A Systematic Review of Augmented Reality in STEM Education

GLORIA AJIT¹, TERRY LUCAS², RINGAH KANYAN³

Faculty of Applied and Creative Arts, UNIVERSITI MALAYSIA SARAWAK.

¹Email: gloriaajitfrancis@gmail.com

²Email: lterry@unimas.my

³Email: kringah@unimas.my

ABSTRACT

This study presents a systematic review of the existing literature on the benefits and challenges faced regarding the use of augmented reality (AR) in Science, Technology, Engineering, and Mathematics (STEM) education. Guided by the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) method, a systematic review of the ScienceDirect database identified 19 related studies. Further investigation of these articles resulted in four themes of AR advantages, namely its contribution to learners, the learning outcomes, the interaction of AR, and other benefits. These four themes further produced a total of 16 sub-themes, while the challenges aspect of AR resulted in 5 sub-themes. The most reported benefit of AR is that it stimulates learning achievement. Some observed that the challenges imposed by AR are concerned with marker detection and usability. Several other problems and advantages of AR usage in STEM education were also discovered, which will be discussed in detail. Additionally, the existing gaps of AR study in the STEM education field were identified, and recommendations are therefore presented for future research.

Keywords: STEM, Augmented reality, systematic review, education

Classification JEL: A10, A21, A22, A23, A29

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1. Introduction

Interest in educational models of science, technology, engineering and math (STEM) is drawn across the global educational landscape. Increasing academic skills in STEM discipline has also become a national priority to ensure that students are well-prepared and eligible for STEM career (Thibaut et al., 2018). Higher STEM education is achieved by increasing student interest in STEM since school years. However, past studies showed disfavours towards STEM discipline as students find it challenging to use their reasoning skills in an abstract representation of scientific concepts that require high spatial visualisation to master (Milton, Flores, Moore, Taylor, & Burton, 2018; Sahin & Yilmaz, 2020). Low conceptual knowledge on STEM disciplines, coupled with learning through memorisation complicates the development of students' thinking skills (Ali & Bakar, 2019; Malhi, 2019; Pirttimaa, Husu, Metsa, Metsärinne, & Metsa, 2017; Umi Fairus Mohd Jamil & Fazlinda Ab Halim, 2018).

To fully capitalise on our students' STEM potential, educators must streamline STEM education and enhance their pedagogy. Previous research supports grounding this education and training in STEM pedagogy through an interdisciplinary approach and leveraging new technologies to assist processes of learning (Conley, Atkinson, Nguyen, & Nelson, 2020; Sahin & Yilmaz, 2020). As new technologies have emerged in recent decades allowing a more thorough exploration of suitable technology to assist STEM learning, immersive technology such as augmented reality (AR) has gained attention in recent years, with an increasing number of studies published in educational setting (Garzón & Acevedo, 2019; Sirakaya & Sirakaya, 2018).

AR technology involves overlaying digital information on a displayed registration, either dependent on the location or the perspective of an operator, into the existing environment. The overlaid virtual elements to the real environment enhance our senses as we can see and also feel the appeared information, which are any materials that can be digitised, for instance, images, audios, and three-dimensional (3D) models (Garzón & Acevedo, 2019; Sirakaya & Sirakaya, 2018). The integration of AR in STEM education will add information to the real object or place that visualises either with mobile devices or computers so that students can observe details related to the object that was digitised.

The interactive digital content of AR makes learning more meaningful and enhance performance (Cai, Chiang, Sun, Lin, & Lee, 2017; Cheng et al., 2019). Students can visualise and understand concretised abstract concepts (Laine, Nygren, Dirin, & Suk, 2016; Moorhouse, Dieck, & Jung, 2019). Combination of animation elements attract the student's attention (T.-C. Huang & Lin, 2016; Safadel & White, 2019), and consequently led to increased motivation (Chang & Hwang, 2018; Erbas & Demirer, 2019; Khan, Johnston, & Ophoff, 2019) and interest (Wang, Lee, & Ju, 2019; Yu, Sun, & Chen, 2019) in the topics and the subject being taught.

While AR research in various educational disciplines has greatly advanced, however, it has not always been clear how these researches can translate into the classroom and assist STEM educational practices. Specifically, a better understanding of the AR technology basis in STEM and organised student-centred learning will play an important role in developing learning activities that allow students to comprehend basic STEM conceptual and procedural knowledge.

1.1 Towards a systematic review framework on AR in STEM education

A systematic literature review is a scientific method of obtaining all available data in compliance with certain predefined requirements to address a particular research question (Gough, Oliver, & Thomas, 2012). Systematic and precise methods classify, select and critically analyses multiple research studies or documents (Tikito & Souissi, 2019). Systematic research has advantages over conventional literature reviews as it improves review consistency, replicability, reliability and validity (Xiao & Watson, 2019). A systematic analysis may explain the authors' claims of rigour in their report, allowing gaps and directions to be defined for future studies.

Though AR studies have been comprehensive in STEM education, attempts to systematically review these studies are still lacking. Several systematic reviews have been conducted in the context of

education in general (Akçayır & Akçayır, 2017; Altinpulluk, 2019; Bacca et al., 2014; Dey, Billingham, Lindeman, & Swan, 2018; Korucu, Usta, & Yavuzaslan, 2016; Saltan & Arslan, 2017) and less focused on specific areas such as STEM. Limited studies were conducted within the framework of AR in STEM education (M. Ibáñez & Delgado-Kloos, 2018) as the available literature ranged from AR trends in education (Altinpulluk, 2019; Bacca et al., 2014), uses and benefits (Diegmann, Schmidt-Kraepelin, Van den Eynden, & Basten, 2015; Korucu et al., 2016; Saltan & Arslan, 2017), theoretical and empirical foundations (Sommerauer & Müller, 2018), AR game-based learning (Pellas, Fotaris, Kazanidis, & Wells, 2019) and AR-based educational technology evaluation (Silva, Teixeira, Cavalcante, & Teichrieb, 2019). Hence, this article aims to fill the void understanding, describe and characterise AR implementation in a STEM classroom.

This research is significant as there is a lack of systematic review consensus on the integration of AR in STEM learning and teaching. Furthermore, this study is essential because the declining interest among students in the STEM discipline will lead to decrease in the number of qualified STEM professionals in the global market (Wan Jaafar & Maat, 2020) and thus trigger an urgent need to adapt and incorporate effective intervention strategies to resolve student interest and performance issues in STEM education. Immersive technology as AR has ample potential in STEM classroom, particularly when the subjects taught are new and difficult to visualise. Therefore, specifics of where the peer-review literature has so far centred provide an opportunity to understand where the emphasis is and where attention needs to be focused.

For a relevant systematic review, the current article was directed by the main research questions: (1) What are the general characteristics of AR in STEM education? (2) What are the benefits of AR in STEM study?; and (3) What are the challenges of AR in STEM study? In this study, we discuss the connection between AR technology and its benefits when applied in STEM education to promote learning, as well as suggesting new research possibilities that await exploration. More specifically, exceptional attention was given to STEM education as this discipline is predicted to benefit significantly from the integration of immersive technologies such as AR due to the nature of the abstract conceptual representations and terminologies (Hayes & Kraemer, 2017) of STEM subjects.

2. Methodology

The study adopts Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) as a guideline to systematically identify and critically evaluate relevant research covered in the study (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). PRISMA is used to answer the research questions following a four-step process: identification of related keywords, screening, eligibility, and data abstraction and analysis. Although often applied within medical research, PRISMA guideline is currently used regularly within the social science field (e.g., Askari et al., 2018; Lai & Bower, 2019; Saltan & Arslan, 2017; Wilhelmsen & Sørensen, 2017) since it specifies the research questions towards the need for a systematic review.

The review identifies relevant published articles on the ScienceDirect journal database based on its relevance to the AR in STEM education domain. ScienceDirect is a large database of scientific and medical research with full-text search coupled with organised topic areas subscribed by virtually every university (Gies, 2018) and can also be used as a principal search system, and it is well-suited to support the synthesis of systematic reviews (Gusenbauer & Haddaway, 2020). ScienceDirect journal database has been used in the review of educational research (Petri & Wangenheim, 2017; Sharma, Torrado, Gómez, & Jaccheri, 2021; Shiner, 2018) in order to systematically select relevant articles.

The systematic review process started with the identification of keywords, which was performed on May 2020 through the following search string suggested by Sirakaya et al., (2020): "augmented reality" AND (STEM OR science OR technology OR engineering OR mathematics), adding "AND education." Next, the screening of articles is performed based on agreed criteria, which includes studies with empirical findings, articles reported in English, and materials complementary to AR and STEM fields (Table 1).

Table 1. The Screening Criteria

Criteria	Document type	Language	Nature of the study
Inclusion	Article with empirical data	English	Articles focusing on AR and STEM education
Exclusion	review articles, book chapters, conference abstract, articles without empirical data	Non-English	Not focused on AR and STEM education

Then, the remaining articles are meticulously examined in the eligibility stage to confirm that the inclusion criteria are met. In short, 59 articles were assessed for eligibility, of which 19 were eligible for review (Figure 1). The remaining 40 articles that were not associated with STEM education are excluded. A total of 19 relevant articles were reviewed to determine appropriate themes and sub-themes, parallel with the formulated research questions. The suitable themes and sub-themes were identified, resulting in four themes, which are a contribution to learners, the learning outcomes, the interaction of AR, and other advantages.

Figure 1. Research Flow Diagram

Source: Adapted from (Moher et al., 2009)

3. Findings and discussion

The results relevant to study characteristics, classification of the evidence base, and thematic analysis are presented in this section.

3.1 Characteristic of AR in STEM Studies

The review recorded 19 relevant articles that are relevant to the research questions, which were published from the year 2012 until May 2020. One study published in 2012 (5.26%), two studies in 2013 (10.53%), five studies published in 2014 (26.32%), one study in 2015 (5.26%), two studies published in 2016 and 2018 (10.53%), one study in 2019 (5.26%) and five studies published up to May 2020 (26.32%) (Figure 2). According to the Horizon Report, AR is one of the emerging educational technologies with significant advances (Brown et al., 2020), and the studies complementary to this evolving technology are expected to increase in the coming years. Regarding journal type, six of the reviewed articles (31.58%) were articles from Computers in Human Behavior, while 68.42% were from Computers and Education.

Figure 2. Study on AR in STEM education published by year

The materials that were assessed referred to the adoption of AR technology in STEM-related subjects from four continents, including Asia (36.84%), North America (21.05%), Europe (36.84%) and South America (5.26%) (Figure 3).

Studies ultimately showed that the common sample groups are secondary school students (45.45%), followed by students in primary school (27.27%), undergraduate and graduate students (22.73%) and teachers (4.55%) (Figure 4). From this result, it is clear that most of the reviewed articles were focusing on the K-12 level (72.72%). Similar results were also achieved by Akçayır and Akçayır (2017) and M. Ibáñez and Delgado-kloos (2018), which concludes that most of the samples in AR-related articles are K-12 students. K-12 students are the most preferred sample groups, possibly because, based on Piaget's developmental level, children in primary and secondary schools are in a stable phase of operation (Kohler, 2014). At this stage, children can comfortably learn more about concrete concepts through classification and reasoning across sensory organs (Ghazi, Ullah, & Jan, 2016). Hence, learning tools such as AR will make it easier to concretise abstract concepts which are necessary during this phase.

The AR in STEM review shows that the common sample size was between 101 and 200 (26.32%). Other articles reported sample sizes between 41 and 60 (21.05%), 21 and 40 (15.79%), 61 and 80 (15.79%), 81 and 100 (15.79%) and between 201 and 300 (5.26%). Unlike data from previous studies, the study showed that the most common sample size reviewed was between 31 and 100 (M.

Ibáñez & Delgado-kloos, 2018; Sirakaya & Sirakaya, 2020). This result may be a direct consequence of the methodology of that particular study, which was mostly an experimental method.

Figure 3. Study on AR in STEM education according to continent

Figure 4. Sample Groups

AR in STEM education is conducted in various STEM fields such as Physics (31.58%), Natural Science (26.32%), Mathematics (15.79%), Chemistry and Astronomy (10.53%), and Science (5.26%). On the other hand, it was found that ten studies (52.63%) were carried out in classroom settings, three studies (15.79%) were conducted in virtual laboratories, four studies (21.05%) were performed on field trips, while two studies (10.53%) were conducted in museum settings. These results agree well with existing reviews on class-context as the most preferred educational context (Figure 5) in AR and STEM study (M. B. Ibáñez & Delgado-Kloos, 2018). Although class-context is preferable among AR studies, Garzón and Acevedo (2019) reported that informal settings produce better learning outcomes than formal settings. Thus, this indicates that teachers need to be encouraged to integrate interactive technology as AR in everyday activities instead of just using AR applications within the classrooms.

Figure 5. Educational Context of AR and STEM Study

The most convenient and frequently used tool in the findings were achievement test (34.21%), survey/questionnaire (28.95%), interview protocol (15.79%), Flow State, Attitude, Cognitive load or Usability scale (10.53%), observation (7.89%) and other (2.63%). Survey and achievement tests are the most preferred tools in conducting studies on educational technology, consistent with Sirakaya and Sirakaya (2018).

Based on type, 13 of the studies included marker-based AR, while five studies include location-based AR (Table 2). Among 13 marker-based studies, nine studies utilised handheld display in five application type. The five studies include simulation-based game (Echeverría et al., 2012), exhibition (Sommerauer & Müller, 2014), problem-based simulator (Ibáñez et al., 2014; Fidan & Tuncel, 2019), flipped learning AR (Chang & Hwang, 2018), collaborative learning simulator (Chen & Liu, 2020), while another three studies application type is unspecified (Akçayir et al., 2016; Conley et al., 2020; Ibáñez et al., 2020). Three marker-based studies incorporate desktop/laptop displays (Cai et al., 2014; Lin et al., 2013; Sahin & Yilmaz, 2020) while Thees (2020) utilise HMD in their study. Meanwhile, all five location-based studies use handheld displays. The most mentioned application types of AR use in STEM studies are inquiry-based simulator and problem-based simulator. Based on the review, intervention that uses location-based AR are conducted in Natural Science subject while the marker-based are widely used in Physics and Mathematics. Marker-based AR was preferred compared to location-based AR as it is easier to use, more comfortable to develop, and is widely used in K-12 studies in the classroom setting (M. Ibáñez & Delgado-kloos, 2018; Sirakaya & Sirakaya, 2020).

Table 2. AR Application Specification

Type of AR	AR Display	Application Type	Subject (Topic)	Study
Marker-based	Handheld display	Simulation-based game	Physic (Electrostatic)	Echeverría et al. (2012)
		Exhibition	Mathematic	Sommerauer and Müller (2014)
		Problem-based simulator	Physic (Electromagnetism)	Ibáñez et al. (2014)
			Physic	Fidan and Tuncel (2019)
		Flipped learning AR simulator	Science (Electromagnetism)	Chang and Hwang (2018)
		Collaborative learning simulator	Chemistry (Periodic table)	Chen and Liu (2020)
		Unspecified	Physic	Akçayir et al. (2016)
			Mathematic	Ibáñez et al. (2020)
	HMD	Unspecified	Physic	Conley et al. (2020)
	Desktop / laptop display	Collaborative learning simulator	Physic (Elastic collision)	Thees et al. (2020)
		Inquiry-based simulator	Chemistry (Molecule)	Lin et al. (2013)
		Unspecified	Astronomy	Cai et al. (2014)
Location-based	Handheld display	Inquiry-based simulator	Natural science	Sahin and Yilmaz (2020)
		Unspecified	Astronomy	Kamarainen et al. (2013) Chiang et al. (2014) Georgiou and Kyza (2018)
			Natural science (Ecology)	Zhang et al. (2014)
				Huang et al. (2016)

Most studies of both AR types commonly uses handhelds display such as tablet and smart phone since it provides better mobility compared to HMD or desktop / laptop display (Dey et al., 2018). Users can move around, whether indoor or in an outdoor setting, while handling handheld displays. However, although lack in mobility, the desktop/laptop displays in Cai et al. (2014) and Lin et al. (2013) suited the context of the study, which related to experimentation in a virtual laboratory.

Table 3. List of AR Developer

Study	AR Developer
Kamarainen et al. (2013)	FreshAiR, Vuforia
Sommerauer and Müller (2014)	Aurasma
Ibáñez et al. (2014)	Unity, Vuforia
Cai et al. (2014)	Native app. (NyARToolkit, 3D modelling tool 3DS Max and graphics engine Java 3D)
Chiang et al. (2014)	Native app. (iOS)
Akçayir et al. (2016)	Metaio
Chang and Hwang (2018)	Unity
Georgiou and Kyza (2018)	TraceReaders
Fidan and Tuncel (2019)	Vuforia, Unity
Conley et al. (2020)	Vuforia, Unity
Thees et al. (2020)	Vuforia, Unity

Regarding AR development tools, only 11 studies mention the development tools used, and the most frequent development tools based on Table 3 are Vuforia and Unity. Regarding types of digital elements used, ten studies mention elements used by the AR application. Most studies employ two types of digital elements (40%), while only one study (10.0%) employ one type of digital element in their intervention. Video and animation are the most frequent types of digital elements used in AR applications among the ten articles.

Table 4. Types of Digital Element Used

Study	Text	Image	3D Model	Audio	Video	Animation
Kamarainen et al. (2013)	✓	✓	✓		✓	✓
Lin et al. (2013)	✓	✓	✓			✓
Sommerauer and Müller (2014)				✓	✓	✓
Akçayir et al. (2016)		✓			✓	
Chang and Hwang (2018)					✓	
Georgiou and Kyza (2018)		✓			✓	
Fidan and Tuncel (2019)			✓			✓
Conley et al. (2020)			✓			✓
Chen and Liu (2020)		✓		✓		✓
Sahin and Yilmaz (2020)	✓		✓		✓	

3.2 AR Advantages in STEM

The benefits of AR in STEM studies are categorised into four themes, such as its contribution to learners, the learning outcomes, the interaction of AR, and other advantages.

3.2.1 Contribution to Learners

The utilisation of AR technology benefits learners through increased achievement (Cai et al., 2014; Chen & Liu, 2020; Echeverría et al., 2012; Fidan & Tuncel, 2019) and learning performance (Chang &

Hwang, 2018; Georgiou & Kyza, 2018; Zhang et al., 2014). AR assists knowledge construction (Chiang et al., 2014), and supports the learner to understand more of the topic learned (Chiu et al., 2015; Fidan & Tuncel, 2019; Kamarainen et al., 2013). The virtual element enhances the learning experience and leads to the memorisation of procedural knowledge among students (Cai et al., 2014). This pattern of finding has been shown in previous work, where learning performance is commonly measured in research complementary to science fields (Lai & Bower, 2019). However, the impact of AR in STEM education differed among learners and the context of their study. For instance, Georgiou and Kyza (2018) reported that secondary students' performance had significantly improved in a science field trip conducted with AR location-based approach. However, in Conley et al., (2020), learning statistic via "MantarayAR" benefit only students with low prior knowledge of the topic taught. Earlier research indicates that the mental imagery process varies among students (Palmiero et al., 2019). Students may improve their skills and achieve desired learning outcomes by spatial visualisation training and the use of proper tools such as in AR. Students will develop positive attitudes (Cai et al., 2014; Sahin & Yilmaz, 2020), thus increasing their interest (Chen & Liu, 2020) and motivation to learn (Chang & Hwang, 2018; M. B. Ibáñez et al., 2014, 2020). AR facilitates learning by allowing students to conduct experiments efficiently and comfortably (Akçayir et al., 2016). Students also benefit from immediate feedback after using the technology to clarify concepts since it encourages further learning (T. C. Huang et al., 2016). Therefore, the implementation of AR increases learner satisfaction (Cai et al., 2014), and leads to positive emotions on the STEM subject area (T. C. Huang et al., 2016).

3.2.2 Learning Outcomes

According to the review, most articles mentioned visualisation as an essential learning outcome by implementing AR in STEM education. AR facilitates learners to visualise abstract concepts (Cai et al., 2014; Sahin & Yilmaz, 2020). Students were able to visualise these abstract concepts (Chen & Liu, 2020) in the form of visual information (Chiang et al., 2014; Safadel & White, 2019), attain more significant learning, and subsequently, increases academic achievement. Learners also claimed that integrating AR in related studies are fun (Cai et al., 2014; Fidan & Tuncel, 2019; Huang et al., 2016). Interaction between the AR application initiates learner interest, and learners gain more enjoyment from learning. However, the practice should be supported by a practical pedagogical approach to assist students throughout the learning period to avoid students being too engaged with their smartphones (Kamarainen et al., 2013).

Other than that, AR effectively increases learner's conceptual knowledge (Echeverría et al., 2012; Thees et al., 2020). Learners were able to deep understanding the theoretical concepts and retain the knowledge gain to resolve future problems arise in their STEM lessons (Lin et al., 2013). AR benefits students' learning outcomes by concretising abstract concepts (Fidan & Tuncel, 2019), enhancing collaboration skills among classmates (Kamarainen et al., 2013), and increasing class engagement (Georgiou & Kyza, 2018). While these results are promising, likely, AR can also support higher-order thinking skills as well as facilitate students for more in-depth learning instead of surface learning. Then again, previous reviews conducted by Garzón and Acevedo (2019) and Akçayır and Akçayır (2017) have already noted that the successful results shown might be possibly due to the novelty effect of the newly introduced technology to the students. Therefore, further studies are necessary to ascertain whether the novelty factor is going to continue to substantially affect the results of research conducted over more extended periods.

Table 5. AR Contribution to Learners

Sub-theme	IA		IM		PA		II		MLE			IS		PL		
Sub-theme code	LA	LP	UT	PK	KC	LE	LM	SM	SA	LA	I	F	IF	S	PE	RK
Echeverría et al. (2012)	√															
Kamarainen et al. (2013)	√		√					√								
Lin et al. (2013)	√		√													
Sommerauer and Müller (2014)		√														√
Ibáñez et al. (2014)		√	√					√							√	
Cai et al. (2014)	√			√				√		√				√		
Chiang et al. (2014)					√											
Zhang et al. (2014)		√									√					√
Chiu et al. (2015)			√													
Huang et al. (2016)		√				√							√		√	
Akçayir et al. (2016)			√						√			√				
Chang and Hwang (2018)		√					√									
Georgiou and Kyza (2018)		√														
Fidan and Tuncel (2019)	√		√						√							√
Sahin and Yilmaz (2020)	√								√							
Ibáñez et al. (2020)	√							√								
Chen and Liu (2020)	√										√					√

Sub-theme: Increases achievements (IA), Increases motivation (IM), Develops positive attitudes (PA), Increases interest (II), Makes learning easier (MLE), Increases satisfaction (IS), Provides permanent learning (PL); **Sub-theme codes:** Learning achievement (LA), Learning performance (LP), understanding of the topic (UT), Procedural knowledge remembered (PK), Knowledge construction (KC), Enhance learning experience (LE), Learning motivation (LM), Student motivation (SM), Students attitudes (SA), Learning attitudes (LA), interest (I), Facilitate (F), Immediate feedback to clarify concept (IF), Satisfaction (S), Positive emotions (PE), Retention of knowledge (RK)

Table 6. Learning Outcomes

Sub-theme	CE	V	F	CL	AC	CK
Sub-theme code	E	SC	FL	CS	SC	CK
Echeverría et al. (2012)						√
Kamarainen et al. (2013)	√			√		√
Lin et al. (2013)						√
Ibáñez et al. (2014)		√				
Cai et al. (2014)		√	√			
Chiang et al. (2014)		√				
Huang et al. (2016)			√			
Chang and Hwang (2018)			√			
Georgiou and Kyza (2018)	√					√
Fidan and Tuncel (2019)			√		√	
Sahin and Yilmaz (2020)		√				
Thees et al. (2020)						√
Chen and Liu (2020)		√				

Sub-theme: Increases class engagement (CE), Visualization (V), Fun learning (F), Collaborative learning (CL), Concretizes abstract concepts (AC), Increase conceptual knowledge (CK); **Sub-theme codes:** Engagement (E), Unobservable scientific concepts (SC), Fun learning (FL), Collaboration skills (CK), Scientific concepts (SC), Conceptual knowledge (CK)

3.2.3 Interaction

AR enhances the interaction between learners, teachers, and the environment. The adopted technology promotes students' interaction with their environment as well as their classmates (Kamarainen et al., 2013). Students are more engaged in communication with the teacher (Zhang et al., 2014) since the teacher has more time to explain and interact with students compared to the traditional classroom, which is based on memorisation (Chang & Hwang, 2018). AR enables student-centred learning (Kamarainen et al., 2013). Students freely explore knowledge regarding the topic (Chiang et al., 2014) as AR provides personalised guidance for students centred-learning (Chang & Hwang, 2018). Students can finish their experiments on time with less help from the laboratory instructor compared to conducting regular experiments (Akçayir et al., 2016).

3.2.4 Other Advantages

Another advantage of implementing AR in the STEM classroom is that it is easy to use for students. Students had little difficulty in handling the AR application (Chiu et al., 2015), and could operate AR software within a short timeframe (Cai et al., 2014).

Table 7. Interaction and Other Advantages

Sub-theme	SCL	SI	Others	
Sub-theme code	SCL	S-E	S-T	E
Kamarainen et al. (2013)	√	√		
Cai et al. (2014)				√
Chiang et al. (2014)	√			
Zhang et al. (2014)			√	
Chiu et al. (2015)				√
Akçayır et al. (2016)	√			
Chang and Hwang (2018)	√		√	

Sub-theme: Student-centred learning (SCL), Increase student interaction (SI), Easy to use (E); **Sub-theme codes:** Student-centred learning (SCL), interaction among student and environment (S-E), interaction among student and teacher (S-T); Easy to use for students (E)

3.3 Challenges in Implementing AR in STEM Education

While articles associated with AR in STEM education emphasised the advantages of its application, there are several obstacles encountered in implementing the technology. The most common identified challenge was the problem in detecting the marker. Students viewed the stability of the AR tool as unsatisfactory (Cai et al., 2014) since the marker was sometimes left undetected (Fidan & Tuncel, 2019; Ibáñez et al., 2014). Excessive or insufficient lighting in the classroom setting may be the cause of this problem (Cai et al., 2014; Chang & Hwang, 2018; Sahin & Yilmaz, 2020). Therefore, Gün and Atasoy (2017) suggest controlling the amount of light in the classroom environment to enable markers to be detected easily. The usability of the device used is also a challenge in implementing AR in STEM education. It requires a more extensive setup such as rearranging furniture to provide enough space for students to move around, locating markers in selected locations, and also monitoring the lighting from time to time (Echeverría et al., 2012). Apart from that, users claimed that the tablets used are heavy to carry around in a study conducted in a museum environment (Sommerauer & Müller, 2014). Users also argued that the use of devices for a more extended period could lead to uncomfortable health conditions such as backache (Fidan & Tuncel, 2019) and getting tired of holding the tablet computer to marker cards for long periods at a time (M. B. Ibáñez et al., 2014).

In terms of AR features, students suggested the need to add realistic animation elements to the application (Cai et al., 2014). Gün and Atasoy (2017) proposed the inclusion of animation in AR applications to enhance student's interest in the medium. Also, animated visualisation benefit students in term of learning outcomes (Nurdyansyah, Mandarani, & Rais, 2020; Sugiharti, Dalimunthe, & Syuhada, 2020) as the animation facilitate students in memorising and understanding of knowledge (Berney & Bétrancourt, 2016; Günbaş, 2020). Through animation, factual and conceptual knowledge can be conveyed simply that both children and adult can easily understand.

Other challenges include technical glitches while operating AR applications (Fidan & Tuncel, 2019; Kamarainen et al., 2013; Sahin & Yilmaz, 2020) and the high cost of the devices (Echeverría et al., 2012). However, the technological developments of portable gadgets and lower prices of these devices may reduce these threats in the upcoming years (Sirakaya & Sirakaya, 2020).

Table 8. Challenges of AR in STEM Education

Sub-themes	Sub-themes codes	f	Sample research
Marker detection problem	Insufficient lighting	3	Chang and Hwang (2018)
	Marker not recognized	2	Ibáñez et al. (2014)
	Stability	1	Cai et al. (2014)
Technical problems	Technical glitches	3	Kamarainen et al. (2013)
Usability of device	Heavy	1	Sommerauer and Müller (2014)
	Uncomfortable if used for a long time	1	Fidan and Tuncel (2019)
	Complexity	1	Echeverría et al. (2012)
Cost	Expensive	1	Echeverría et al. (2012)
Features of AR	Not realistic	1	Cai et al. (2014)
	Less animation element	1	Cai et al. (2014)

Figure 6. Overall Themes and Sub-themes of AR Benefit to STEM Education

4. Conclusion

This study presents a systematic review of the present research in AR as a developing technology for assisting STEM education learning. The review shows that the first empirical articles on AR in STEM education were published in 2012, and the integration of technology in education has been continually explored until recently and is expected to further studies in various aspects for betterment in the coming years. Other findings from this study can assist the upcoming AR integration in STEM studies. Preferred sample groups in previous studies were secondary school students. Since secondary school students are ideal sample groups based on the review in AR and STEM studies, the potential of AR could be further extended apart from only focusing on student's performance and learning outcomes. Most studies applied the quantitative method with a preferred sample size between 101 and 200, while the favourable data collection methods are achievement tests and surveys or questionnaires. The studies were conducted in STEM subject-based learning environments, which focus mainly on science and mathematics. Further research can include studies within the element of technology and engineering in a STEM context.

The first research question aimed to uncover the general characteristics of AR technology implemented in STEM studies. Two categories of application types of AR use in STEM studies are discovered in the literature, which is AR as an inquiry-based simulator and problem-based simulator. Other than that, it is also reported that marker-based AR is frequently used compared to location-based AR in this review. However, the literature reviewed shows that marker-based AR is commonly used in Mathematics and Physics studies as a problem-based simulator and commonly conducted in class and virtual laboratory. The location-based AR, on the other hand commonly used in Natural Science inquiry-based learning, conducted mostly at the out-of-school context. Regarding AR display, a handheld display is preferred compared to HMD and desktop/laptop due to its mobility and ease of use. The most frequent development tools used in this study are Vuforia and Unity, while nearly half of the related studies employ two types of digital elements. Video and animation are the most frequently mentioned types of digital elements used in AR applications to enhance the learning experience. It would be interesting to explore more types of digital elements that can be used in AR development that can stimulate other senses apart from sight.

The second research question refers to the benefits of AR use in STEM education. The most stated benefit of AR is that it stimulates learning achievement, assists in visualisation, and promotes student-centred learning. However, the AR impact on learners might be contributed by the novelty of the innovation. Measures such as piloting before the actual application and delaying the implementation phase are recommended to ease the novelty effect. Although the overall result is encouraging, the results in individual studies may be dependent on various factors such as learner type, subject, learning environment or methodology, length of intervention conducted, and student's computer attitude. Hence, these advantages of AR implementation in STEM education signify that under certain circumstances, AR has a positive influence on learning achievement and visualisation. Therefore, further study should consider the impact of AR use on different individual characteristics (e.g., level of performance, motivation, spatial ability) as it will produce remarkable outcomes.

The third research question on challenges encountered while integrating AR in STEM studies was generally associated with problems of marker detection and the usability of the devices. However, technical issues identified with the detection of the markers may be overcome in the coming years with technological advancement. This current review is centred on the characteristics, gains, and difficulties of AR in the field of STEM education. Further research can be conducted through a pedagogical approach and the potential of AR applications to support students' higher-order thinking skills in STEM education studies.

5. Limitations of the study

The articles studied in this research are limited to the journals indexed in the ScienceDirect database. However, other databases such as SSCI, ERIC, ProQuest, and Springer may also be used in

future research. This research is also limited to studies presented in article format. Future researchers may include the examination of a wider variety of documents such as conference papers, editorials, theses, and dissertations, as it may lead to the discovery of many more advantages and obstacles regarding educational uses of AR technology in STEM education.

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APPENDIX

List of AR Application

Reference	Topic	Name	Application type	Scenario
Echeverría et al. (2012)	Physic (Electrostatic)	First Colony	Game-based simulator	Students play the role of an astronaut from the first human colony on an extra-solar planet. The astronaut was given a mission to bring back a precious electrically charged crystal from space to gather energy for their colony. The player moves the crystal in different direction and acceleration and avoiding obstacles through manipulating the value of electrical charged (Coulomb's law).
Kamarainen et al. (2013)	Natural science	EcoMobile	Inquiry-based simulator	Students explore a pond to determine the types of causal dynamics it exhibits
Lin et al. (2013)	Physic (Elastic collision)	AR Physics	Collaborative learning simulator	The student in each dyad visualised two 3D virtual cubes on a marker. Student manipulated the mass and the initial velocity of the cube to simulate elastic collision. Numerical data of mass, velocity, momentum, and kinetic energy of the two objects are displayed on the screen.
Sommerauer and Müller (2014)	Mathematic	Unspecified	Exhibition	Students are divided into two groups and visit an exhibition. The exhibition consists of 275 exhibits divided into four rooms, and only twelve exhibits are augmented.
Ibáñez et al. (2014)	Physic (Electromagnetism)	Unspecified	Problem-based simulation	The learning activity involves exploring the effect of a magnetic field on a circuit and Lorentz's law by constructing a circuit to solve the proposed problem. Students are required to add a new element to the circuit constructed in each stage and can read about the concept involved.
Cai et al. (2014)	Chemistry (Molecule)	Unspecified	Inquiry-based simulation	Students use markers to represent particles and construct molecules and substances in a virtual laboratory. Students explore and conclude their inquiry-based learning and are given instruction needed.
Chiang et al. (2014)	Natural science (Ecology)	Unspecified	Inquiry-based simulator	The students used the location-based AR to browse the knowledge and information about aquatic plants. Students

				also recorded knowledge and information gain along the field trip.
Zhang et al. (2014)	Astronomy	MDAS	Inquiry-based simulator	Students involved in night time stargazing activities and are given outdoor instruction
Chiu et al. (2015)	Science (Gas properties)	Frame lab	Inquiry-based simulator	Students worked through a series of five activities to discover scientific phenomena and to interpret data gathered from the Frame lab. Students observe molecules simulation and adjusting the heat by placing the hot and cold jars near the Frame.
Huang et al. (2016)	Natural science (Ecology)	eco-discovery AR-based learning system (EDALM)	Collaborative inquiry-based simulator	Students toured a museum garden to learn the ecology of plants. Students use EDALM to observe an interactive virtual plant silhouette while guiding them to experience and explore the surrounding environment.
Akçayir et al. (2016)	Physic	Unspecified	Inquiry-based simulator	Students conducted their experiments using their AR-assisted laboratory manuals
Chang and Hwang (2018)	Science Electromagnetism	AR-based flipped learning system	flipped learning AR simulator	The students complete an electromagnet project before the learning activity. They watch the pre-class videos and finish the worksheets at home with AR operating guidance system.
Georgiou and Kyza (2018)	Natural science	Mystery at the Lake	Inquiry-based simulator	Students assumed the role of environmental investigators and are investigating the mysterious decline of the lake's mallard ducks.
Fidan and Tuncel (2019)	Physic	FenAR	Problem-based simulator	FenAR apps present problem scenarios. Based on the scenarios, the students learned the physics concept through a problem-based learning process.
Sahin and Yilmaz (2020)	Astronomy	AR-based booklet	Inquiry-based simulator	The subject was taught via the AR-based activity booklet
Ibáñez et al. (2020)	Mathematic Geometry	ARGeo	Inquiry-based simulator	Student answer question related to geometric bodies in ARGeo
Conley et al. (2020)	Mathematic Probability	MantarayAR	Problem-based simulator	Students play a role as an environmental scientist and need to investigate a recent oil spill that happened near a small bay side town in Alaska. Students were briefed on the behaviour and treatment plan for the different types of oil, the participants were tasked with trying to pinpoint the

				source of the contamination by taking multiple samples of the fish from different drinking water sources.
Chen and Liu (2020)	Chemistry (Periodic table)	Elements 4D	Collaborative learning simulator	Students observed the features of the six elements in one block. The elements were based on periodic tables. Then, the students collaboratively learned to form chemical reactions by manipulating the two blocks.