Title	Examining the use of emerging technologies in schools: A review of artificial intelligence and immersive technologies in STEM education
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Abstract

While justifications have been made for emerging technologies' transformative potential in STEM education, the roadmap for their eventual implementation in schools is underexplored. To this end, we review research works in artificial intelligence (AI) and immersive technologies which have been applied to facilitate STEM learning. Through a systematic literature search, we identified 82 papers and analysed them for three aspects – (1) types of emerging technologies used, (2) science education goals, and (3) implementation value. Our findings indicate that augmented reality and natural language processing are common technologies used to enhance students' learning experiences. These technologies helped students build conceptual understanding as well as epistemic practices in science. On the other hand, mixed reality and computer vision were the least popular technologies, which may be indicative of the low maturity of these technologies. Of all the science education goals, social aspects were the least commonly tackled through emerging technologies. Moreover, 58.9% of technological applications transformed science teaching and learning through automated ways of providing individualised feedback to students involved in argumentation and reasoning activities. Finally, based on our findings, we derive three research agenda that we believe would further the eventual implementation of emerging technologies in schools.

Keywords: STEM Education, Emerging Technologies, Science Practices

Introduction

We live in a unique era of human history whereby cycles of technological innovations are much shorter than the average human lifespan. Throughout our ancestors' lives, they experienced little to no fundamental change to the way they live or work. By contrast, modern day humans often find themselves having to adapt to the use of new technology from time to time. The same parallel can be drawn for our education systems. Previous generations of teachers most likely experience a similar classroom setup as their students with little to no change (Gardner, 2006). However, in today's context, discussions of how the next wave of emerging technologies will fundamentally alter teaching and learning commonly appear in journal articles and academic reports (Pelletier et al., 2022; Spector, 2013).

On the surface, the fast-paced development of new technologies that can help address educational issues seems like a blessing, but this deluge of new technologies presents an unexpected conundrum for educators in reality. To begin with, the incorporation of any new technology into an existing curriculum requires substantial reworking and attention to detail. Also, teachers need to be adequately trained to be able to use these new technologies in classrooms effectively. As well, the deployment of new technologies might require infrastructure or resources that schools lack. Therefore, given the significant amount of investment in effort and resources in deploying a new technology, it is impractical for educators to adopt every piece of emerging technology that comes with every wave of technological innovation. With this in mind, this review aims to examine the use of emerging technologies in schools to deepen our understanding of how emerging technologies can be deployed, unpack the educational role of emerging technologies, and understand the inherent value that emerging technologies bring in transforming teaching and learning.

This paper is organised as follows. To scope this review, we would only be considering the use of artificial intelligence (AI) and immersive technologies in STEM education. The theoretical background section leverages theoretical work accomplished previously to explicate our understanding of STEM learning and emerging technologies. This derived understanding then frames our review - setting our scope for the paper, influencing our search protocol used, and shaping our analysis approach taken. In particular, to carry out this review, we analysed collected papers in three aspects: (1) types of emerging technologies used, (2) science education goals, and (3) implementation values of technology. The methods section gives a detailed description of our search protocol for papers, inclusion and exclusion criteria, and analysis approach. In total, two research questions guided our review: (1) *What AI and immersive technologies have been used for the teaching and learning of STEM to advance its educational goals?* (2) *Where does the implementation value of AI and immersive technologies in STEM education lie?* Lastly, the results section shares the key results of our review while the discussion section provides an in-depth discussion of the implications of our findings, including the limitations of this work.

Theoretical background

This section leverages theoretical work accomplished previously to explicate our understanding of STEM learning and emerging technologies. Specifically, the STEM learning subsection dissects the acronym STEM and discusses frameworks for STEM education goals and implementation value of emerging technologies to set the stage for our search protocol and analysis approach. The emerging technologies subsection elaborates on our literature search for a working definition of emerging technologies, which ultimately affects our choice of emerging technologies for this review.

STEM learning

The acronym STEM was coined by the National Science Foundation (NSF) for the ease of referring to the four disciplines of Science, Technology, Engineering, and Mathematics (Bybee, 2013). The term STEM has been used in varied ways for different purposes. For some, STEM is used to refer to educational outcomes related to any one of the four disciplines while others argue STEM must involve some forms of integration between at least two disciplines (Kelley & Knowles, 2016). For this review, we take an inclusive perspective of STEM to consider learning either within a single STEM subject or integration between two or more disciplines. Specifically, we focus on linking scientific inquiry, by formulating questions that can be answered through investigation to inform the students before they engage in engineering processes to solve the problems (Kennedy & Odell, 2014). As such, our eventual search protocol only included STEM education as a keyword instead of using individual keywords of science, technology, engineering, and mathematics.

To distil STEM education goals for our first research question, we adopted the framework by Kelly and Licona (2015) that considers the conceptual, epistemic, and social aspects of inquiry within disciplines of learning. The defining disciplinary features of STEM inquiry include (1) an emphasis on empirical evidence, (2) explanations that are crafted based on available evidence, and (3) multi-modal ways of representing scientific knowledge and solutions. These disciplinary practices suggest that students and teachers need to be familiar with and proficient in the use of various technologies to gather evidence. Furthermore, the use of graphical, pictorial, and textual representations in STEM suggests the potential of using technology to enhance ways of representing knowledge. As such, it would be interesting to examine the range of emerging technologies that could be deployed in STEM education and establish how each application of emerging technology fulfils the conceptual, epistemic, and social aspects of inquiry.

To extract the implementation value of emerging technologies for our second research question, we considered strategies that are currently used in science teaching and learning and compared them to parallel strategies that harness emerging technologies. We studied how the inclusion of technology enhanced learning and understanding of scientific concepts by asking ourselves how the students' learning experiences would have changed if the concerned technology was removed. If students still manage to learn the concepts holistically without technology, then we consider the implementation value of the concerned technology to be "do things better". If the removal of technology resulted in incomplete or sub-standard learning experiences for students, then the concerned technology is considered "do better things". Examples of "do things better" and "do better things" are further described in the implementation values subsection, and a discussion of other similar frameworks that we have contemplated for the implementation value of emerging technologies can be found in the coding process subsection.

Emerging Technologies

To better concretise our discussion of emerging technologies and to define the scope for this review, we first attempt to define the term *emerging technologies*. Our search into the literature uncovered a few observations: 1) the term *emerging technologies* has been widely used but often carries different meanings, 2) few researchers delved into the characterisation of emerging technologies, and 3) some organisations have been providing periodic updates of which technologies are considered as emerging. In the following paragraphs, we elaborate on each of these observations before describing our justifications for selecting AI and immersive technologies as the emerging technology focus for this review.

Our first observation stems from the fact that the term *emerging technologies* has been used by different authors to not only highlight different types of technologies, but also to attribute different roles and importance. Much of these noted differences can be explained by differences in time periods. For instance, in 2007, Krusberg described the use of "Physlet Physics, the Andes Intelligent Tutoring System (ITS), and Microcomputer-Based Laboratory (MBL)

Tools" (Krusberg, 2007, p. 401) as emerging technologies. Fifteen years on, in 2021, Ustun listed eleven different emerging technologies ranging from social networks, augmented and virtual reality, affective computing, natural user interface, mobile learning and so on. Comparing the two, it is clear that the list of emerging technologies has expanded over the last 15 years. In addition, Ustun (2021) described more diverse applications for the use of emerging technologies and attributed greater importance to the role of emerging technologies in MOOCs as learning in higher education becomes increasingly global and virtual. Therefore, beyond superficial changes in the types of emerging technologies discussed, the authors conveyed different meanings (such as level of importance) when they use the term *emerging technologies*.

Given the fluid nature of emerging technologies, it is unsurprising that only a handful of researchers discussed potential definitions or characteristics of emerging technologies. Some researchers, such as Haag et al. (1998), chose to describe the characteristics of emerging technologies by dividing them into four distinct but interrelated groups: emerging technologies for senses, internet explosion, wireless revolution, and personal life. Other researchers, such as Veletsianos (2010), explicated a list of different characteristics for emerging technologies but surmised the anchoring criterion of emerging technologies as technologies that are still in an evolving state of change - either in technical development or related applications. In other words, "newness" in technical development is not the sole criterion for emerging technology as there could be "older" technologies that have evolving new applications that are not yet fully researched. For example, virtual reality (VR) technologies have been reported in the 1990s (e.g., Dede, 1996), but new applications in education and continuing research are still evolving. Consequently, Veletsianos (2010) provided us with a concise working definition of emerging technologies as:

> tools, concepts, innovations, and advancements utilised in diverse educational settings (including distance, face-to-face, and hybrid forms of education) to serve varied education-related purposes (e.g., instructional, social, and organisational goals) (pp. 12-13)

To address the issue of changing emerging technologies from different time periods, a number of organisations published compiled reports of emerging technologies to inform the field. For example, the Horizon Report is an annual report by EDUCAUSE and the New Media Consortium (NMC) on the key trends of emerging technologies. On occasion, special reports, such as the Renaissance Computing Institute (RENCI)'s 2015 white paper on 10 emerging technologies for higher education, receive circulation. Ultimately, these compiled reports provide us with a snapshot of the emerging technologies of the day and give us a trend-like understanding of the development of emerging technologies.

Overall, the above observations underscore the fact that there exists no definite list of emerging technologies, and that emerging technologies may evolve according to different time periods and leading opinions. This vague understanding of emerging technologies posed many challenges for us when identifying relevant articles for review. For instance, many studies do not even use the term *emerging technology* in their title or abstract, which renders such keyword searches futile. Nonetheless, we managed to overcome this issue by first relying on compiled reports on emerging technologies. For instance, the 2022 Horizon Report cites AI for learning analytics, AI for Learning Tools, Hybrid Learning Spaces, Mainstreaming Hybrid/Remote Learning Modes, Microcredentials and Professional Development for Hybrid/Remote Learning as emerging technologies. This offered us a first clue that AI and immersive technologies could be the next wave of emerging technologies since the use of AI is cited in two domains and a number of hybrid/remote spaces involve immersive technologies. Next, we searched for STEM education papers with technology tags and discovered that there is increasing research on the use of AI and immersive technologies within the last five years. Finally, examining the definition of emerging technologies provided by Veletsianos (2010), we see that AI and immersive technologies could be "utilised in diverse educational settings to serve varied education-related purposes". Thus, AI and immersive technologies were selected to be the emerging technologies for this review.

Methods

Search Procedure

In searching for papers needed for this review, we followed the guidelines as set out in the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) framework (Liberati et al., 2009). Doing so allowed us to identify relevant papers in a methodical and principled manner (see Figure 1). Using EBSCOhost, three relevant databases were selected for our paper search - Academic Search Premier, Education Source, and Education Resource

Information Center (ERIC). Since the focus of this review is on AI and immersive technologies (as highlighted in the emerging technologies subsection), we used a dual keyword search approach to look for papers that involved research in STEM education and a subcategory of either AI or immersive technologies. The search combinations of dual keywords used include “STEM Education AND Artificial Intelligence”, “STEM Education AND Computer Vision”, “STEM Education AND Natural Language Processing OR NLP”, “STEM Education AND machine learning OR deep learning OR neural network”, “STEM Education AND Augmented Reality”, “STEM Education AND Virtual Reality” and “STEM Education AND Mixed Reality”. We did not specify specific years in our search as we wanted to surface all uncovered research publications in the databases. This is because our analysis focused on emerging technologies used and does not relate to when the papers were published. Moreover, once the papers emerged, we further reviewed their year of publication and found that only a small proportion of papers were of age (see results section).

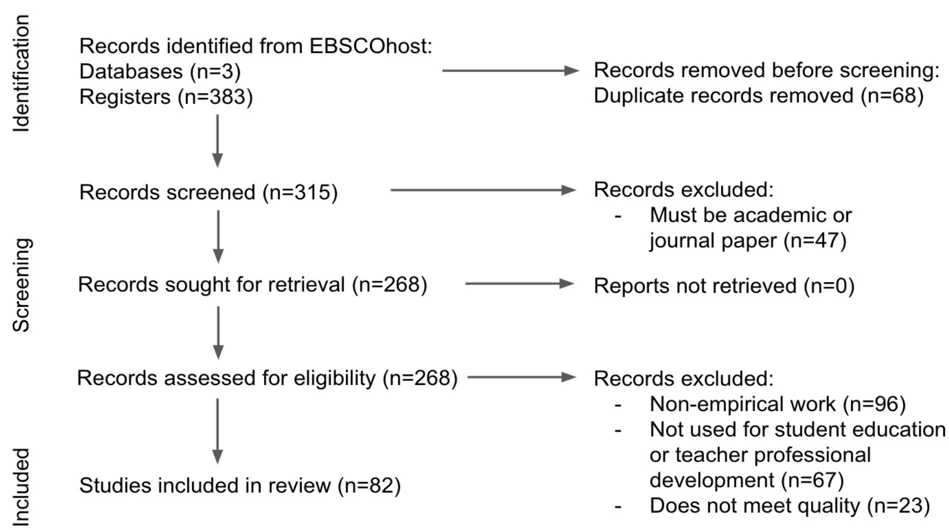

Figure 1. PRISMA flow chart depicting the process of selecting papers for review

Selection Criteria

Our initial keyword search yielded 383 papers in total. After removing duplicate records (n=68) and excluding papers that are neither academic nor journal papers (n=47), we are left with 268 papers that we assessed for eligibility for inclusion. The first inclusion criterion is that the paper must involve empirical work. This is because we are interested in the eventual practical implementation of the stated emerging technology within schools. Therefore, we would only consider works that are of an empirical nature and exclude others such as reviews, commentaries, and opinion pieces (n=96). The next inclusion criterion is that the concerned emerging technology must be used for either student education or teacher professional development. Once again, this criterion exists because of our prior interest in using emerging technology to support teaching and learning in classrooms. Papers that do not meet this criterion include the use of emerging technology as a research method, the showcase of emerging technology as a tool, or the learning of emerging technology as a content area. Lastly, we conducted a quality check to ensure that the reviewed papers represented quality research work. Questions that we asked during the quality check include: Are the research methods described in sufficient detail? Is the data provided adequate to support the stated claims? For example, the research methods ought to minimally include demographic details of the participants (such as sample size and education level), a breakdown of the data collection process (including the instruments used and frequency of data collection), and an account of the analysis approach (with ample information for replication by another researcher). For quantitative studies, we rely on the sample size to determine if adequate data exists to support the stated claims. On the other hand, for qualitative studies, we rely on the coding process and the number of coders to arrive at our judgement.

Coding Process

After tracking down the needed papers for review, we did two levels of analysis. Firstly, we examined the years in which the papers were published and if the selected papers focused on the use of emerging technologies in K-12 education, higher education, or both. Secondly, we analysed the papers for three aspects – (1) types of emerging technologies used, (2) science education goals, and (3) implementation value of technology. Knowing the types of emerging technologies used provides us with a landscape view of the current usage of emerging technologies and addresses the first portion of our first research question directly - What AI and immersive technologies have been used for the teaching and learning of STEM? Classifying the targeted science education goal by the emerging technology gives us a preliminary understanding of the scenario in which deploying the said emerging technology might be useful and addresses the second portion of our first research question - How has the proposed use of AI and immersive technologies in STEM education advanced its educational goals? Finally, studying the implementation value of technology allows us to reveal the underlying motivation in using the concerned emerging technology in classrooms and addresses our second research question – Where does the implementation value of AI and immersive technologies in STEM education lie?

The coding process involved all authors of this review. The initial stages began with extensive discussions on the relevant codes required for this work and their represented meanings. Debate persisted over the type of coding scheme to be used and the level of code granularity. For instance, a number of potential coding schemes existed for analysing the implementation value of technology such as those expounded by Kirkwood and Price (2016) and Puentedura (2013). While Puentedura (2013)'s Substitution, Augmentation, Modification, and Redefinition (SAMR) model provides a finer classification of implementation value, the distinction between each level proved too subtle for our purpose. In the end, we adopted Kirkwood and Price (2016)'s basic distinction of 'doing things better' and 'doing better things'. Throughout the discussion process, paper samples were pulled out for trial coding and examples were selected to elucidate the represented meanings of various codes. Table 1 details the finalised codes and their represented meanings.

Table 1. Final coding scheme used for this review.

Codes	Represented Meaning
Types of emerging technologies used	
Computer Vision (Khan & Al-Habsi, 2020)	A type of AI used to make sense of images video data. Examples include object recognition, facial recognition, pose estimation and emotion detection
Natural Language Processing (Hirschberg & Manning, 2015)	A type of AI used to make sense of speech or text data. Examples include automatic analysis of linguistic structure and machine language translation.
Predictive Analytics (Bird et al., 2021)	A type of AI used to predict student or programme outcomes. Typical predictive analytics make use of current student characteristics to forecast future outcomes.
Intelligent Tutoring System (Sedlmeier, 2001)	A type of AI that seeks to mimic the role of a tutor. Most intelligent tutoring systems interact with learners directly to provide feedback based on learner inputs.
Augmented Reality (Cipresso et al., 2018).	A type of immersive technology that augments the user's physical surroundings by superimposing computer-generated information on real-world vision.
Virtual Reality (Cipresso et al.,	A type of immersive technology that creates a virtual environment for the

2018).	user to interact with.
Mixed Reality (Allcoat et al., 2021)	A type of immersive technology that creates an environment for both physical objects and virtual elements to interact.
Science education goals (Kelly & Licona, 2015)	
Conceptual	Focus on learning scientific facts, models and how they are linked
Epistemic	Building skills related to scientific inquiry, scientific reasoning, and use of evidence to craft explanations and assertions. Epistemic practices include attention paid to scientific writing, reading, and speaking
Social	Understanding of interactions among scientists, their careers and developing dispositions related to how scientists work
Implementation value of technology (Kirkwood & Price, 2016)	
Doing things better	Technology helps to speed up or improve ways in which teachers teach and students learn
Doing better things	Technology used to transform the way teaching and learning is perceived or enacted

After initial discussions about the codes, the first author coded all papers in this review using the finalised coding scheme while the other authors coded a subset of 30%. Further discussions were held to resolve disagreements in coding and to handle corner cases. The end result of the discussions is an agreement on all the codes to achieve the inter-rater agreement.

Results

Our final sample consists of 82 papers (see Appendix 1 for a list of reviewed papers) across 32 journals. Of the 82 papers, it was observed that 4.9% (n= 4) of them were published before 2000. Thereafter, between 2000-2004, only 1.2% (n=1) of work published was related to AI and immersive technologies. On the contrary, during the periods of 2005-2009, 2010-2014, 2015-2019, and 2020-2022, 6.1% (n=5), 11% (n=9), 31.7% (n=26) and 45.1% (n=37) of work published were related to AI and immersive technologies (see Figure 2). This increasing trend of work published during later periods suggests an increased interest and understanding of the fields and qualification of AI and immersive technologies as emerging technologies. Furthermore, these papers either described the development of a STEM programme using an emerging technology or described the testing of a developed emerging technology product for science teaching and learning. Based on what was described by the researchers in each paper, we analysed them for the emerging technology used, the science teaching goals achieved, and the implementation value of the emerging technology used.

For the grade levels, 59.8% of the papers involved work done at K-12 levels while 36.6% comprised work done at the higher education level (see Figure 3). There was one piece of work carried out by Streibel et al. (1989) that deals with students from both K-12 and higher education settings. Two pieces of work (2.4%) did not report on participants' education level as they focused on describing the affordances and development of technologies used (Good et al., 1986; Good, 1984). The prevalence of emerging technology research carried out in K-12 settings is not surprising since there are comparatively more students in K-12 compared with higher education. Further, there could be greater interest in harnessing technology for a greater repertoire of teaching strategies to engage younger learners of STEM.

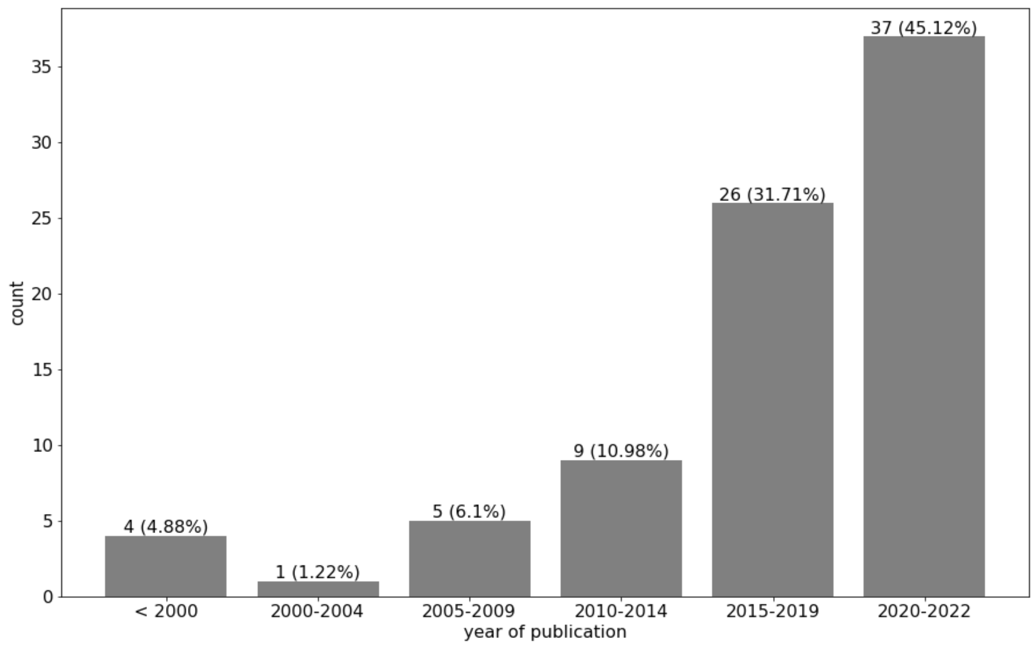

Figure 2. Distribution of paper publication year

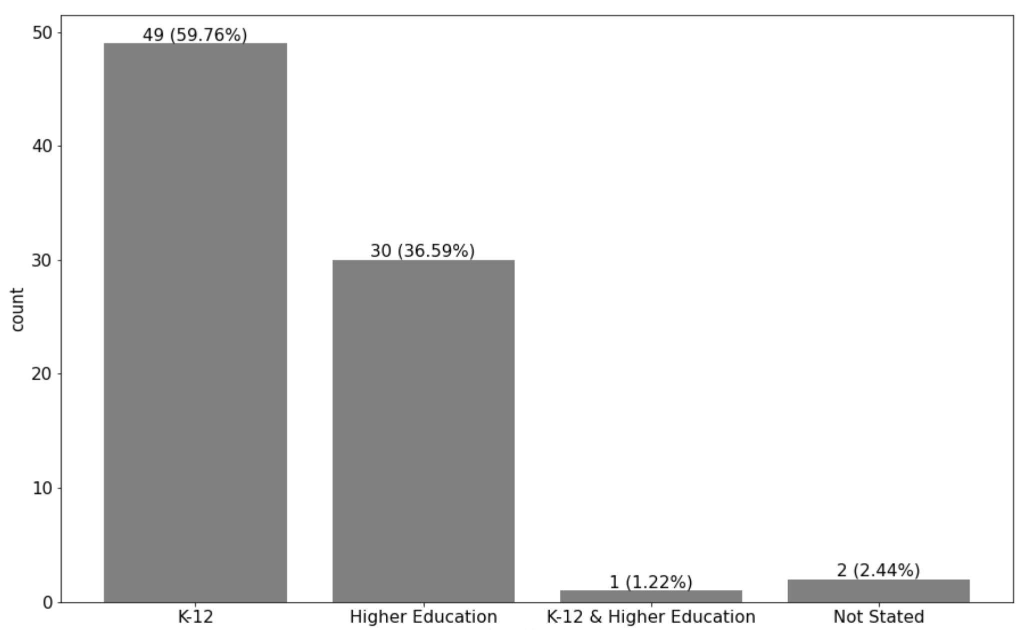

Figure 3. Distribution of education level

Emerging technologies used to fulfil science learning goals

Different technologies were deployed in science classrooms to fulfil different learning goals. The two most common emerging technologies used are augmented reality (n=23, 25.6%) and natural language processing (n=20, 22.2%). The least popular emerging technologies are computer vision (n=3, 3.3%) and mixed reality (n=4, 4.4%) (see Figure 4).

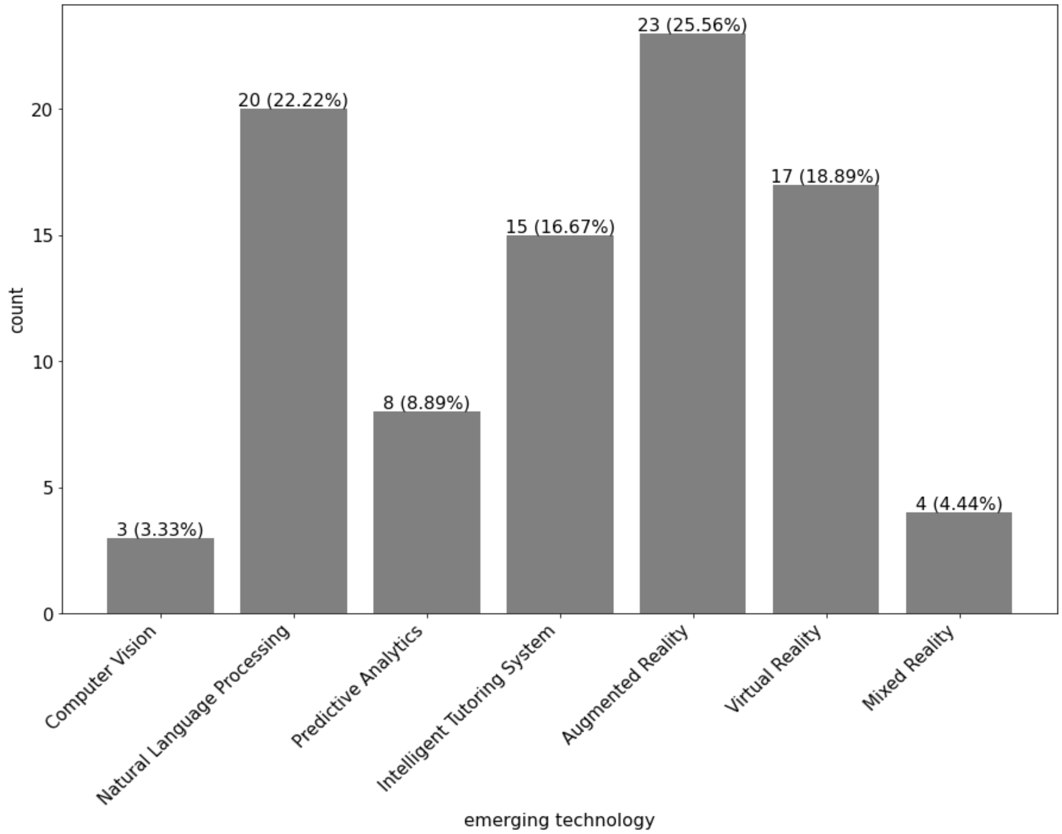

Figure 4. Distribution of Emerging Technologies (organised by AI followed by immersive technologies).

The distribution of emerging technologies provides us with an overall understanding of where current research efforts lie. Its uneven distribution suggests different levels of appeal for the use of different emerging technologies in STEM education (see the first subsection of the discussion section for further discussion). Beyond examining the raw distribution of emerging technologies used, we can also inspect the relationship between emerging technologies and science education goals. Referring to Figure 5, we see that immersive technologies such as augmented reality, virtual reality and mixed reality were used commonly to develop the social aspects of science learning. For instance, augmented reality was used in developing the subject interest in science (Estapa & Nadolny, 2015; Hsu et al., 2017; Linder et al., 2019; Salar et al., 2020), building collaborative abilities (Borrero & Marquez, 2012), and engage in socio-scientific reasoning with others (Chang et al., 2018). Virtual reality was similarly used to develop science subject interest (Brown et al., 2021; Petersen et al., 2020; Starr et al.2019). Besides science subject interest, virtual reality was also harnessed to increase students' confidence (Huang, 2022; Nelson & Ketelhut, 2008), which is an important social aspect in the practice of science and science learning.

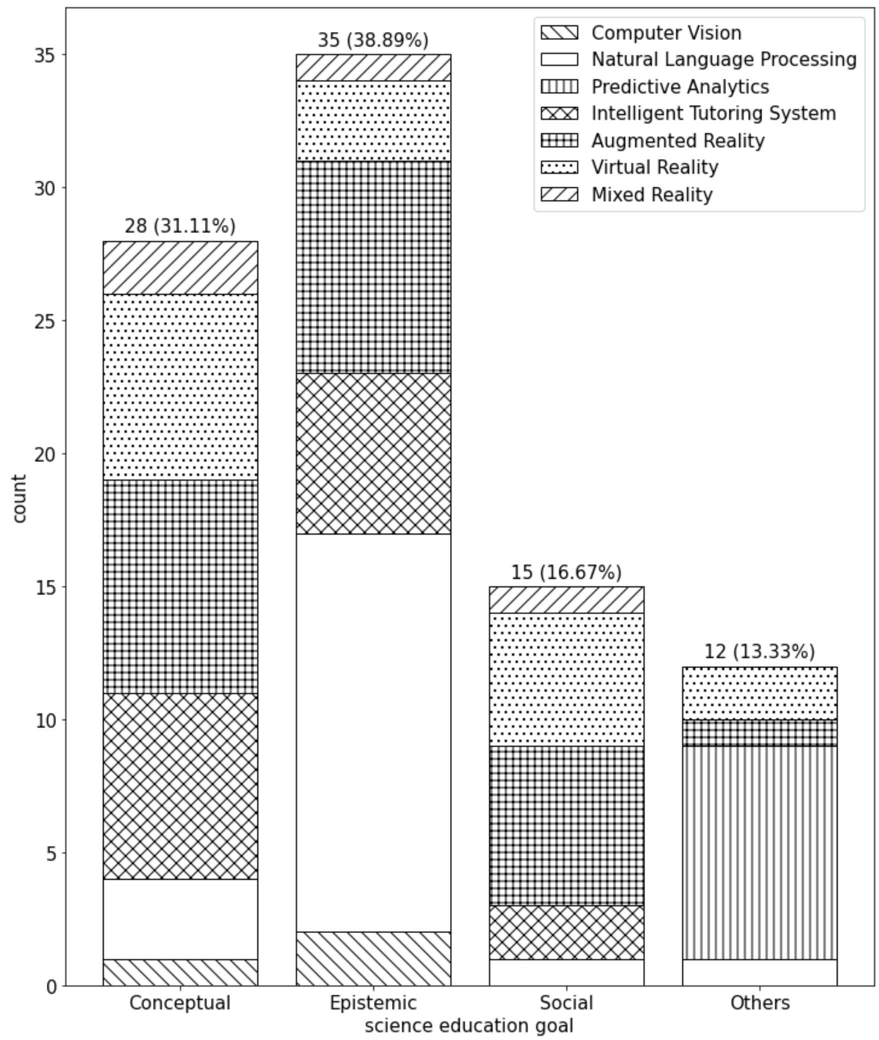

Figure 5. Technology category by science education goals *(Others refers to studies that do not fall under conceptual, epistemic, or social aspects of science learning. It could be modelling and predicting students' intention to take up a STEM career)*

In the development of epistemic understanding of science, augmented reality was used to facilitate scientific inquiry (Enyedy et al., 2012; Linder et al., 2022; Wang et al., 2014), development of experimental skills (Kapp et al., 2202; Shirazi & Behzadan, 2015; Villanueva et al., 2021), and increasing scientific literacy skills (Dunleavy et al., 2009; Wahyu et al., 2020;). Virtual reality was similarly applied in the development of experimental skills (Paxinou et al., 2020), scientific inquiry (Jiang et al., 2021) and science problem solving (Moon et al., 2020).

Immersive technologies were widely used to help learners develop scientific conceptual knowledge. Eight research studies reported the use of augmented reality to develop a conceptual understanding of topics such as virus characteristics (Jones et al., 2005), dynamics of circular motion (Gregorcic & Haglund, 2018), and physics in space (Tscholl & Lindgren, 2016). Similarly, virtual reality is another technology that is popularly used to develop scientific conceptual understanding. Seven research studies used virtual reality to teach topics such as electricity, kinematics, energy, and energy conservation (Chen et al.2019), and organic chemistry (Miller et al., 2021).

The immersive technology that is least commonly reported is mixed reality. The four reported instances were in the development of conceptual understanding of science (Chao et al., 2016; Keifert et al., 2020), development of subject interest (Barrett et al., 2018) and engaging students in scientific inquiry (Yannier et al., 2020).

Besides immersive technologies, AI is also used in STEM learning. For AI, natural language processing is popularly used in science learning. Of the 20 studies using natural language processing, 15 were applied in the areas of epistemic process skills such as the development of argumentation skills (Lee et al., 2021; Lee et al., 2019; Wang et al., 2021), scientific explanations (Gerard et al., 2019; Tansomboon et al., 2017; Wiley et al., 2017) and critical thinking (Lamb et al., 2021). Only two studies (Dzikovska et al., 2014; Liu et al., 2018) aimed at increasing science conceptual understanding of students.

Seven (for example Chase et al., 2009; Pek & Poh, 2000) of the 15 studies reviewed used intelligent tutoring systems to help learners develop conceptual understanding in science such as conceptual physics or redox reactions in chemistry. Intelligent tutoring systems reviewed generally afforded some form of adaptive instruction based on students' inputs or prior knowledge and some researchers have shown greater achievements of students using intelligent tutoring systems compared to traditional instructions (Own, 2010).

For predictive analysis, our exploration suggests that this technology was applied in helping learners in STEM career projection (Yeung et al., 2018) and modelling attrition of STEM course of study (Alkhasawneh & Hargreaves, 2014; Wang et al., 2020). They were not applied directly in the attainment of formal science education goals that we have identified for this study.

Computer vision is the least common emerging technology used in STEM learning. Of the three studies that used computer vision, two were used together with immersive technologies (Enyedy et al., 2012; Yannier et al., 2020). Computer vision was used on its own by Mason et al. (2019) to develop students' visual representation in STEM learning.

Figure 5 from the systematic review also showed that the development of epistemic skills (n=35, 38.9%) was an important goal for researchers applying emerging technologies. The epistemic skills of interest include scientific inquiry, scientific argumentation, crafting scientific explanations, scientific reasoning, problem-solving, critical thinking, experimental skills, and reflective writing. For instance, Kapp et al. (2022) used Microsoft HoloLens 2 to create an augmented reality experiment environment to help high school students carry out experiments related to electricity, thereby building their experimental skills. In another study, Lee et al. (2021), applied natural language processing to develop an automated feedback system to support secondary students' argumentations related to understanding issues related to underwater storage systems. To understand the interaction and regulatory mechanisms of students engaged in collaborative problem-solving processes in STEM, Emara et al. (2021) applied log data analysis and natural language processing and found that students engaged in more socially shared regulation and productive collaboration in more changing and open-ended tasks than more scaffolded tasks.

The development of conceptual understanding in science (n=28, 31.1%) is another important area that researchers considered. Chen and Wang (2015) embedded augmented reality in an e-learning module to reduce the effects of individual differences among junior high school students as they learn the concepts related to the phenomena of change of season and day and night. They found that their three-stage AR-embedded e-learning could enhance the instructional adaptiveness of students. Dzikovska et al. (2014) enhanced the teaching of conceptual knowledge related to basic electricity and electronics using symbolic natural language processing techniques in a dynamic adaptive feedback system.

The social aspects of science learning were not commonly addressed using emerging technologies (n=15, 16.7%). Kelly and Licona (2015) defined the social aspects of a discipline to include the procedures used to generate, communicate, and evaluate knowledge claims. For STEM learning, this will include learning how to propose, communicate, evaluate, and legitimise knowledge claims confidently and appropriately within specific STEM learning contexts. Through engaging their avatars in a multi-user virtual environment (MUVE) in River City, students inquire and explore to discover why the residents in the town were unwell. Through presenting their hypothesis and evidence, students were given opportunities to propose, critique ideas and evaluate claims with avatars within the virtual environment. This process helps to raise the science self-efficacy of students (Nelson & Ketelhut, 2008).

There were 12 (13.3%) research studies that used science as a context, but the study was not directly related to the science education goals that we identified for our discussion. These studies focussed on aspects of STEM education such as predicting STEM career participation (Almeda & Baker, 2020), modelling the outcomes of STEM related programmes (Bertolini et al., 2021), and using virtual mentors to support STEM career developments (Nye et al., 2021).

Implementation Values

Our analysis revealed that emerging technologies are largely used to transform STEM education by *doing better things* (n=53, 58.9%). Slightly fewer studies (n=37, 41.1%) reported that emerging technologies were applied to make existing ways of *doing things better*.

For AI technologies, the three applications of computer vision were targeted at transforming STEM teaching and learning by doing better things. For instance, Mason et al. (2019) transformed the way students' perceptual competencies related to Lewis structures can be understood. Harnessing computer vision, they were able to assess students' perceptual competencies implicitly without the need for visualisation or assuming explicit visual attention. The assessment of students' perceptual competencies implicitly would not have been possible without the application of computer vision and machine learning. Similarly, most of the studies (n=10, 66.7%) in intelligent tutoring systems described applications that characterise transformative and better ways of STEM teaching and learning. An example is described by Good et al. (1986) who explored the development of an expert system to diagnose the problem-solving state of students. Expert systems allow for rapid and customised feedback to be given to students to facilitate the remediation of their learning trajectory. The increased accessibility of feedback to students empowers them and provides agency for the students for their learning.

All the research studies using predictive analytics (n=8, 8.9%) were applied to augment STEM education, that is for *doing things in a better way*. Stadlman et al. (2022) used predictive analytics to develop a system to predict students' performance in synchronous online courses. This predictive system augments current methods, such as classroom observations and test performances, of evaluating students' performance. This predictive analytics adds to the repertoire of evaluative tools available. Similar to predictive analysis, natural language learning (n=15, 75%) was used largely as a means to augment current ways of learning to make them better (see Figure 6). An example is the automated scoring system for scientific argumentation developed by Wang et al. (2021). The automated scoring system offers an alternative way of grading students' responses for argumentation tasks. In another study, Lamb et al. (2021) used natural language processing to study the relationship between science writing heuristics and the development of critical thinking.

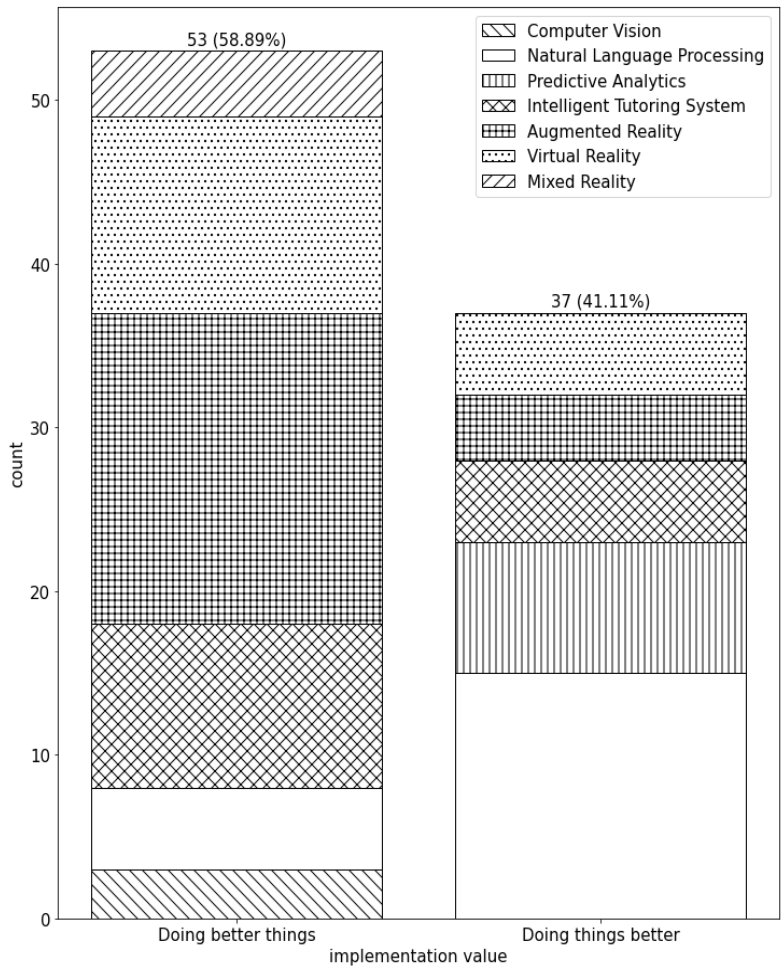

Figure 6. Technology category by implementation value

The three immersive technologies, virtual, augmented, and mixed reality were largely applied to *do better things* in STEM learning. For augmented reality, 82.6% (n=19) of the applications were categorised as *doing better things*. This trend is similar for virtual reality (n=12, 70.6%) and mixed reality (n=4, 100%). For augmented reality, Shirazi and Behzadan (2015) developed an augmented reality-based tool where students were exposed to a virtual environment in which they could interact with an AR instructor (avatar) to receive information about the materials, weight, cost and dimensions of various objects to learn about abstract construction and civil engineering topics in a particle manner. The immersive environment allows students an embodied experience as they make decisions and see the results of the decisions that they make. Further, within such an environment, they were able to control the pace and the number of times they like to go through the lesson. Similarly, to expose students to remote sensing data and methods, Linder et al. (2022) developed an app to allow students to browse, understand and work with raw data related to harmful algal bloom in Lake Erie in America. Such exposure to authentic data and sense making of raw data is an important epistemic practice of science. Without the application of the AR app, it would be difficult, if not impossible for learners to have access to and interact with these authentic data sets with such ease.

For virtual reality, Miller et al. (2021) used a VR headset to virtually raise students into a large platform in the sky where they interacted with molecular structures that they could manipulate with a hand controller. Students select different atoms and bonds and combine them into molecules. They used these different molecules to solve problems presented to them. As the students solve the problems, they are given feedback in the form of environmental changes in the virtual environment. The researchers observed improved learning outcomes for students who used VR for their learning. Unlike traditional learning of molecular structures through either reading about them in 2-dimensional representations in textbooks or manipulating them using ball-and-stick models, the VR environment allows students to experience different orientations of the molecules via rotations on different planes. Feedback on the different orientations of molecules can also be given to students instantly. This offers a different way of learning for students.

For mixed reality, Keifert et al. (2020) described how tracing bodies through liminal blends within a mixed reality environment helps to harness all sensemaking resources such as bodily movements to enhance the learning of science. They applied the STEP curriculum and involved students in being particles of water in different states while observing the computer screen as they moved in different ways. This interface between the embodied experience and the resultant movement of the screen helps students to visualise their movement and how this is represented scientifically.

Discussion

We present our discussion by relating the findings of our review to our identified research questions and the overall aim of closing the gap between what is known in research and how these novel technologies might function in real-world classroom settings. In particular, we derive three research agenda that we believe would further the eventual implementation of emerging technologies in schools.

More research is needed to reduce the barriers to using each emerging technology

With reference to the first research question: *What AI and immersive technologies have been used for the teaching and learning of STEM to advance its educational goals?*, we observed that a diverse range of emerging technologies have been used for STEM teaching and learning even though the application of each technology is uneven. For instance, within the realm of AI technologies, the most commonly used technology is natural language processing while the least popular technology is computer vision. The reason behind this observed disparity is not immediately clear but it could be partly explained by the availability of data. Natural language processing techniques typically rely on text data which is easily gathered with a lower degree of privacy concern. By contrast, computer vision techniques usually rely on video data which not only requires a camera setup but also holds more concerns about privacy of participants. This could have contributed to fewer research studies exploring the use of computer vision in STEM education.

Nonetheless, this should not be taken as an indication that we ought to favour the use of natural language processing over computer vision in STEM education. On the contrary, this is a signal to researchers that, for technologies with more practical considerations, more research work needs to be done to reduce barriers to usage. In fact, during our review of papers, we notice that few researchers make explicit reference to the practical challenges of using each stated technology. This is of concern because schools essentially represent grounds that are resistant to change (Keengwe et al., 2008; Rogers, 2000) and the lack of knowledge in this area can ultimately hinder the rate of technology adoption in schools. In this regard, researchers can play a more active role by uncovering knowledge that can ease the use of technology adoption in schools. For example, researchers could reduce the barrier of using each emerging technology by enhancing the maturity of individual technology (Roussel, 1984). The maturity of technology refers to how developed the knowledge base for the technology is and the ease of accessibility. Mature technologies are more stable and hence users are less likely to have to deal with downtime. Even if the technology fails, help is more readily available. By contrast, when technology requires too much technical knowledge to implement, teachers and students would be less receptive to them since they may need technical support to troubleshoot should the technology fail. Moreover, having a mature technology would enable teachers to consider questions of resources (what are the technical knowledge and physical infrastructure required for using the technology and how do I access them?). Overall, if researchers could develop the required knowledge base to improve the maturity of each technology, then it is likely that the subsequent pervasiveness of each technology in science classrooms would increase.

More research is needed to unpack the mechanisms through which emerging technologies advance STEM educational goals

With regard to the advancement of STEM educational goals, we observed that various AI technologies have been used to help learners experience science epistemic practices and develop conceptual understanding, but there are fewer examples of how emerging technologies can be applied to social aspects to help learners learn and practise how scientists interact as a community. Nonetheless, we find in our review that researchers have established the advancement of STEM educational goals through emerging technologies. One such example would be the use of natural language processing to support the development of the epistemic practice of scientific argumentation. Epistemic practices such as scientific argumentation, reasoning and explanations are emphasised in the Next Generation Science Standards (NGSS Lead States, 2013), making them important practices that students ought to be fluent in. Within the context of argumentation in classrooms, teachers face the constant challenge of trying to assess students' claims, reasoning, and evidence within a short time (Zhu et al., 2017). As such, it is almost impossible for teachers to deliver quality individual feedback to students. The use of emerging technologies such as natural language processing can help teachers overcome these time challenges by providing instant targeted feedback to improve the overall quality of students' arguments. Another example would be the use of immersive technologies as a teaching tool to enable students to be part of and 'become' different aspects of physical and living systems. Through the use of augmented, virtual and mixed reality technologies, learners can become molecules, observe electrical conductivity, or even turn into red blood cells travelling around circulatory systems. These embodied experiences ultimately allow students to experience intricate details of the properties, adaptations, characteristics, and limitations of different explanatory models of science. In essence, models are at the core of scientific theories and hence model construction is fundamental to scientific inquiry (Halloun, 2004). In other words, the application of various emerging technologies for more embodied forms of learning allows students to experience the complexities involved in scientific models, which is a marked improvement over the current methods of building non-interactive physical models or reading about a scientific model in textbooks.

However, the mechanisms through which emerging technologies advance STEM educational goals remain unclear from current research work. From our review, we detect a lack of discussion on the conditions under which the researched emerging technology is expected to work and an elaboration on the immediate impacts of the use of the researched emerging technology. Without such information, it is difficult for school administrators to ascertain if the stated research findings are applicable to their local context and challenging for classroom teachers to determine if certain operational differences are critical. By contrast, having such information could enable teachers to respond to questions of purpose (is the technology applied to help me teach better or is it used to transform my teaching?), and questions of learning outcomes (which aspect of science practices does the technology help students to learn better?). Furthermore, besides establishing external validity for practitioners, unpacking the operating mechanisms of current emerging technologies could also enhance our theoretical understanding of how STEM educational goals could be promoted by new emerging technologies. This would reduce the research cycle for each new emerging technology and increase the amount of translational impact for the entire education practice. In sum, researchers ought to move beyond a simple dissection of empirical findings to a more rigorous examination of the underlying mechanisms through which emerging technologies operate.

More research is needed to understand the pedagogical affordances of each emerging technology

For the second research question: *Where does the implementation value of AI and immersive technologies in STEM education lie?,* we paid attention to teaching and learning purposes that were enabled by specific technologies. AI and immersive technologies have been applied to radically change how students experience STEM content. Compared to traditional pedagogy where students read about kinetic theory or watch a video about the movement of particles, the affordances of immersive technology allow students to have more embodied forms of learning. Students can now be part of the scientific process of boiling and freezing by being particles of water and observing how their bodily movements change the state of matter. This would increase the amount of student agency in the learning process and could lead to significant knowledge building by students (Scardamalia, 2002). Compared to traditional pedagogy where students are passive recipients of knowledge, the affordances of AI technology allow students to experience more adaptive forms of learning. The personalisation of learning remains a challenge for teachers to achieve in our current education system because of the large number of students they have to deal with in the classroom. In this respect, AI can help democratise teacher intelligence and produce instruction that is more responsive to learners. This would decrease the amount of student struggle during the learning process and could possibly lead to substantial independent learning by students (Kapur, 2008). Further, Cviko et al (2014) and Ouyang and Jiao (2021) argued that when AI is applied in STEM education, the traditional roles of the instructor and learners shift to adopt a more student-centric mode.

Despite all the pedagogical potential and promises of emerging technologies, there exists little to no mention of the pedagogical affordances of each emerging technology in the papers that we reviewed. This challenge in distilling the pedagogical implications of AI and emerging technology in STEM education is also highlighted in the latest review on AI in education by Xu and Ouyang (2022). They opined that since AI in STEM education is a highly technology-dependent field, it is likely that the focus is on technology rather than on education and pedagogical. In this instance, to allow the technology to transform the way students learn, teachers need to have knowledge of the alignment of the technology to sound pedagogical principles, so as to create meaningful learning experiences for students. Eventually, the disruptive pressure created by emerging technologies would force STEM teachers to re-examine, re-create and re-imagine how valued STEM pedagogies and strategies such as doing experiments, demonstrations, argumentation, and modelling can co-exist with emerging technologies. Furthermore, when researchers commit more research effort in understanding the pedagogical affordances of each emerging technology, teachers would be able to address questions of pedagogical implications such as "Will the application of emerging technologies change the way I teach STEM?", "What are the most appropriate strategies or e-pedagogies to support the application of emerging technologies for STEM teaching and learning?". Ultimately, the two key considerations of technological affordances and pedagogical affordances need to be contemplated for transformational teaching and learning to happen.

Limitations

While we aimed to be as comprehensive as possible in our systematic search, the use of the acronym of STEM as a search term may result in missing papers that do not include the acronym. In addition, the use of immersive technologies as a search term could also limit our search returns since some researchers may employ alternative terms such as virtual reality, mixed reality, or augmented reality. Furthermore, despite choosing EBSCOhost, one of the most extensive collections with three databases, the single reliance on EBSCOhost as a search engine may inadvertently omit certain relevant papers from our review. In this regard, future work could apply more expansive search engines and comprehensive search terms to uncover as many published works as possible. Lastly, we only focused on research papers published in journals and did not review books for this review. Books also represent a rich resource for emerging ideas in technological applications for education. As such, future work could also review books for emerging technological applications in STEM education.

The focus of this review is to uncover a roadmap for the eventual implementation of AI and immersive technologies in school systems. In this case, we examined the use of these technologies through the lens of science education goals and implementation value, which is admittedly not the only approach to do so. For instance, in Xu et al. (2022)'s review of AI application in STEM education, they made use of the general system theory framework to examine the use of AI technologies along the dimensions of instructor involvement, instructional strategy, educational level, learning outcome, learning content, educational medium and educational context. This approach ultimately provides the reader with a more contextual understanding of how AI could be deployed in the classrooms. A natural extension of Xu et al.'s and our work would be to examine the immersive technologies' application in STEM education through the lens of the general system theory framework.

Conclusions

This systematic review presented the state of emerging technologies as applied in STEM teaching and learning. From the trends revealed, we proposed three broad research agendas that are worthy of more in-depth examination - (1) How can usage barriers of using each emerging technology be lowered?, (2) What are the mechanisms through which emerging technologies advance STEM educational goals? and (3) What are the pedagogical affordances of each emerging technology? Additionally, we draw inferences for practice from insights gleaned from this review. From a practitioner and application perspective, to encourage STEM teachers to adopt emerging technologies in their classrooms in meaningful ways, we infer that teachers can consider four key areas to guide their professional decision making - (1) resources (what are the technical knowledge and physical infrastructure required for using the technology and how do I access them?), (2) purpose (is the technology applied to help me teach better or is it used to transform my teaching?), (3) learning outcomes (which aspect of science practices does the technology help students to learn better?), and (4) pedagogical implications (will the application of emerging technologies change the way I teach STEM? What are the most appropriate strategies or e-pedagogies to support the application of emerging technologies for STEM teaching and learning?).

With reference to the resources to guide teachers to use emerging technologies in STEM classrooms, more professional development opportunities focusing on understanding the affordances of each technology can be made available. For instance, rather than just knowing how to use the technology, teachers can be equipped with knowledge of how the technology works and what the technology can do with regard to helping students learn. In that way, teachers will be able to make better pedagogical decisions about the choice of technology to adopt. Of particular interest in STEM education is the application of technology in investigative laboratory work. The pandemic has resulted in an increased interest in remote science laboratory activities and how students can learn laboratory skills in a remote setting. How could emerging technologies be applied to help learners learn and acquire investigative laboratory skills without being physically in science laboratories? In this respect, immersive technologies could potentially be further developed to facilitate remote laboratory learning.

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