MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2024, 20(8), em2488
ISSN:1305-8223 (online)
OPEN ACCESS Review Article https://doi.org/10.29333/ejmste/14914

Augmented reality in environmental education: A systematic review

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Received 04 April 2024 ▪ Accepted 18 June 2024

Abstract

Digital technologies are opening up new ways to involve students in environmental education (EE). Augmented reality (AR) is one of these technologies and can potentially engage students and improve their learning outcomes. In this article, we systematically analyze the use of AR in EE. We searched the ERIC, Scopus, and Web of Science databases for articles related to AR and found 20 articles that met the inclusion and exclusion criteria of the research question. The results showed that most articles examined were published after 2017, and the researchers used experimental research methods. The results also showed that the research participants were mostly primary school students, and the most common sample size was between 50 and 100. In addition, the results revealed four categories: (1) contribution to student learning, (2) affective outcomes, (3) interaction, and (4) other benefits and advantages. We also found that only two articles reported the challenges of using AR in EE. In light of the findings, we recommend suggestions for future studies.

Keywords: augmented reality, environmental education, systematic review, Scopus, Web of Science

INTRODUCTION

The 20th century has opened up great opportunities for humanity, but the unconscious consumption of natural resources and environmental problems have become one of the world's biggest problems (Chamas et al., 2020; Gao & Tian, 2016; Nash et al., 2019). These problems are caused by humans' unconscious consumption of natural resources and the disruption of the balance of ecosystems (Gao & Tian, 2016). The challenges facing humanity today–global warming, the disruption of the natural balance, air and water pollution, and the depletion of the ozone layer–illustrate the critical environmental problems. Environmental education (EE) is a good alternative for tackling and overcoming these problems. It aims to minimize environmental problems and issues at local, regional, and global levels and ensure that humans do not negatively impact other living beings' safety, health, and lives by not causing pollution (Liu et al., 2023; Wu et al., 2023). For this reason, national and international conferences were organized to develop solutions to environmental issues and problems (Hsu, 2021). However, because environmental problems have become increasingly complex (Gao & Tian, 2016), there is a need to use effective teaching methods to raise awareness of environmental issues and problems (Arici, 2024; Safitri et al., 2023).

In this sense, EE is about improving today's and tomorrow's environment. Through EE, students can acquire knowledge, skills, attitudes, and values about the environment and its problems (Glowinski & Bayrhuber, 2011; van Kraalingen, 2021). Since there is no single solution to environmental problems, they become complex because they are interdependent. To prevent environmental problems, the first place to look is the

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Contribution to the literature

- Research has shown that augmented reality (AR) can be used effectively in environmental education. It has been used as a teaching method to increase the effectiveness of environmental education.
- Although many researchers have explored the use of AR in environmental education, no study has reviewed or systematically examined the benefits and advantages of using AR.
- Therefore, the aim of this article was to examine the use of AR in environmental education. The results show that AR technology offers significant benefits and advantages for environmental education and will soon be an important area of research in environmental education, especially if advances in AR technology continue.

out-of-school environment, where learning occurs through experiential learning environments (Glowinski & Bayrhuber, 2011; Schmäing & Grotjohann, 2022). This is because extracurricular learning environments in EE allow students to experience complex ecosystems that support effective learning about their problems (Thompson et al., 2023). Furthermore, out-of-school learning environments allow students to learn about their environment with limited time and materials - (Pombo et al., 2019). Integrating technology applications into the classroom can provide a solution. One of the digital technologies for solving environmental problems and implementing effective EE is augmented reality (AR) (Ardyansyah & Rahayu, 2023; Arici, 2024). It allows users to interact with virtual images in authentic contexts. The concretization of abstract concepts and the possibility of ubiquitous learning are some of the positive features of AR applications. Today, as we increasingly seek effective solutions to environmental problems and recognize the importance of EE, the lack of interaction with the real world can lead to ineffective communication on environmental issues. Since exposing students to real-world environmental issues in the classroom is very difficult, assistive technology applications such as AR can provide access to effective EE (Cakirlar-Altuntas & Turan, 2023).

Research studies show that AR arouses students' interest (Chin et al., 2020; Garzón et al., 2020; Safitri et al., 2023) and increases their motivation (Huang et al., 2019; Liu et al., 2009; Shakirova et al., 2023) and lessons are more fun (Chen, 2022; Huh et al., 2020; Liu et al., 2009; Pombo et al., 2019) and useful (Huh et al., 2020; Liu et al., 2009; Mei & Yang, 2019), and lead to increased student participation (Huh et al., 2020; Kamarainen et al., 2013; Safitri et al., 2023). AR has, therefore, gained considerable popularity over the last ten years and has been the main topic of educational research (Ardyansyah & Rahayu, 2023; Bulut & Ferri, 2023; Masalimova et al., 2023). AR is applicable at all levels of education, from preschool to university (Arvola et al., 2021; Chen, 2022; Garzón et al., 2020). According to this reasoning, AR can be used efficiently in EE (Pombo et al., 2017; Shakirova et al., 2023). It is used both as a teaching method and as an EE study subject. However, no study has reviewed or systematically examined the benefits and advantages of using AR in EE. Therefore, this study aimed to investigate the use of AR in EE.

Augmented Reality

There are many definitions of AR in the literature. Some studies have shown that AR and virtual reality, as well as some other terms, are confused or used incorrectly (de Moraes Rossetto et al., 2023). AR allows interaction with virtual objects in the real world and, therefore, the representation of computer-generated digital content in the real world. Researchers have defined AR as a technology in which computer-generated virtual images appear simultaneously on real objects (Chin et al., 2020). Although AR technology has many definitions, it has three important characteristics: the combination of real and virtual, simultaneous interaction, and three-dimensionality (Sazly et al., 2021).

Because of these characteristics, AR is a new technology that connects virtual objects with the real world. In a way, it is the digital extension or improvement of concrete reality. There is a real world and virtual objects in the natural environment. From another point of view, AR technology requires that the digital content created by the computer interacts with the user in the real world. The digital content created is three-dimensional and has various functions such as audio, video, and GPS, i.e., applications that can be provided with AR to change a digital view of the real world and specific objects in the real world. In AR, the environment consists of the natural world and virtual objects. The real environment consists exclusively of real objects or environments. In recent years, studies on AR in education have increased due to the effectiveness of the applications (Maas & Hughes, 2020; Tzortzoglou et al., 2023; Zhang et al., 2022). AR allows users to simultaneously experience the real and virtual worlds (Bulut & Ferri, 2023). It interacts with the natural experience and helps to increase students' motivation, attention, and natural experience by bringing it to life (Marín-Díaz et al., 2022).

AR technology supports the sensory perception of the real world through a computerized contextual information layer and a computer-generated representation of objects in the real world. AR is a form of digital learning combined with rich content. AR

Table 1. Inclusion & exclusion criteria

Criteria type	Criteria
Inclusion	• Peer-reviewed articles in ERIC, Scopus, and Web of Science databases • Articles focused on the use of AR in EE • Articles published in English language • No year limit for published articles
Exclusion	• Literature review, systematic review, and meta-synthesis articles • Conference proceedings, book chapters, and editors etc. • Articles that did not focused on the use of AR in EE • Articles focused on virtual reality and mixed reality

applications combine images, text, video, and audio components with existing images or media. AR technology allows us to develop our visual, auditory, and tactile senses by transferring digital information into the real world. When using AR in the classroom, the superimposition of real and virtual objects enhances the effect. It refers to the navigation process, where users do not notice the time passing. AR has recently gained considerable popularity and is now being used in many areas of education (Lin & Yu, 2023; Masalimova et al., 2023; Tzortzoglou et al., 2023; Zhang et al., 2022). From this perspective, AR technology offers opportunities to enhance learning and create effective learning environments (Bulut & Ferri, 2023). It helps students to explore interactively and learn independently, encouraging creativity and imagination. Especially in recent years, low-cost gamified AR applications, a dynamic and accessible system, have begun integrating into EE (Marín-Díaz et al., 2022).

Previous Review Studies

Although many scholars have explored the use of AR in educational research and researchers are increasingly considering the benefits and advantages of AR, no review study examines the benefits and advantages of AR in EE. To our knowledge, there is only one study by van Kraalingen (2021), who conducted a systematic review of studies dealing with the use of mobile technology in outdoor learning. She examined 33 articles on mobile technology and outdoor learning. The findings of their study reveal three main strategies: Mitigation, Intensity, and Adaptation. She also pointed out that mobile technology can support and hinder outdoor learning experiences and promote meaningful, situated, personalized, and collaborative learning outside the classroom. She also pointed out that there are some challenges in implementing mobile technology. As no study has systematically investigated the use of AR in EE, there is a need to better understand the impact of implementation in EE. Therefore, in this study, we aimed to investigate the use of AR in EE. This study's results can contribute to the literature by presenting the results regarding the status of research focused on AR and EE and advantages and challenges related to these studies.

METHOD

Data Collection

The systematic review method was used for data collection. In systematic reviews, the results of the topic under investigation are selected and summarized according to certain criteria. Several systematic approaches are used to create an objective assessment. In systematic reviews, there are stages of determining the purpose, defining the scope, applying some inclusion criteria, and selecting data screening and collection methods. A literature search used the identified data-collection keywords as inclusion criteria. The inclusion and exclusion criteria are given in **Table 1**. For AR, we used keywords including AR, augment, AR-based learning, and AR-based instruction. For EE, we used keywords including EE, outdoor education, sustainable education, ecological education, and environmental literacy. As filtering options while searching databases with keywords, we used filtering options for social sciences and journal articles published in English. In this study, we focused on research articles published in English.

For data collection, we searched articles in ERIC, Web of Science, and Scopus databases. We did not use a time limit while searching the articles. In total, 20 articles were found when searching databases according to inclusion and exclusion criteria with the identified keywords. After removing duplicated articles from three data sets, we included 20 articles in the analysis. Two researchers reviewed the abstracts, keywords, and the purposes of the articles in the databases. 90 articles were excluded from the initial analysis because they did not meet the inclusion criteria. Thus, 20 articles that met the requirements were analyzed in this research. **Table 2** shows a list of reviewed articles in this research.

Data Analysis

In the analysis phase, two authors created a table to examine the articles according to identified criteria. Then, they reviewed the articles according to the analysis parameters and discussed whether an article should be included when they needed clarification. Thus, the analysis of data was completed.

Table 2. List of reviewed articles in this research

Author(s) & year	Title	Source title
Ardyansyah and Rahayu (2023)	Development and implementation of augmented reality-based card game learning media with environmental literacy in improving students' understanding of carbon compounds	Orbital
Arici (2024)	Investigating the effectiveness of augmented reality technology in science education in terms of environmental literacy, self-regulation, and motivation to learn science	International Journal of Human-Computer Interaction
Arvola et al. (2021)	Mobile augmented reality and outdoor education	Built Environment
Chen (2022)	To explore the impact of augmented reality digital picture books in environmental education courses on environmental attitudes and environmental behaviors of children from different cultures	Frontiers in Psychology
Chin et al. (2020)	Effects of augmented reality technology in a mobile touring system on university students' learning performance and interest	Australasian Journal of Educational Technology
Cakirlar-Altuntas and Turan (2023)	Effectiveness of documentary-based augmented reality application in teaching environmental problems	Journal of Biological Education
Garzón et al. (2022)	Promoting eco-agritourism using an augmented reality-based educational resource: A case study of aquaponics	Interactive Learning Environments
Hewitt et al. (2023)	Ecosystem education with augmented reality: A flexible tool for in-field learning	Professional Geographer
Huang et al. (2019)	Do learning styles matter? Motivating learners in an augmented geopark	Educational Technology & Society
Huh et al. (2020)	Augmented reality (AR)-based intervention to enhance awareness of fine dust in sustainable environments	Sustainability
Kamarainen et al. (2013)	EcoMOBILE: Integrating augmented reality and probeware with environmental education field trips	Computers and Education
Kumpulainen et al. (2023)	Fostering children's ecological imagination with augmented storying	Journal of Environmental Education
Liu et al (2009)	Outdoor natural science learning with an RFID-supported immersive ubiquitous learning environment	Educational Technology & Society
Lo et al. (2021)	The study of AR-based learning for natural science inquiry activities in Taiwan's elementary school from the perspective of sustainable development	Sustainability
Mei and Yang (2019)	Nurturing environmental education at the tertiary education level in China: Can mobile augmented reality and gamification help?	Sustainability
Pombo et al. (2017)	Moving learning into a smart urban park: students' perceptions of the augmented reality EduPARK mobile game	Interaction Design and Architectures
Pombo et al. (2019)	Evaluation of a mobile augmented reality game application as an outdoor learning tool	International Journal of Mobile and Blended Learning
Safitri et al. (2023)	Development of augmented reality-based interactive learning media to increase interest in environmental education	Eurasian Journal of Educational Research
Shakirova et al. (2023)	The effects of immersive AR technology on the environmental literacy, intrinsic motivation, and cognitive load of high school students	Education and Information Technologies
Wang et al. (2021)	Evaluating the effectiveness of an augmented reality game promoting environmental action	Sustainability

RESULTS

Our results show that the first study on the use of AR in EE was conducted in 2009. The second article on AR and EE was published in 2013. Our results show that after 2017, the number of articles increased.

In 2023, we found six published articles on AR and EE. Almost all 21 articles we examined in this paper were published after 2017. This result shows that the number of articles about AR-EE has increased, indicating the existence of hot topics related to AR and EE (see **Table 3**).

Regarding the methods used in research on AR and EE, our results showed that researchers used experimental research methods in more than half of the studies (e.g., Garzón et al., 2020; Huang et al., 2019; Huh et al., 2020). We also found that some researchers included qualitative methods in experimental methods (e.g., Cakirlar-Altuntas & Turan, 2023; Pombo et al., 2019). This finding is followed by publications that use a mixed research methodology that includes both quantitative and qualitative methods in the research (e.g., Ardyansyah & Rahayu, 2023; Chen, 2022; Kamarainen et al., 2013; Mei & Yang, 2019). In addition,

Table 3. Number of articles according to years

Year	Number of published articles
2009	1
2010	0
2011	0
2012	0
2013	1
2014	0
2015	0
2016	0
2017	1
2018	0
2019	3
2020	2
2021	4
2022	2
2023	5
2024	1

we found that only two articles used qualitative methods in their articles (e.g., Arvola et al., 2021; Hewitt et al., 2022). **Table 4** provides a list of methods used in the research.

Our findings concerning the participants used in the research show that researchers worked with primary school students in more than half of the studies (e. g., Arici, 2024; Arvola et al., 2021; Huang et al., 2019). This finding is followed by five researchers who included students in their research on AR and EE (e.g., Chin et al., 2020; Garzón et al., 2020; Hewitt et al., 2022).

In addition, we found that four articles were conducted with high school students (e.g., Ardyansyah & Rahayu, 2023; Cakirlar-Altuntas & Turan, 2023; Huh et al., 2020). In addition, we found that middle school students were involved in the research in three articles (e.g., Chen, 2022; Kamarainen et al., 2013; Pombo et al., 2017).

Table 5 shows a list of research participants who were involved in the research.

Table 6 shows the number of participants in the research. According to **Table 6**, the most common sample size in AR and EE studies was between 50 and 100 (n=12). This result was followed by studies that used sample sizes between zero-50 (n=2) and 150-200 (n=2). In addition, we found only one study with a sample size of 100-150 (n=1) and more than 200 (n=1).

These results indicate that the researchers favored research participants between 50 and 100. This result could be related to using experimental methods in research, as this method generally requires two classes to compare results between experimental and control groups.

Benefits & Advantages of Augmented Reality-Environmental Education

In this research, we sought to identify the benefits and advantages of research on AR-EE. Our analyses yielded four categories:

Table 4. List of research methods used in research

Research method	Researchers used method
Experimental	Ardyansyah and Rahayu (2023), Arici (2024), Chin et al. (2020), Garzón et al. (2020), Huang et al. (2019), Huh et al. (2020), Liu et al. (2009), Safitri et al. (2023), Shakirova et al. (2023), & Wang et al. (2021)
Experimental & qualitative	Cakirlar-Altuntas & Turan (2023), Lo et al. (2021), & Pombo et al. (2019)
Qualitative	Arvola et al. (2021) & Hewitt et al. (2022):
Quantitative & qualitative	Ardyansyah and Rahayu (2023), Chen (2022), Kamarainen et al. (2013), Lo et al. (2021), & Mei and Yang (2019)

Table 5. List of research participants used in research

Research participants	Researchers involved these participants
Primary	Arici (2024), Arvola et al. (2021), Huang et al. (2019), Liu et al. (2009), Kumpulainen et al. (2023), Lo et al. (2021), Pombo et al. (2017), & Safitri et al. (2023)
Middle	Chen (2022), Kamarainen et al., (2013), & Pombo et al. (2017)
High School	Ardyansyah and Rahayu (2023), Cakirlar-Altuntas & Turan (2023), Huh et al. (2020), & Shakirova et al. (2023)
Undergraduate	Chin et al. (2020), Garzón et al. (2020), Hewitt et al. (2022), Mei and Yang (2019), & Wang et al. (2021)

Table 6. Number of participants in research

Number of participants	Researchers
Between zero-50	Ardyansyah and Rahayu (2023) & Garzón et al. (2020)
Between 50-100	Arici (2024), Chen (2022), Chin et al. (2020), Huang et al. (2019), Kamarainen et al. (2013), Kumpulainen et al. (2023), Liu et al. (2009), Lo et al. (2021), Mei and Yang (2019), Pombo et al. (2017), Safitri et al. (2023), & Wang et al. (2021)
Between 100-150	Cakirlar-Altuntas and Turan (2023)
Between 150-200	Huh et al. (2020) & Shakirova et al. (2023)
More than 200	Hewitt et al. (2022)

Table 7. Analysis of benefits & advantages of research on AR-EE

Categories	Sub-categories	Codes	Research
Contribution to students' learning	Contributes to EE	Environmental literacy	Ardyansyah and Rahayu (2023), Arici (2024), & Shakirova et al. (2023)
		Environmental behavior	Shakirova et al. (2023)
		Ecological imaginations	Kumpulainen et al. (2023)
	Increases student achievement	Students' understanding	Cakirlar-Altuntas and Turan (2023), Kamarainen et al. (2013), Pombo et al. (2019), & Wang et al. (2021)
		Increasing students' achievement	Chin et al. (2020), Cakirlar-Altuntas and Turan (2023), Huang et al. (2019), & Liu et al. (2009)
		More effective	Cakirlar-Altuntas and Turan (2023) & Mei and Yang (2019)
		Increase in knowledge acquisition	Chin et al. (2020), Garzón et al. (2020), Hewitt et al. (2022), & Wang et al., (2021)
	Contributes to	Understanding of what scientists do	Kamarainen et al. (2013)
		Personal hygiene management	Huh et al. (2020)
		Self-regulation skills	Arici (2024)
		Spatial visualization skills	Safitri et al. (2023)
Affective outcomes	Develops affective factors	Interest	Chin et al. (2020), Garzón et al. (2020), Huh et al. (2020), & Safitri et al. (2023)
		Self-efficacy	Kamarainen et al. (2013)
		Development of positive attitudes	Chen (2022), Mei and Yang (2019), Shakirova et al. (2023), & Wang et al. (2021)
		Motivation	Ardyansyah and Rahayu (2023), Arici (2024), Garzón et al. (2020), Huang et al. (2019), Liu et al. (2009), Pombo et al. (2017), & Shakirova et al. (2023)
Interaction	Increases learning environment	Active participation	Huh et al. (2020) & Safitri et al. (2023)
		Student interaction	Kamarainen et al. (2013)
		Parent-student interaction	Chen (2022)
		Student engagement	Hewitt et al. (2022)
		Technology supported independence	Kamarainen et al. (2013)
Other advantages and benefits	AR in EE leads to	Satisfaction	Ardyansyah and Rahayu (2023), Garzón et al. (2020), Huh et al. (2020), & Shakirova et al. (2023)
		Useful	Huh et al. (2020), Liu et al. (2009), Mei and Yang (2019), & Pombo et al. (2019)
		Enjoyment	Ardyansyah and Rahayu (2023), Chen (2022), Hewitt et al. (2022), Huh et al. (2020), Liu et al. (2009), Mei and Yang (2019), & Pombo et al. (2017, 2019)
		Flexibility & accessibility	Hewitt et al. (2022)

(1) contribution to students' learning,

(2) affective outcomes,

(3) interaction, and

(4) other advantages and benefits.

Table 7 shows these categories and subcategories, identifying the benefits and advantages of research on AR-EE.

Contribution to students' learning

Our results showed that articles about AR in EE mainly contributed to increasing or developing students' learning. We identified three subcategories to identify the benefits and advantages of research on AR EE. Accordingly, we found that AR-EE helped to enhance or develop students' environmental literacy, environmental behavior, ecological imagination, comprehension, achievement, knowledge acquisition, understanding of scientists' work, personal hygiene management, self-regulation skills, and spatial visualization skills. For example, Shakirova et al. (2023) reported that AR technology helped develop high school students' environmental literacy. Similarly, the study by Ardyansyah and Rahayu (2023) found that a learning medium developed for carbon compounds based on AR and environmental literacy helped develop high school student's understanding of carbon compound concepts in chemistry. In addition, Arici (2024) found that AR technology in developing environmental literacy helped to improve the environmental sensitivity, knowledge, and skills of fifth-grade elementary school students.

Also, our results show that AR-based instruction in EE helps to improve students' understanding of topics or concepts, achievement, and knowledge acquisition. In

addition, the studies in this subcategory found that AR applications provided more effective results than control groups. For example, Wang et al. (2021) found that a game developed based on AR improved students' knowledge of sustainability and climate change issues. Similarly, Chin et al. (2020) found that an AR-based mobile touring system developed for an authentic learning activity improved students' learning achievements in outdoor settings. Mei and Yang (2019) found that a geolocation-based mobile AR activity increased students' learning achievement and enhanced their learning experience and environmental awareness. In addition, Hewitt et al. (2022) found that they developed an AR to teach topics about forest ecology field trips for students, improving students' knowledge acquisition and consolidation. In addition, publications in the category of contribution to student learning showed that AR-EE articles contributed to a better understanding of what scientists do (Kamarainen et al., 2013), managing personal hygiene (Huh et al., 2020), self-regulation skills (Arici, 2024), and spatial visualization skills (Safitri et al., 2023). The results of these studies suggest that using AR in EE helps improve students' knowledge and skills.

Affective outcomes

Our results also show that AR-EE articles contribute to developing affective factors. Many publications (Chin et al., 2020; Garzón et al. (2020; Huh et al. (2020; Safitri et al., 2023) have reported that AR-based activities increase students' interest. The studies in this subcategory have shown that AR helps to increase self-efficacy (Kamarainen et al., 2013) and to develop positive attitudes (Chen, (2022; Mei & Yang, (2019; Shakirova et al, (2023; Wang et al., (2021) and to increase their motivation (Ardyansyah & Rahayu, (2023; Arici, (2024; Garzón et al., (2020; Huang et al., 2019; Liu et al., 2009; Pombo et al., (2017; Shakirova et al., 2023). For example, research by Huang et al. (2019) found that AR technology was friendly and stimulating for primary students to improve learning performance and motivation. They concluded that AR helps to stimulate learning intention in outdoor learning environments and provides participants with contextualized information about outdoor learning environments. Similarly, the study by Huh et al. (2020) investigated the effects of AR technology on improving students' attitudes toward fine dust. Their results showed that using AR sparked students' interest and made them engage better in learning activities. Therefore, they found that AR effectively enhanced their understanding of learning materials and positively affected affective factors.

Interaction

The "interaction" category results showed that AR-EE studies supported participants' learning environments. These studies suggest that AR increased participants' active participation (Huh et al., 2020; Safitri et al., 2023), student interaction (Kamarainen et al., 2013), parent-student interaction (Chen, 2022), student engagement (Hewitt et al., 2022), and technology-enhanced independence (Kamarainen et al., 2013). For example, Kamarainen et al.'s (2013) findings show that the teachers in their research emphasized that AR promoted student interaction and student-centered instruction and provided many benefits for classroom learning. They also reported that AR-enhanced technology-enhanced independent learning environments and student interaction.

Other advantages and benefits

Finally, our results have shown that AR in EE leads to increased satisfaction in the learning environment (Ardyansyah & Rahayu, 2023; Garzón et al., 2020; Huh et al., 2020; Shakirova et al., 2023). The results also showed that AR benefits learners (Huh et al., 2020; Liu et al. (2009); Mei & Yang, 2019; Pombo et al., 2019). In addition, studies (Ardyansyah & Rahayu, 2023; Chen, 2022; Hewitt et al., 2022; Huh et al., 2020; Liu et al., 2009; Mei & Yang, 2019; Pombo et al., 2017; Pombo et al., 2019), have reported that AR leads to enjoyment of the learning environment in EE. Furthermore, Hewitt et al. (2022) found that AR in EE is flexible and accessible to learners. Furthermore, Huh et al. (2020) showed that AR improved high school students on fine dust. Their results also showed that the satisfaction rate for AR-based lessons on this topic was very high. The students in their research stated that they enjoyed the lessons through AR-EE and actively participated in the lessons. Most students felt that AR-based lessons were useful for them in EE. They also emphasized that AR effectively stimulated students' interest, encouraged participation in learning activities, and improved students' understanding of the learning material.

Challenges

In the articles we reviewed, we attempted to determine the challenges of studies on AR-EE. Only two articles reported the challenges participants experienced when using AR in EE subjects. For example, Pombo et al. (2017) stated that there are some challenges related to the design principles of educational games developed based on AR for EE. Similarly, the study by Arvola et al. (2021) identified the challenges in the pedagogical use of AR in the classroom, including creating or selecting appropriate content and activities aligned with the learning objectives.

DISCUSSION

Our findings indicate an increase in the number of publications after 2017. The majority of the articles we analyzed were published after 2017. This result shows that the number of publications on AR-EE has increased,

indicating the existence of trending topics related to AR and EE. This result confirms the findings of Masalimova et al. (2023) and Zhang et al. (2022). For example, Zhang et al. (2022) concluded that AR is attracting significant interest in educational research, including EE, as it has the potential to facilitate student-centered learning and enhance educational experiences through digital transformation. Similarly, Masalimova et al. (2023) found an increasing trend in the number of publications about the use of AI in educational publications. AR technology offers novel opportunities to engage learners and promote innovative and sustainable educational practices. This could explain the growing number of publications dealing with AR in EE. Our findings on the research methods used in the study of AR and EE also show that experimental research methods were used in more than 50% of the studies. We also found that the researchers used a mixed approach that included both quantitative and qualitative methods. One reason for these findings could be that experimental research methods, such as the one-group pretest-posttest design used in their study, are used in AR research to investigate the effects of AR-based applications in EE on specific learning outcomes, such as student achievement and attitudes. Researchers can evaluate the effectiveness of AR interventions by comparing experimental methods using pre and post-test methods (Cetin & Turkan, 2021).

The results of our study show that the researchers worked with primary school students in over 50% of the studies. This result aligns with the findings of Maas and Hughes (2020), who examined and confirmed the studies on using virtual, augmented, and mixed reality technologies with K-12 students. They found that most of the studies were conducted with elementary school students. Students in this group are more likely to learn concrete concepts, and therefore, the researchers could assume that AR facilitates the understanding of abstract concepts for primary school students. Another finding is that the predominant sample size in AR and EE studies was often between 50 and 100, with 11 cases. This finding could be related to the use of experimental methods in research, as this approach usually requires the inclusion of two groups to compare the results between the experimental and control groups.

Our findings on the use of AR in EE suggest that there are numerous advantages and benefits. The results of our analysis suggest four distinct categories:

(1) effects on student learning,

(2) emotional effects,

(3) interaction, and

(4) other factors.

The results show that AR-EE contributes to students' learning by improving or developing students' environmental literacy, environmental behavior, ecological imagination, comprehension, achievement, knowledge acquisition, understanding of scientists' work, personal hygiene management, self-regulation skills, and spatial visualization skills. Furthermore, research has shown that AR apps deliver more efficient results than control groups. In addition, we have found that AR-EE items contribute to a better understanding of what scientists do (Kamarainen et al., 2013), personal hygiene management (Huh et al., 2020), self-regulation skills (Arici, 2024), and spatial visualization skills (Safitri et al. (2023). The results of these studies suggest that using AR in EE can improve students' knowledge and skills. Our results confirm the findings of Lin and Yu (2023), who found in their meta-analysis study that AR significantly affects knowledge acquisition outcomes. This result also aligns with the findings of Hamzah et al. (2021), who found positive effects of AR on the development of students' engagement and spatial skills.

Furthermore, our findings suggest that AR instruction in EE tasks plays a role in cultivating affective factors. For example, AR has helped to increase students' interest (Chin et al., 2020; Garzón et al., 2020; Huh et al., 2020;) and self-efficacy (Kamarainen et al., 2013) while promoting a positive attitude (Chen, 2022; Mei & Yang, 2019) and increasing their motivation (Ardyansyah & Rahayu, 2023; Garzón et al., 2020; Huang et al., 2019). The results regarding the contribution to increased interaction in the learning environment showed that AR-EE studies supported participants' learning environments. These studies suggest that AR supported learners' active participation (Huh et al., 2020; Safitri et al., 2023), student interaction (Kamarainen et al., 2013), parent-student interaction (Chen, 2022), student engagement (Hewitt et al., 2022), and technology-enhanced independence (Kamarainen et al., 2013). This result supports the findings of Lin and Yu (2023), who found that AR supported increased student engagement, self-efficacy, and motivation and improved positive attitudes.

Finally, regarding the contribution of AR to EE research, the results have shown that AR in EE leads to increased satisfaction in the learning environment (Ardyansyah & Rahayu, 2023; Garzón et al., 2020). The results also showed that AR benefits learners (Huh et al., 2020; Liu et al. (2009); Mei). In addition, studies (Ardyansyah & Rahayu, 2023; Chen, 2022) have reported that AR leads to enjoyment of the learning environment in EE. The result is similar to findings of Lin and Yu (2023) and Sáez-López et al. (2020).

CONCLUSIONS

In this article, we have systematically analyzed the use of AR in EE research. The results show that AR is one of the new technologies used to teach environmental issues and topics at all levels of education. It can engage students' interest and improve their learning outcomes. Our findings from 20 articles indexed in the ERIC,

Scopus, and Web of Science databases support this argument. Similarly, our results also show that AR technology offers essential opportunities for EE. This study aimed to identify the current state of AR EE research and determine the benefits, advantages, and challenges associated with using AR in EE. The first question of the study focused on the general characteristics of AR-STEM studies. Our results showed that the first publication was published in 2009 and that most studied articles were published after 2017. From this, we can conclude that AR will be one of the most important research topics in EE in the next few years, along with the development of AR technology day by day. As this work is the first study to systematically analyze the use of AR in EE, the results of this research can contribute to the literature and provide essential insights for researchers studying AR in EE. In this study, we reviewed 20 articles based on our inclusion and exclusion criteria and believe that there is a need to investigate the impact of AR on learning outcomes in the field of adult education.

Thus, future studies focusing on using applications in EE and outdoor learning environments may fill a research gap by adding new knowledge to researchers' existing knowledge. For this reason, we suggest that studies be conducted to determine the effectiveness of AR in informal and formal EE. This research has also shown that future studies must be conducted on teachers and adults. We believe fewer studies investigate the effects of using AR in EE. This research shows that AR technology can support EE in formal or informal contexts. As our research focused on the current situation by analyzing the benefits, advantages, and challenges of using AR, the impact of pedagogical approaches and teaching strategies should be examined in further studies. Another finding of this research is that these groups were not included in AR-EE studies. We suggest that future studies include these groups in their investigations. Our other findings show that AR in EE has many advantages and benefits. Our results show that using AR in EE supports the learning and teaching process in terms of

(1) contribution to student learning,

(2) affective outcomes,

(3) interaction, and

(4) other advantages and benefits.

Furthermore, the articles we examined did not focus on individual characteristics. The studies we analyzed focused on the general use of AR in teaching EE topics. Therefore, there is a need to examine the effects of AR use on groups with different individual characteristics, including various background factors such as achievement, age, gender, motivation, and self-regulation skills. Finally, although our findings on the challenges students and teachers faced while using AR in EE contain very little information, we believe necessary instruction on using AR in teaching environmental topics and well-designed activities and applications to overcome these challenges must be provided. In future studies, researchers can focus more on the challenges of using AR.

RECOMMENDATIONS

This paper presents a comprehensive examination of the utilization of AR in studies related to EE. The findings of our study indicate that AR technology offers substantial prospects for the field of EE. Our research indicates that AR will emerge as a prominent research area in EE soon, particularly while advancements in AR technology persist. Due to the limited number of papers examined, it is necessary to do further research on the influence of AR on learning outcomes in adult education. Moreover, it is necessary for future research to specifically examine the utilization of applications in EE and outdoor learning settings to assess the influence of AR on the expansion of the current knowledge foundation. Consequently, we propose that additional research be undertaken to ascertain the efficacy of AR in both casual and structured EE. Thus, there is a need for additional investigation into educators and grown-ups. Furthermore, there is a need for further research that specifically examines individual traits. It is necessary to examine the impact of AR usage on different groups with distinct individual traits. This investigation should encompass a range of background elements, such as achievement, age, gender, motivation, and self-regulation skills. Our study reveals a few challenges to students and teachers using AR in EE. Hence, future research should prioritize developing comprehensive instructions for utilizing AR in instructing environmental subjects and creating meticulously planned exercises and programs to address these obstacles.

Limitations

The scope of this study is restricted to publications published in journals included in the ERIC, Scopus, and Web of Science databases. The use of these databases has a limitation for data collection. Additionally, ScienceDirect, Springer, and the Web of Science are acceptable choices for database usage. The scope of this study is restricted to peer-reviewed articles conducted in empirical studies. The systematic and meta-synthesis studies were not reviewed in this research.

Author contributions: All authors have sufficiently contributed to the study and agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that they have considered the highest ethical practices when preparing the article. The study does not require approval from an ethics committee. It is based on existing literature.

Declaration of interest: No conflict of interest is declared by the authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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