirical Research Data: Analysis of the Impact of Learning Outcomes and Cognitive Load

Numerous empirical studies have investigated the impact of AR-based teaching materials on learning outcomes and cognitive load, yielding a conditionally positive pattern. Regarding learning outcomes, multiple meta-analyses consistently demonstrate that in disciplines involving spatial structures and abstract reasoning—such as science, technology, engineering, and medicine—the use of AR materials generally enhances knowledge acquisition and retention rates to moderate degrees [5]. A 2022 meta-analysis of 37 global experimental studies found that students using AR learning materials achieved average test scores approximately 12 percentage points higher than those using traditional materials, with particularly significant differences observed in knowledge application and transfer skills. For instance, in learning about molecular stereostructures in organic chemistry, students using AR models achieved a 78% accuracy rate in identifying isomers, compared to only around 52% in the control group. However, these improvements come at a cost, often accompanied by potential cognitive load risks. Cognitive load theory categorizes psychological resource consumption during learning into intrinsic, extrinsic, and related loads [6]. Poorly designed AR interfaces can significantly increase harmful extrinsic loads. Research indicates that when AR interfaces display excessive complexity or unclear interaction guidance, approximately 30% of learners—particularly those with limited digital experience—exhibit attention deficits and visual fatigue, which deplete their cognitive resources needed for understanding core concepts. An eye-tracking study revealed that when students encountered poorly designed AR-based historical scene reconstructions, their visual focus dispersed across multiple non-critical animation elements, resulting in a 40% reduction in fixation time on core narrative threads [7]. Therefore, maximizing the effectiveness of AR teaching materials hinges on meticulous design balance: leveraging their advantage of reducing intrinsic load (e.g., by

making abstract concepts concrete) while employing concise, intuitive interaction designs to keep extrinsic load below a critical threshold, thereby directing more cognitive resources toward deep knowledge construction.

2.3 The Role of Technological Integration in Reconstructing Teaching Interaction Models

The integration of AR technology with educational materials is profoundly transforming traditional teaching interaction models, shifting from unidirectional information transmission to multidirectional, context-driven social knowledge construction. While conventional classroom interactions primarily revolve around binary dimensions of "teacher-student" and "student-student," the introduction of AR-based materials essentially adds a crucial interactive dimension: "learner-enhanced content." Learners no longer passively read texts or observe two-dimensional illustrations but directly interact with virtual objects through gestures, movements, or touch controls to manipulate, analyze, and explore them [8]. For instance, in astronomical AR materials, students can "grab" and zoom on planets within the solar system to observe their orbits and rotation—this hands-on experience fosters a sense of agency, transforming learners from passive recipients into active explorers of knowledge. This fundamental shift subsequently drives a transformation in teacher-student roles: educators evolve from authoritative knowledge providers at the podium into designers of learning contexts, facilitators of inquiry processes, and technical supporters. Their core responsibilities now include designing meaningful AR-based learning tasks, providing scaffolded guidance during group AR collaborations, and helping students integrate virtual experiences with real-world knowledge. Simultaneously, student-student interactions gain new forms and depth through AR technology. AR-powered collaborative tasks—such as jointly completing virtual chemistry experiments or reconstructing historical scenarios—require team members to engage in real-time spatial referencing, task allocation, and perspective negotiation [9]. Research indicates that within this shared enhanced space, students employ approximately 60% more linguistic communication to refer to, explain, and discuss specific objects, fostering a more refined cognitive division of labor and social negotiation

of knowledge. Consequently, the core value of the interactive model reconstructed by AR technology lies in creating a "triple interaction space" that integrates physical, virtual, and social dimensions, providing an unparalleled context for developing students' inquiry skills, collaborative abilities, and capacity to solve complex problems.

3. Management Challenges in the Application of AR Teaching Materials

3.1 Sustainability Issues in Technical Infrastructure and Resource Allocation

The widespread and sustained adoption of AR educational materials first encounters persistent challenges in technological infrastructure and resource allocation—issues that cannot be resolved through one-time procurement. The core difficulties stem from a three-pronged structure involving hardware iteration costs, software platform maintenance and upgrades, and stable network support [10]. While many educational institutions can initially acquire tablets or head-mounted displays during pilot phases, a survey of 200 K-12 schools in North America revealed that these devices exhibit combined failure and obsolescence rates of up to 40% within three years, creating ongoing renewal pressures for schools. Software-related issues are equally prominent: AR applications often rely on specific operating system versions or development engines; any underlying technological updates may cause compatibility problems with existing content, requiring additional development budgets for adaptation. For instance, a mature anatomical AR application at a university experienced severe rendering errors after a major mobile OS update, with repair costs approaching one-third of initial development expenses. More fundamentally, network conditions pose significant challenges—high bandwidth and low latency are essential for smooth loading of complex 3D models and real-time interactive data, yet many regions, particularly resource-scarce schools, struggle to ensure stable connectivity. Field research indicates that in classrooms with poor wireless coverage, AR-based learning experiences result in an average 15% loss of instructional time due to loading delays or interruptions, severely disrupting teaching continuity. These sustained technological investments starkly contrast with the traditional

linear model of textbook procurement, usage, and renewal. They necessitate educational administrators to establish a dynamic, forward-looking resource planning framework that treats technological infrastructure as a "living system" requiring regular maintenance and iteration, rather than a one-time fixed asset-a significant management challenge for institutions accustomed to static budget allocation practices.

3.2 Content Quality Control and Academic Ethical Risks

When textbook content evolves from static texts published by authoritative publishers into dynamically generated, immersive experiences, quality control and academic ethical risks escalate significantly, creating a regulatory gray area. The primary concern lies in the accuracy and scientific rigor of the content itself. Traditional textbooks undergo rigorous expert review and editorial processes, whereas many AR materials-particularly models and animations rapidly developed by third-party tech companies-often lack equivalent levels of scientific scrutiny. There have been cases where AR applications for middle school biology simplified cell division processes with misleading labels, presenting erroneous knowledge despite visually appealing presentations. Secondly, issues of content objectivity and value orientation prove particularly sensitive in AR applications involving history or social sciences. Developers' selective representation of historical events or portrayal of characters may inadvertently reflect subjective biases. For instance, an AR application depicting ancient civilizations might emphasize palace splendor while neglecting everyday life, thereby fostering a one-sided historical perception-a risk exemplified by "technology-driven narratives" for which effective oversight standards remain lacking. Additionally, immersive experiences trigger new ethical considerations regarding emotional and cognitive impacts: overly realistic disaster scenarios or violent historical reenactments could adversely affect young learners' psychological well-being, yet current guidelines lack clear categorization of emotional intensity levels or age-appropriate usage parameters for AR content. Finally, data privacy and security pose inherent risks inherent to interactive technologies. AR applications often require

collecting users' location, movement, and even eye-tracking data to enhance user experience, making the storage, utilization, and ownership of such data particularly critical in educational settings. A 2023 independent audit revealed that nearly 30% of educational AR apps did not explicitly state in their privacy policies whether collected student data was used for commercial analysis or shared with third parties. Therefore, establishing comprehensive quality standards for AR educational content-including accuracy verification, value assessment, ethical considerations, and data privacy protection-has become an urgent management priority to mitigate risks and ensure technology empowers education without causing misguidance or harm.

3.3 Lag in Teachers' Professional Development and Differences in Technology Acceptance

The effective application of AR educational materials ultimately depends on teachers as key practitioners. However, current teacher professional development systems generally lag behind the pace of technological adoption, and significant disparities in technical acceptance among educators further complicate implementation. This developmental gap manifests primarily in superficial and fragmented training content. Many programs remain confined to operational-level guidance on "how to use specific AR applications," failing to help teachers grasp the underlying pedagogical principles-such as designing AR-based inquiry tasks or conducting effective questioning and assessment within augmented environments. As a result, teachers often mechanically follow technical procedures without flexibly integrating AR into personalized instructional designs. A survey revealed that only approximately 35% of teachers who received standard operational training could independently design AR-based learning activities beyond vendor-predefined lesson plans in subsequent teaching practices. More fundamentally, collaborative networks and time resources supporting continuous exploration and innovation among teachers are severely inadequate. Educators frequently face isolation when attempting to integrate AR technologies, lacking mechanisms for in-depth dialogue with subject experts, technology developers, and fellow practitioners. Moreover, already limited classroom teaching and lesson preparation time makes exploring new

technologies an additional burden rather than a natural extension of instruction. Additionally, significant variations in AR technology acceptance exist among educators, influenced by factors such as age, disciplinary background, and personal technological beliefs. Some educators, particularly those teaching STEM subjects, may embrace AR as a teaching tool more proactively; others may exhibit reservations or even resistance due to unfamiliarity with the technology, concerns about classroom control, or doubts about its educational value. Research reveals that within the same school, teachers' willingness to adopt AR-based instructional materials varies significantly—from strong enthusiasm to outright rejection—creating internal divisions that hinder the implementation of unified AR integration policies. Without differentiated support strategies—providing innovation platforms for pioneers, safe pilot opportunities with robust pedagogical support for hesitant educators, and preserving traditional teaching options for resistant practitioners—any management initiatives aimed at promoting AR materials may face covert resistance, ultimately leading to a significant gap between technological investment and actual implementation outcomes. Therefore, shifting teacher professional development from mere technical training to a systematic approach encompassing pedagogical refinement, community building, time allocation, and tailored support strategies is key to addressing this managerial challenge.

4. Strategies and Implementation Paths for AR Teaching Material Management

4.1 Establishing a Cross-Departmental Collaborative Standardization System for AR Teaching Materials

To address the chaos and risks in AR educational material development and application, the immediate priority is to establish a standardized framework that transcends the confines of standalone educational technology and fosters cross-departmental collaboration. This framework should not become a rigid technological constraint but rather a dynamic, guiding structure centered on establishing baseline consensus regarding technical interoperability, content quality, and data ethics. Technical interoperability standards aim to overcome device dependency and platform

barriers by requiring textbook development to adhere to universal file formats and interface protocols, ensuring core learning content can be transferred across different hardware and operating systems. For instance, drawing on initiatives from the International Alliance for Immersive Education, lightweight 3D model standards and scenario description specifications tailored for educational contexts could be developed, reducing content adaptation costs by approximately 50%. Content quality standards are more complex and require joint efforts from subject experts, educational psychologists, frontline educators, and technology developers. They should encompass at least three tiers: scientific accuracy review processes, teaching suitability assessment frameworks (e.g., alignment with cognitive objectives at specific educational stages), and guidelines for emotional and ethical impacts. Historical AR content particularly requires clear definitions regarding how to balance factual evidence with historical interpretation during scenario reconstruction. Data ethics and security standards serve as fundamental safeguards for student rights, necessitating explicit regulations on the scope of behavioral data collection, encryption methods, anonymization procedures, strict access controls, and compliance with educational application requirements under frameworks like the EU's General Data Protection Regulation or similar regional legislation. The establishment of this standardization system cannot rely solely on education administrative departments; instead, it requires a collaborative governance mechanism led by educational authorities and involving standardization organizations, academic research institutions, industry associations, and leading enterprises. Through flexible approaches such as publishing white papers, launching certification pilots, and providing compliance development toolkits, the industry can be gradually guided from disorderly competition toward a well-regulated, collaborative ecosystem.

4.2 Design a hierarchical mechanism for enhancing teachers' technological capabilities and providing development support

To address the challenges of lagging professional development and varying levels of technology adoption among teachers, it is essential to move away from a one-size-fits-all training approach and establish a tiered empowerment system that respects individual differences and supports

progressive growth. This system should center on teachers' pedagogical knowledge, treat technology as a tool to enhance teaching rather than an end goal, and be structured around three interconnected phases: "Consciousness Activation," "Skill Foundation Building," and "Innovation Leadership." For teachers in the "Consciousness Activation" phase—particularly those with low technology acceptance or heavy teaching workloads—the focus should be on reducing anxiety and demonstrating practical value. This can be achieved by organizing short, subject-specific AR demonstration classes or providing easy-to-use case libraries of "five-minute AR activities" that allow teachers to experience how technology addresses real teaching challenges (e.g., quickly displaying 3D geometric cross-sections using AR). For educators in the "Skill Foundation Building" phase, support should shift toward in-depth workshops and ongoing professional communities. Workshops should go beyond basic button operations; they should guide teachers in analyzing which AR features to use under specific teaching contexts and for achieving particular learning objectives, while practicing designing concise learning tasks and assessment criteria. Most importantly, establishing subject-based or grade-level teacher communities, where school technology advisors or subject leaders organize regular discussions to share successes and lessons learned, has proven to significantly boost sustained technology adoption. For the minority of pioneering teachers who lead innovation initiatives, resources should be provided to support their research on teaching methodology innovations, such as project funding, opportunities for collaboration with university researchers, or encouragement to develop school-based AR cases with corresponding intellectual property recognition. The entire empowerment process must be supported by essential institutional safeguards: incorporating teachers' time dedicated to AR-related professional development into their workload, and establishing a comprehensive teacher evaluation model that integrates technology application, instructional design, and student learning outcomes—thereby combining external incentives with intrinsic motivation to systematically cultivate teachers' ability to integrate AR into routine teaching practices.

4.3 Exploring Sustainable Models for

Operating and Evaluating AR Teaching Resources

To ensure the long-term vitality of the AR educational ecosystem, it is essential to move beyond the short-term mindset of project-based procurement and explore operational models that balance economic sustainability with enduring educational impact. At the operational level, the closed "school procurement–manufacturer delivery" model struggles to accommodate rapid content updates and ongoing equipment maintenance demands. A viable approach involves integrating the concept of "open educational resources" with AR technology, encouraging educational institutions or academic alliances to fund the development of high-quality, foundational AR resource libraries under open licensing agreements. Schools and educators can then adapt and innovate these resources locally, reducing initial costs while fostering creativity. Additionally, hybrid models combining "subscription services" and "co-development partnerships" should be explored: schools may subscribe to annual professional services for widely-used, frequently updated AR content, while establishing long-term collaborations with tech firms for customized school-specific curricula—where schools provide instructional expertise and companies deliver technical solutions for joint development and sharing. Regarding evaluation, a comprehensive framework covering "investment–process–outcomes" is urgently needed, shifting focus from superficial metrics like "usage rates" or "satisfaction" to learning processes and deep competency development. Process-oriented assessments should leverage AR's data collection capabilities to analyze students' inquiry pathways, decision-making sequences, and collaborative dialogue quality—formative data that provides real-time feedback for instructional improvement. Outcomes-based evaluation requires more rigorous quasi-experimental designs or longitudinal tracking studies, focusing not only on short-term improvements in subject knowledge but also on the long-term impact of AR experiences on students' spatial thinking, problem-solving skills, and attitudes toward scientific inquiry. For example, a two-year tracking study can verify the sustained effects of AR teaching materials by comparing differences in complex system modeling abilities between experimental and control groups. Regular

feedback of evaluation results to operational decisions, forming a closed-loop process of "design-implementation-evaluation-optimization," is essential to transform AR teaching materials from impressive technological demonstrations into a sustainable infrastructure for enhancing educational quality through deep learning.

5. Conclusion

This study systematically examines and demonstrates that AR technology brings far more than mere formal innovations to educational materials; its deeper value lies in creating an "enhanced knowledge domain" that fosters deep understanding and contextualized learning. Empirical data shows that in disciplines such as science and engineering, AR-based teaching materials can improve knowledge application and transfer skills by an average of 12–15%, a benefit largely dependent on precise alignment between technological features and pedagogical principles. However, the research also highlights significant constraints on fully realizing this potential: persistent challenges in infrastructure investment, inadequate quality control within content ecosystems, and lagging teacher empowerment systems. For instance, nearly 40% of educational institutions have seen AR initiatives stall due to unsustainable costs for equipment upgrades and content maintenance. Existing fragmented technical solutions prove insufficient; a systematic ecosystem approach is imperative. Key future directions include establishing interdisciplinary and cross-departmental AR education standards to regulate development, ensure quality, and uphold ethical guidelines; designing tiered empowerment models based on teacher communities to transform technical training into pedagogical knowledge reproduction; and adopting sustainable operational models combining open resources with subscription services to maintain resource vitality and accessibility. Ultimately, the success of AR-based educational materials should not be measured solely by technological novelty, but rather by their ability to evolve into a widely accessible, effective support system for personalized learning, and a continuously evolving component of conventional educational infrastructure—all within a robust management framework. This requires researchers, practitioners, and policymakers to adopt a cautious yet proactive long-term perspective.

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