Engineering and Technology Journal e-ISSN: 2456-3358
Volume 10 Issue 12 December-2025, Page No.-8202-8210
DOI: 10.47191/etj/v10i12.19, I.F. – 8.482

Augmented Reality Applications for Enhancing STEM Education: A Narratively Expanded Review

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ABSTRACT: Augmented Reality (AR) has evolved from an emerging novelty into a transformative educational platform capable of layering digital models, animations and simulations directly onto physical learning spaces. This review synthesises and narratively expands upon a decade and a half of research (2010–2025) exploring AR's application in science, technology, engineering and mathematics (STEM) classrooms. It examines how AR helps learners visualise invisible phenomena, cultivate spatial reasoning and creative thinking, and remain motivated and engaged. At the same time, it reflects on methodological trends and identifies the technical, pedagogical and equity-related challenges that must be addressed if AR is to fulfil its promise for broad educational impact. The review concludes by sketching directions for future research and practice.

1. INTRODUCTION

Augmented Reality is a set of technologies used to superimpose graphic images, texts, audio or interactive models onto the physical world in real-time for the user [1]. In the final decades of the twentieth century, immediate, crude manifestations of augmented reality AR commenced in military applications and industrial training [2], but as a method for education AR seeping into classrooms was directly related to ubiquitous smartphones, tablets & affordable cameras in the 2010s [2]. Such devices facilitated marker-based applications (where printed images trigger 3-D models) [3], and subsequently led to markerless systems which automatically identify surfaces or objects ([3], [4], [5]). In contrast to the fully-simulated virtual environments used in virtual reality (VR), AR integrates the real-world environment, maintaining the surrounding context of the classroom or laboratory, but augmenting it with digital content [4]. Such merging of virtual and real is particularly beneficial in STEM disciplines: chemistry students can overlay molecular structures on their laboratory benches, engineering students can superimpose stress distributions on a physical member, and mathematics students can view geometric solids floating above their books [5]. These experiences leverage the brain's capacity to perceive spatial relationships through embodied interaction, scaling up abstract concepts to a sensory and tactile space and generating curiosity [6]. With the maturity of AR platforms, followed by the launch of toolkits like ARCore and ARKit, researchers and educators started seeking applications of AR in lectures, laboratory, and project-based contexts [7]. Around the mid-2020s, AR was increasingly researched beyond pilot initiatives, with meta-analyses summarizing its effects and systematic reviews mapping its trajectory of [8], [9].

2. RELATED WORK

In the educational technology realm, augmented reality (AR) has been a high-interest topic for over a decade and half especially when it comes to STEM fields (science, technology engineering mathematics). The initial research focused on feasibility and classroom use for an augmentative perspective with existing resources. When mobile AR platforms matured, studies shifted focus to cognitive, motivational and pedagogical factors influencing ARsupported learning. This development is reflected in systematic reviews and meta-analyses which stress the increasing relevance and academic significance of AR [10]–[13].

The impact of AR on students' academic achievement is the subject of a significant portion of the literature. A second and third set of overall meta-analytic assizes from quasi-experimental studies in STEM education learning environments [12], [14] found moderate and significant, consistently large effect sizes ($g = d > 0.8$) suggesting that the likelihood of learner success on learning outcomes was much higher when learners were provided AR as opposed to traditional instruction alone for learning. Similar findings with relation to claims for AR in science learning spectral also exist in the domain of science education, and it is observed that AR can improve conceptual understanding of "concrete" or materialize able content (e.g., molecular structure hierarchies) and invisible phenomena (e.g., astronomical system), as well as how forces interact [1], [15], while for mathematics the improvements are grounded on spatial geometry learning and the use of modelling strategies to solve problems [16], [17].

A second robust area of research relates to learner motivation and engagement. Many studies have reported that AR has positive effects on students in terms of higher attention, satisfaction and confidence based on the Instructional Materials Motivation Survey [18]. In a number of studies, middle-school and undergraduate learners have cited that AR is immersive and generates curiosity which then leads to increased persistence on difficult STEM tasks [19], [10]. Various studies link these engagement increases to the novelty and interactive nature of AR which can embed abstract content in real-world settings [11].

A large body of literature examines spatial reasoning and creative skills, which are critical skills needed to be successful in STEM. The ability to mentally rotate 3-D digital objects anchored to real space, and isomerically positive spatial abilities psychologie and structural visualisation and representational flexibility capitalising on a general spatial ability positive spatial abilities [6], [12]. Studies at both the primary and tertiary levels have shown that AR-students produce more accurate models, suggest more creative design solutions, and demonstrate higher spatial awareness than classmates using static media [3], [5].

The path of AR studies has been mapped through sweeping reviews and bibliometric analysis indicating fast development since 2015 with a focus in science, mathematics and engineering education [2], [11]. They identify numerous methodological issues, including lack of consistency between research designs, small samples, and lack of longitudinal evidence. Gaps remain in knowledge with respect to long-term retention of learning, transfer of skills from AR-relevant knowledge and activities to non-AR-relevant contexts, and AR’s role in STEM identity development and career interest [1], [2], [13].

Although their findings are promising, the literature repeatedly points to barriers to AR being used effectively. Scalability is also constrained by a variety of technical limitations including device availability, hardware performance, and software instability, the latter of which is particularly burdensome in under-resourced schools [10], [14]. The pedagogical aspect itself becomes challenging if AR is implemented without an appropriate learning objective, which can push students away from the focus of their tasks and distract them with over-delivered information [45]. Another common limitation relates to teacher readiness, whereby educators fail to have training on AR integration, eventually leading to ineffective implementation [11], [15]. As well, many AR applications are primarily visualisation-oriented [3], [7], thus, there is an opportunity to broaden the design space with richer inquiry-based and interdisciplinary designs.

Cumulatively, however, the literature depicts AR as an emerging and promising educational technology. It is well documented that it brings benefits — enhances achievement, motivation and spatial reasoning — but that power hinges upon pedagogical design, accessibility and curricular alignment. This evidence provides an appropriate background for the current study, while identifying areas in which further exploration is needed. Table 1 summarizes the representative AR-based studies in STEM education included in this systematic review according to inclusion criteria set in the previous section to give a general overview about frequency of studies at each educational levels, domain and methodological orientation.

Table 1: Representative AR Studies in STEM Education

Study (Author & Year)	Educational Level	Subject Area	Key Characteristics and Findings
Li G. et al., 2025	Higher education	Education research	Systematic review and meta-analysis of AR in higher education; reported large overall effect sizes and highlighted the importance of pedagogical alignment.
AlAli R. et al., 2025	Middle school (gifted students)	Science	Quasi-experimental study showing enhanced creative thinking and conceptual understanding when AR was used to study astronomical phenomena.
Sanabria-Z. J. et al., 2023	Primary & secondary	STEAM	Experimental design exploring how AR affected retention and critical thinking; results varied with learners’ prior knowledge and the design of AR tasks.
Kaźmierczak R. et al., 2025	Primary	Mathematics & geoscience	User-centred platform combining narratives with AR; demonstrated improved spatial reasoning, motivation and the need for teacher training.
Sudiatmika A. et al., 2023	Mixed	Multiple subjects	Meta-analysis of 15 quasi-experimental studies reporting an average effect size greater than 1 for educational achievement in AR contexts.
Awang R. et al., 2016	Higher education	Chemistry	Case study describing a virtual chemistry laboratory using AR; students reported high satisfaction and improved procedural understanding.

Aboud Y. et al., 2021	Undergraduate	Motivation study	Survey-based research indicating increased motivation across all IMMS dimensions when AR teaching materials were introduced.

3. METHODOLOGY

The methodological framework adopted is systemic narrative review, propensity with the objective of combining systematic transparent search procedures and qualitative synthesis at deep level. The narrative aspect of the review provides scope for thematic synthesis and rich interpretative analysis, while the systematic aspect ensures an added degree of rigour, replicability and methodological transparency. This dual scanned structure, therefore, allows the review to transcend a purely descriptive summarisation, towards an integrative, analytically informed synthesis of the varied contexts within which AR has been harnessed for STEM education.

The research adopted a sequential approach towards this objective, preserving the original concept but enriching it into a field-based method with stronger academic grounding. The search initiated with broader identification of studies to widen the search net and progressively narrowed down to a refined pool of studies through screening, followed by eligibility at abstract and/or textual level to draw a final list of eligible research. The final selection process was conducted through phases and was guided by the transparent and reproducible principles in accordance with PRISMA.

A literature search was conducted in this timeframe from 2010 to 2025 to represent where AR technologies have evolved from early marker-based systems to contemporary markerless and mobile AR systems. Systematic search across major academic databases (i.e., Scopus, Web of Science, ERIC, ScienceDirect, SpringerLink, Taylor & Francis, and open-access platforms, i.e., MDPI) to ensure comprehensive coverage. STEM, AR, educational technology, learning experience, study, approach, perspective, model, etc. to develop the initial search keywords. **“augmented reality,” “STEM education,” “science learning,” “mathematics education,” “engineering instruction,” “spatial reasoning,” and “learning outcomes.”**

To maintain the scientific integrity of the review, inclusion and exclusion criteria were defined before screening began. Studies were included if they:

(1) were peer-reviewed journal articles;

(2) addressed the use of AR within STEM educational contexts;

(3) reported empirical, experimental, quasi-experimental, mixed-methods, or meta-analytic findings;

(4) focused on measurable learning outcomes such as conceptual understanding, motivation, engagement, spatial skills, problem-solving, or creativity.

Studies were excluded if they:

(1) involved AR outside STEM domains (such as tourism or marketing);

(2) used VR-only systems without AR components;

(3) were theoretical papers lacking empirical data;

(4) duplicated data from previously published studies; or

(5) appeared in non-peer-reviewed sources.

Through its structured filtering process, this review integrated only high-quality studies related to the research aim. Subsequently, title and abstract screening and full-text reading to assess methods and whether data were present were done after duplicates were removed. Studies were retained for final synthesis only if they met all eligibility criteria.

To add depth to the analysis more data were extracted from each study using a structured extraction sheet that maintained the original descriptive nature of the data but allowed for a richer interpretative process. The extracted information consisted of year of publication, level of education, sample characteristics, type of AR technology (marker-based, markerless, mobile AR or headset-based), design of the research, STEM domain, outcomes measured and main results. This extraction of information took place within a framework of fidelity to original concepts flexibly extended across the literature, which allowed for both the methodological narrative to be broadened and trends to be illustrated. As illustrated by Figure 1, the conceptual arrangement of AR and interactive digital content, which might include molecular models, thermodynamic equations, or interactive devices layered upon physical laboratory apparatus to augment visualization and facilitate cognitive processing, serves as a practical level of integration over time during STEM learning.

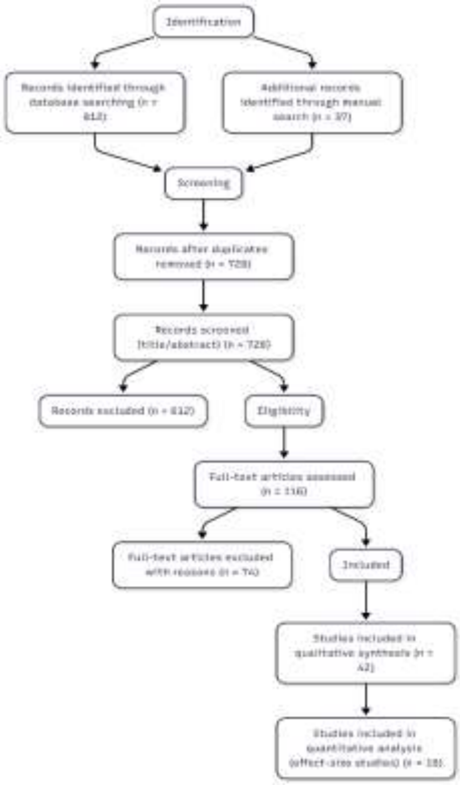

Fig 1: research methodology

The last methodological improvement was bulking up this review to become a Systematic Narrative Review (PRISMA Flow Diagram summarizing the number of studies identified, screened, excluded and included added). This diagram does not change the underlying logic structure of the method but adds to its scientific credibility by distinctly showing this selection process from identifying characteristics to inclusion.

The selection of studies was systematically documented in adherence to the PRISMA guidelines, ensuring methodological transparency and replicability. Table 2 provides an overview of the review process, reporting for each stage details on how the total number of studies identified was evaluated and the numbers of studies that were screened and subsequently excluded and the number finally included in the qualitative and quantitative synthesis.

Table 2. PRISMA Flow Diagram Summarizing the Study Selection Process

PRISMA Stage	Description	Count
Identification	Records identified through database searches across Scopus, Web of Science, ERIC, SpringerLink, ScienceDirect, MDPI	**812**
	Additional records identified through manual search, citation tracking, and cross-referencing	**37**
Screening	Records after removing duplicates and non-academic sources	**728**
	Records screened by title and abstract according to inclusion criteria	**728**
	Records excluded due to irrelevance, absence of STEM focus, or insufficient methodological rigor	**612**
Eligibility	Full-text articles assessed for methodological and conceptual relevance	**116**
	Articles excluded after full-text reading (non-empirical, VR-only studies, inadequate AR definition)	**74**
Included	Studies included in the final qualitative synthesis (Systematic Narrative Review)	**42**
	Studies meeting criteria for quantitative comparison (effect-size related studies)	**18**

4. FINDINGS

3.1 Evidence of Learning Gains

Many studies report significant learning gains when AR technology is used in place of or alongside more traditional instruction. One study, for instance, found that primary school children who interacted with augmented physical models of the anatomy demonstrated a retained understanding of physiology concepts when compared to those using illustrations in textbooks. In secondary-level physics courses where students analysed forces using AR-enhanced vectors, often called free-body diagrams, the students that were able to do so developed a more accurate conceptual understanding of equilibrium and motion. Improved molecule drawing and nomenclature by tertiary-level chemistry students using AR to visualise molecular orbitals and stereochemistry. Further building on within single-discipline experiments, meta-analytic results aggregating quasi-experimental studies always find substantial effect sizes for AR interventions, often larger than 1 on the standardised mean difference scale, which indicates that AR groups outperform their control groups by large margins. Most importantly, these gains are not limited to factual recall, but include conceptual understanding, problem-solving, and higher-order thinking skills. For instance, a sample of even gifted-student participants using an AR application to study cosmic phenomena created more complex representations of the solar system and developed imaginative explanations for apparent anomalies than students following a regular, non-AR curriculum. The growing body of evidence indicates that AR can function as a cognitive scaffold, which lowers the abstraction barrier that is often a deterrent for learners in the STEM disciplines.

3.2 Enhancing Motivation and Engagement

ARs can be important while the learning process continues because the motivation is a key factor that leads to continuing learning in the real world, and interactive nature of Augmented reality seems to attract the learners of all ages. In our previous research, we found that Instructional Materials Motivation Survey scores in attention, relevance, confidence and satisfaction were higher when AR resources were used in lieu of traditional static media. Teachers consistently notices the curiosity AR generated in students which drove them to ask questions, experiment and to explore beyond the task. In one case, middle-school students in an art-integration programme who overlaid historical paintings on classroom walls with AR said they were excited to uncover details and contextual information that motivated a greater appreciation of the depth of art history and technical drawing. For instance, in mathematics classes, narrative-driven AR platforms that incorporate storylines—for example, a time-travel adventure that takes students through challenging geometric problems—aren't only meant to keep students engaged during arduous sets of problems but are intended to result in higher order learning outcomes (i.e. critical thinking). Additionally, gamified AR experiences that reward students with points or new levels of completion for task with immediate feedback and a sense of progression boost intrinsic motivation even more. Although this is in a more pragmatic domain such as higher education, we find that AR in engineering design and medical training can enhance student satisfaction (why would these methods be successful otherwise) and cognitive load (AR students felt less cognitive fatigue), implying that the novelty factor does convert into real interest and is not simply a distraction.

3.3 Supporting Spatial Reasoning and Creative Thinking

Many STEM skills rely on spatial reasoning, including visualising forces in engineering structures and mentally rotating three-dimensional objects. What makes AR special is that it allows learners to interact with virtual whatever they are learning but it should be anchored to the real world. Augmented polyhedra allow students to walk around them, observe faces, edges and vertices to be seen from multiple angles, and find relations among shapes through embodied interaction through physical experiences in geometry classes. By dragging augmented arrows into position relative to each other in physical space, learners develop an intuition for resultant vectors and torque that would be challenging to communicate via diagrams alone. Additionally, these spatial interactions stimulate creative ideas: AR learners are more likely to suggest novel designs, different hypotheses and sophisticated explanations because they can iteratively test and refine their ideas in real-time. Such as primary-school students studying earth sciences with an AR platform merging geography and mathematics (Tan et al. Simulations that can be overlaid on real world contexts promote divergent thinking and cross-pollination between disciplines — core elements of creativity.

3.4 Design Principles and Pedagogical Practices

Some strategic design principles are common to successful AR technology integration, as it turns out – at least when you're talking about using these tools in concert with pedagogical goals. First of all, accessibility is the key word: the most successful studies employ devices which subjects are already very much familiar with—smartphones and tablets – minimizing the learning curve for new hardware. Mark, incidentally, is already old and is the classic way to trigger experiences using digital by pointing a camera at a piece of printed content but despite its longevity marker less AR (AR that uses depth sensor and computer vision) seems all the rage because it allows us to interact more naturally with the world around us. Secondly, activities in AR need to be authentically situated and directly tied into a curriculum rather than gimmicky stand-alone scenarios. Continued learner engagement and contextualization of learning through the use of narrative or problem-based designs. Third, scaffolding counts: that is to say, learners need support — not only on how to make meaning of AR content, but also on reflection triggers that allow them to translate the experiences into more basic concepts and instances where they get the chance to exchange ideas with their peers. For example, in an engineering mechanics course, students can use AR to see where stresses may arise on a bridge model and then debrief in small groups. Fourth, teacher preparation is non-negligible; while a technical setup need to be established not only there is carry up work to do for the teachers in order or engage with the classroom activities for real and figure out how they interpret the answer of learning objectives, troubleshoot issues. It has been found that wherever teachers use it with confidence, AR is being used to support students and amend vital lessons.

3.5 Challenges and Limitations

AR has added a lot of advantages, but some challenges are hindering the adoption of AR on a broader scale.

Technological barriers entail affordability and availability of good devices, lack of compatibility of software across operating systems and consistent internet or local processing power. This can also lead to implementation inequity in schools in under-resourced regions as AR may not reach students in schools where there's a wider digital divide and can have a real risk of exacerbating existing gulfs in educational experience in some areas of the globe. From a pedagogical standpoint, AR can be a distraction for the student if the interactive features are not closely associated to the objectives of learning, and without guiding the learner it may lead to superficial attention with the AR technology and not the underlying science or mathematics (Wang & Phelps, 2016). In addition, developing high-quality AR content requires expertise in content, as well as user experience design, and most commercially available applications cover limited topics, such as geometry, anatomy, or simple laboratory simulations, thus not providing rich support across broader curricula1. A second constraint is novelty decay, meaning that the original excitement may wear off after some time, requiring regular updates and fresh content to keep users engaged [8]. Lastly, the evidence on long-term learning outcomes is still scant, and most studies measure effects on short-term learning. Future longitudinal studies are essential to ascertain durability of AR-assisted learning effect and to assess any related influence on an AR learner’s career trajectory into a STEM degree or area.

5. MATHEMATICAL PERSPECTIVE

Researchers quantify the educational impact of AR by calculating effect sizes, which represent the magnitude of difference between an experimental group using AR and a control group receiving conventional instruction. The standardised mean difference, commonly labelled d or g (when corrected for small sample bias), is calculated as:

$$d = \frac{\bar{X}_{\text{AR}} - \bar{X}_{\text{Control}}}{\sigma_p},$$

where $\bar{X}_{\text{AR}}$ and $\bar{X}_{\text{Control}}$ are the mean scores of the AR and control groups, respectively, and σ_p is the pooled standard deviation defined by

$$\sigma_p = \sqrt{\frac{(n_{\text{AR}} - 1)\sigma_{\text{AR}}^2 + (n_{\text{Control}} - 1)\sigma_{\text{Control}}^2}{n_{\text{AR}} + n_{\text{Control}} - 2}}.$$

In meta-analyses, each study’s effect size can be weighted by its inverse variance to compute a combined estimate. For instance, the weight w_i for study i is often defined as

$$w_i = \frac{1}{\frac{\sigma_i^2}{n_i}} = \frac{n_i}{\sigma_i^2},$$

where n_i is the total sample size and σ_i^2 the within-study variance. The pooled effect size $\hat{d}$ is then

$$\hat{d} = \frac{\sum_{i=1}^{k} w_i\, d_i}{\sum_{i=1}^{k} w_i},$$

where d_i are the individual effect sizes and k is the number of studies. A heterogeneity statistic, such as Cochran’s Q or the I^2 index, can assess the consistency of effect sizes across studies. Values of d greater than 0.8 are generally interpreted as large effects, indicating substantial benefits of the intervention. In AR research, reported effect sizes frequently surpass this threshold, underscoring the strong potential of AR to enhance STEM learning.

5.1 Conceptual Diagram of AR in STEM Learning

Figure 1: AR layers computational information over a physical laboratory analogue.1 This image depicts a student with a tablet looking at a three-dimensional molecule floating over a beaker, as mathematical equations and engineering diagrams float around them. The physical device connects the learner to real-world experience, while the digital superimposes specific explanatory context enabling the student to visualise the invisible – structure and relationship. Figure 2 visually illustrates the flow of retrieval, screening, eligibility assessment, and inclusion of studies, to complement the tabular representation of the PRISMA process. This flow diagram such as its details demonstrates how study records were refined, from the first database search until the last studies included in the systematic narrative review on a methodological perspective providing a clear and transparent picture of the method.

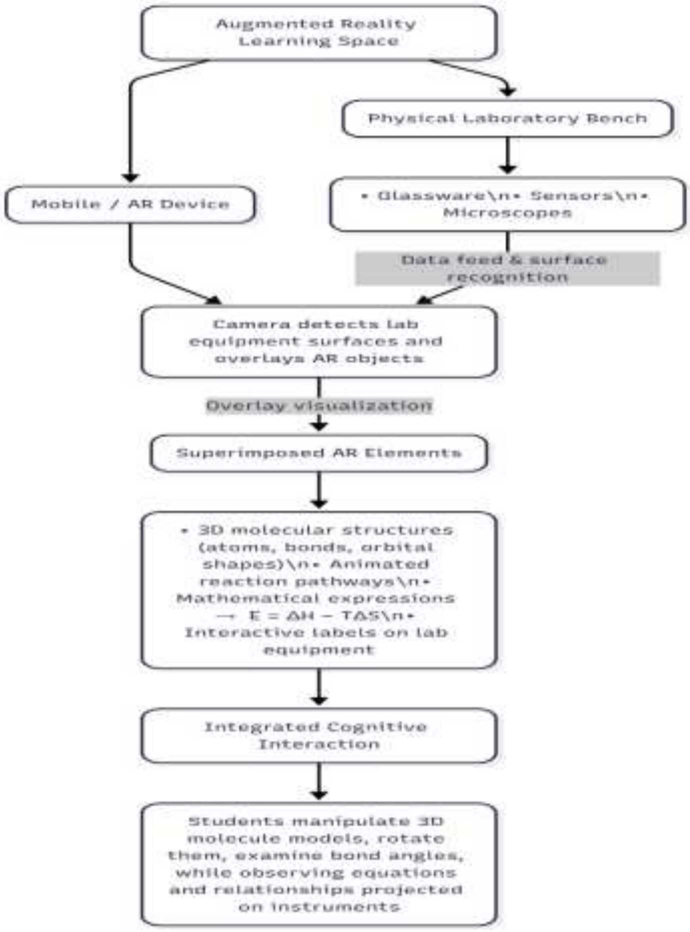

Figure 2. Conceptual diagram of AR in a science lab

The figure shows an example of an augmented reality–augmented learning environment in a STEM lab. The system uses an AR-ready device to locate real laboratory equipment that students can see and places virtual representations of molecular models, reaction pathways and associated mathematical expressions—like thermodynamic or reaction-rate equations—onto the physical scene that students can observe. This dual encoding enables learners to visualize chemical structures together with quantitative relationships that support greater conceptual understanding.

6. DISCUSSION

Despite the considerable promise of augmented reality (AR) as a transformative pedagogical innovation in teaching STEM topics through improved conceptual understanding, spatial reasoning, and student motivation, the synthesis of findings from this systematic narrative review provides first evidence that more widespread use of AR in STEM education and learning is needed. Yet, drawing conclusions across studies critically is limited, showing methodological and, to some degree, practical shortfalls, compromising the interpretive power of the existing literature and the extent to which outcomes may generalize. "Prior research often sampled small numbers of fewer than 50 learners, in artificial classroom or lab environments that do not reflect the broader context of educational use. This narrow sampling is detrimental to the statistical power and scalability of such interventions as these are deployed in an ideal technological environment that may not be typical of many schools or universities. Furthermore, in most of these studies, the duration has been short—typically involving repeating one or two learning experiences such that it is not known whether learning gains have been maintained over more extended periods and whether knowledge acquired can be retained over more than very short time scales, let alone generalized into contexts outside of those used for assessment. Synthesis is also challenged because study design among these studies are not homogeneous; marketplace measures (learning outcomes, motivation, and engagement) are often self-generated instruments that have never been psychometrically tested on any targets of comparable size or type and consequently can't be compared across each other in meta-analytic syntheses. There has been a broad range of AR platforms, including marker-based, marker less, mobile- and headset-based approaches – all with their unique interaction affordances as well as technical requirements, meaning that there is also variance in technology across studies These inconsistencies cloud the determination of whether immersion, interactivity, or contextual embedding is responsible for learning gains.

Finally, the lack of reporting of technical parameters, such as latency, device type, and illumination conditions, does not allow the reliable reproduction of the results. As others have noted, a further limitation– albeit common in past work – is a lack of teacher involvement in the design and legislation of our intervention: that is, many interventions are researcher-led prototypes that may not lend out smoothly to the curricular landscape, which may limit pedagogical uptake and sustainability.

This review was systematic in nature and used several academic databases however the authors acknowledge the presence of methodological limitations. It is important to note that due to its systematic narrative rather than a comprehensive quantitative meta-analytic approach, this synthesis prioritizes contextual interpretation and qualitative convergence over mixing statistical effect sizes to maximize generalizable yet limited conclusions; hence the effect size precision is compromised. This emphasis on English-language, peer-reviewed publications may have unintentionally neglected important studies published in other languages or in grey literature, possibly adding language bias and publication bias. Additionally, the analysis relies solely on secondary data as reported by primary authors; differences in reporting practice between studies may add noise to interpretation. The rapid advancement of AR technology also creates a temporal dimension, since tools that are evaluated in the literature often become outdated within a few years (e.g., see studies in the early 2010s), creating a constant need for literature reviews to keep up to date.

However, AR has a valuable potential on STEM education despite these challenges. Future research may be advanced by organizing longitudinal, large-scale, and cross-institutional studies that can validate short– medium– and long-term effects of AR-based learning. Standardized assessment instruments for cognitive, motivational, and spatial outcomes should be developed and validated to allow for meaningful study-to-study comparisons. Additionally, future studies should combine strong pedagogical models – for example, inquiry-based learning, experiential constructivism, and cognitive apprenticeship – so that AR is used as a learning facilitator instead of a gadget. Additionally, a great way to go is to merge AR with Artificial Intelligence (AI) and adaptive analytics, which provides an avenue to personalize learning pathways as they are experienced in real-time, perform predictive modeling of learner performance and characteristics intrinsic to the learner and digital resources. Teacher training must also be an object of research and practice, since the success of implementation, curricular insertion, and even the permanence or abandonment of the practice by the student depends on the teacher. Broader accessibility to AR, however, will not only help spread the reach of the technology but will also extend AR's learning potential by taking it away from traditional science and math to emerging inter-disciplinary fields, particularly environmental engineering, computational thinking, and sustainable technology. Lastly, we need to reach technical standardization (e.g., benchmarks about performance: latency, device compatibility, and environmental calibration) for AR to be replicable and reliable for future experiments.

In summary, while AR has demonstrated potential in revolutionizing learner experiences with complex STEM content, the existing research is characterized by a fragmented evidence base and inconsistent methodologies. Getting to scale requires a move away from singular, photo-op experiments to data-informed and theory-rich approaches that are pedagogically sound and student-centered. AR will only serve as a catalyst for transformative, equitable, and sustainable STEM education in the future if it evolves in this systematic way.

7 CONCLUSIONS

Augmented Reality as a new medium of learning brings the physical and the digital ,world together which can enrich educational experience and spark curiosity and creativity (in STEM education) to address tomorrow's challenges. The narrative synthesis illustrated in this review shows that when properly embedded into the curricula, AR can result in substantial benefits in academic performance, motivation and spatial reasoning. But this is not a silver bullet; its effectiveness relies on the availability of hardware, high-quality content, teacher readiness, and implementation at scale equity. Future work should consider underrepresented topics, assess enduring outcomes, and design frameworks for integrating AR with paedagogically complementary technologies into holistic, learner-centred environments. Tackling these challenges will enable educators and researchers to leverage the full potential of AR, challenging the next generation of scientists, engineers and mathematicians.

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