

PAPER

Augmented Reality in STEAM Education: A Systematic Review of Collaborative Practices for Primary Schools

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ABSTRACT

This systematic literature review aims to evaluate empirical research on various study types and their outcomes, exploring the potential for enhancing students' collaboration skills through an augmented reality (AR)-based science, technology, engineering, arts, and mathematics (STEAM) approach in primary education. Key findings include improved student motivation, learning efficiency, the use of visual aids, and hands-on experiences. Furthermore, the study demonstrated enhancements in spatial ability, comprehension of teaching materials, and the creation of an enjoyable learning environment. Additional findings include students' analytical skills, heightened curiosity, teamwork, and problem-solving abilities. This study emphasizes the utilization of AR-based STEAM in both Western and non-Western countries, showcasing the potential for improved student collaboration. The indicators of improved collaboration include communication, problem-solving, responsibility, and collective decision-making in primary education. This is a crucial issue that requires attention in future research. Therefore, teachers and practitioners must implement interdisciplinary approaches that utilize technology to enhance students' collaboration skills. Moreover, policymakers need to ensure sufficient technological infrastructure support and training for teachers to effectively utilize AR in teaching.

KEYWORDS

science, technology, engineering, arts, and mathematics (STEAM), augmented reality (AR), collaborative skills, primary education

1 INTRODUCTION

The science, technology, engineering, arts, and mathematics (STEAM) model presents a promising interdisciplinary approach to modern education. It has the potential to stimulate creativity, critical thinking, and collaborative learning [1], [2], [3]. However, a significant gap exists between the theoretical potential of STEAM and its practical implementation in the field. Key obstacles include inadequate teacher readiness, particularly at the primary education level [4], as well as limited resources,

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insufficient funding, and time constraints that hinder in-depth exploration of the material. These factors seriously impede the optimization of STEAM's benefits [5]. This issue presents an urgent challenge: how can we bridge the gap between the potential of STEAM and the reality of its implementation, particularly in the context of limited resources and educator readiness? Given the relevance of STEAM to the demands of 21st-century skills, it is crucial to address these challenges to ensure the effectiveness and sustainability of this learning model within contemporary education systems.

The challenges encountered in implementing STEAM in primary schools significantly impact the effectiveness of learning, with technology optimization being crucial. augmented reality (AR) provides solutions by visualizing interactive STEAM concepts, boosting teacher confidence, and simulating cross-disciplinary experiments [6]. While AR has the potential to address these challenges through interactive visualization, experimental simulations, and facilitating virtual collaboration [5], [7], [8], a critical question arises: to what extent can AR technology effectively bridge the STEAM implementation gap in primary schools? Additionally, how can we ensure that AR integration not only resolves technical issues but also enhances the overall quality of STEAM learning.

Numerous studies have demonstrated the effectiveness of AR-based STEAM in enhancing the critical and creative thinking abilities of primary school pupils. However, there is a notable lack of research on its capacity to develop collaborative skills. These skills are essential for adapting to global advancements and meeting the demands of the modern workplace. This underscores the importance of fostering these skills from elementary school [9], while the national association of colleges and employers [10] reports that teamwork and collaboration are often regarded as more important than technical skills. Consequently, incorporating collaborative skill development through an AR-based STEAM methodology is a vital component of primary education.

To address these gaps, a systematic review of empirical studies published between 2020 and 2024 was conducted. This timeframe was strategically chosen to explore the insights offered by various studies on the use of AR-based STEAM to enhance students' collaborative skills. Additionally, selecting this period ensures that the information collected is relevant, up-to-date, and reflects the latest developments in the field of science. This study aims to align current educational practices with previous research findings, providing new insights and practical recommendations for designing learning experiences that prioritize the enhancement of collaborative skills among elementary school students.

2 LITERATURE REVIEW

2.1 Science, technology, engineering, arts, and mathematics

The STEAM approach at the foundational level of education aims to develop students' problem-solving skills through interdisciplinary thinking [11] by integrating the arts into various fields within a holistic learning process [12]. This approach enhances the understanding of academic concepts while also fostering essential 21st-century skills, including critical thinking, creativity, collaboration, and communication [13]. This approach also helps students strengthen the connection between their attitudes and motivation toward learning [14]. Moreover, it fosters a clearer

understanding of abstract concepts by engaging students in practical activities and collaborative projects that relate directly to their everyday experiences [4]. STEAM also has several disadvantages, including needing more resources and a long time [15]. Applying STEAM in basic education will be more effective in addressing these weaknesses when combined with virtual-based learning media, such as AR [16]. This allows the disadvantages of the STEAM approach to be addressed through the use of AR, which enhances students' collaboration, communication, and problem-solving skills, thereby better equipping them to tackle complex challenges in the future.

2.2 Augmented reality

The application of AR in primary education offers opportunities for students to learn through more interactive and immersive experiences [17]. As mobile technology becomes increasingly widespread, AR enables students to use commonly accessible devices, such as smartphones and tablets, to observe digital objects seamlessly integrated into the real world [18], [19]. This convergence of mobile technology not only enhances engagement but also promotes learning that is pertinent to students' daily experiences [20]. For example, in science learning, students can visualize and interact with three-dimensional models of environmental phenomena, like climate change, directly in the classroom using their mobile devices [21]. This technology promotes active student engagement, facilitating the comprehension of abstract concepts while nurturing both interest and motivation in the learning process [22].

Augmented reality can be applied across a wide range of subjects, from mathematics to art, thereby reinforcing a multidisciplinary approach within the STEAM framework [23]. Such integration creates a more engaging learning experience, triggering positive emotions such as enthusiasm, fun, and curiosity [24]. Additionally, AR empowers students to explore knowledge independently and interactively [25], enhancing their understanding and memory retention of the material being learned. However, AR also presents certain drawbacks, such as limitations in providing a comprehensive understanding of concepts, which necessitate that students have a solid foundation in scientific and mathematical knowledge [26]. Furthermore, students may find it challenging to connect the real world with the virtual world, which necessitates a deeper understanding of scientific concepts [27].

Considering the advantages and disadvantages, integrating AR into basic education is most effective when combined with a multidisciplinary approach like STEAM. This combination not only enhances the quality of the teaching and learning process but also leverages mobile technology to create a more adaptive and scalable learning environment that optimally supports students' cognitive development [28], [29]. The scalability of AR-based STEAM tools ensures their effective implementation across various classroom environments, making quality education more accessible to all students.

2.3 Collaborative skill

Collaboration skills at the basic education level are essential competencies that should be instilled in students from an early age. Collaboration encompasses students' ability to work together with others [30], share ideas, listen to different

perspectives, and solve problems collaboratively. This skill not only aids students in completing group assignments but also fosters the development of various scientific skills while simultaneously refining their social, communication, and empathy skills, which are indispensable for their future endeavors [31]. Through collaboration, students learn to appreciate diversity, manage conflict, and work effectively with others [32]. Collaborative learning is also closely related to project-based learning methods, group discussion activities, and various other cooperative activities [33]. Research also indicates that cooperation can enhance active participation and boost student learning motivation [34].

To assess the collaboration skills of students at the basic education level, several indicators can be observed. These include their capacity for effective communication [35], proficiency in collaborative problem-solving [30], ability to share responsibility [33], and competence in shared decision-making [36]. In primary education, collaboration skills are essential for preparing students to face the challenges of higher education and their social lives.

2.4 Primary education

Primary education serves as a fundamental cornerstone in shaping children's cognitive, social, and emotional development. In addition to teaching essential skills such as reading, writing, and arithmetic, it also fosters character, instills social values, and better prepares children for future challenges [37]. Basic education is vital for ensuring equal access to learning opportunities for every child. This, in turn, leads to improved literacy levels, greater social engagement, and enhanced contributions to society [38]. At this stage, it is crucial for teaching to adopt a holistic approach that emphasizes the creation of an inclusive learning environment, nurturing the comprehensive development of each child's potential [39]. Additionally, implementing interactive, needs-focused basic education programs is essential for creating meaningful learning experiences that are relevant to students' lives [40]. Primary education plays a vital role in children's cognitive, social, and emotional development. It significantly contributes to character formation and prepares them for future life challenges.

3 RESEARCH PURPOSE AND QUESTION

The purpose of this study is to systematically review research findings on the implementation of AR-based STEAM in basic education, focusing on publications from 2020 to 2024. This study aims to address several key questions, as follows:

- RQ1: What types of empirical research have been conducted, and what are the main findings related to the application of AR-based STEAM in Primary Education?
- RQ2: How much is the potential for improving students' collaborative skills through the application of AR-based STEAM at the basic education level, in terms of indicators such as communication skills, cooperation in problem solving, responsibility, and collective decision making?
- RQ3: How do the findings of this systematic review inform practical recommendations for overcoming the challenges educators face in implementing STEAM education?

4 METHODOLOGY

This study adopted the preferred reporting items for systematic reviews and meta-analyses (PRISMA) methodology, which offers a structured approach for systematically selecting research articles with transparency and completeness. PRISMA emphasizes the importance of clear reporting, allowing readers to assess the quality of research methodologies and results.

The research was conducted using two primary databases: Scopus and Google Scholar. These databases were selected for their extensive coverage of STEAM and AR in the educational field, as well as their well-established reputations for quality. Articles were subjected to predefined inclusion criteria that focused on relevance to STEAM and AR, with a particular emphasis on collaboration within an educational context. Specifically, studies needed to contribute significantly to understanding how AR enhances collaboration in STEAM learning.

The search for articles utilized keywords such as “STEAM education,” “Augmented Reality,” “collaboration skills,” “primary school,” and “junior secondary school.” This study focused on research published between 2020 and 2024. Articles related to junior high school were included to better understand the developmental transition of students from primary to secondary education. Additionally, this study addressed issues of student data privacy and the digital divide, as AR technology often involves the collection of personal data for personalized learning. Emphasis was placed on complying with data management regulations to ensure research quality. Furthermore, the study incorporated research findings from both western and non-western countries to illustrate the variations in research results between these regions. The initial search yielded 1,096 articles, which were subsequently screened based on the inclusion and exclusion criteria outlined in Table 1. These criteria are essential for selecting empirical studies that align with the focus of the systematic review.

Table 1. Inclusion and exclusion criteria for article selection

Inclusion Criteria	Exclusion Criteria
<ol style="list-style-type: none"> 1. Research that applies AR-based STEAM in learning. 2. This study involved students in basic education (primary and junior secondary schools). 3. Research exploring the potential of students' collaboration skills in primary education. 4. Research that reports on research methods and outcome measures. 5. Research conducted in both Western and non-Western countries, in English and non-English languages. 	<ol style="list-style-type: none"> 1. STEAM research that is not based on AR. 2. Research focusing on higher education and preschool education. 3. Research that emphasizes special needs education or remedial teaching.

Following the exclusion of studies that did not meet the criteria, 32 articles were selected for further evaluation. At this stage, the abstract of each article was carefully examined, focusing on research related to the integration of STEAM and AR, and its impact on improving students' collaboration skills. For a more comprehensive overview of the article selection stages according to the PRISMA method, please refer to Figure 1.

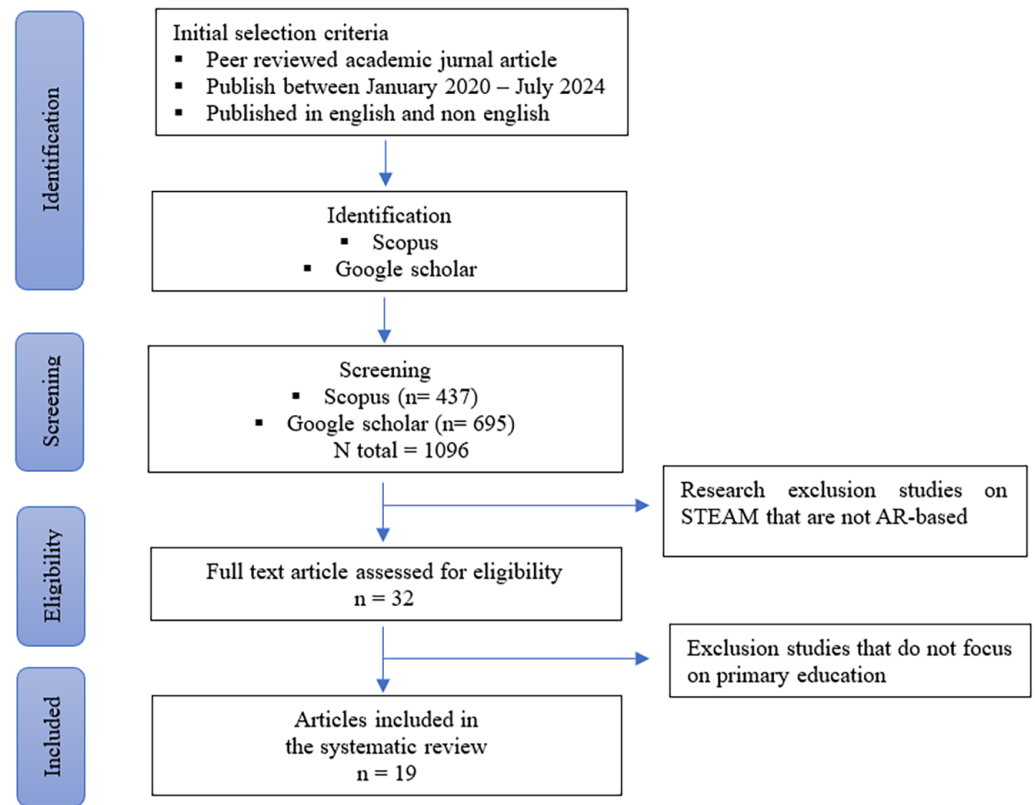


Fig. 1. The flowchart illustrating the article collection and selection process following the PRISMA method

Based on the review results, 19 selected articles were deemed eligible for thorough and detailed analysis. The findings and assessments of these articles are presented in Table 2, which includes a summary of the main ideas, variables studied, and types of studies conducted, with an emphasis on collaboration indicators.

Table 2. Main finding and measure variable of 19 eligible articles

No.	Study/Type of Research	Main Finding	Variable Measure
1	Petrov & Atanasova, 2020, [41]. Quantitative Method, Bulgaria.	The use of AR in STEAM learning creates an interactive and immersive experience that fosters collaboration and enhances student participation and learning outcomes.	The impact of using AR in STEAM education on student learning outcomes was assessed by comparing pre- and post-application test results.
2	Jesionkowska et al., 2020, [7]. Mixed Methods, England.	The use of AR-based active learning in STEAM education supports the development of a wide range of technical skills, as well as essential 21st-century competencies, such as teamwork and problem-solving.	This research evaluates the implementation of active learning within a STEAM context using a case study approach. It adopts a workshop format as an extracurricular activity for students.
3	Saroko, 2021, [42]. Quantitative Method, Ukraine.	AR technology can enhance the learning experience, motivate students, and improve efficiency in STEAM education. Additionally, AR supports teachers in delivering materials that are more contextualized and meaningful to students.	This study evaluates the application of the AR approach in STEAM learning within schools, aiming to assess the resulting pedagogical experience.

(Continued)

Table 2. Main finding and measure variable of 19 eligible articles (*Continued*)

No.	Study/Type of Research	Main Finding	Variable Measure
4	Yegorina et al., 2021, [43]. Mixed Methods, British.	AR is increasingly playing an important role in education, particularly in its application to STEAM, which enriches the learning process. Advances in technology platforms also facilitate the integration of AR in schools.	This systematic literature review examines the application of AR in STEM education, emphasizing collaboration and gamification elements specifically for geometry and geography subjects at the elementary school level.
5	del Cerro Velázquez & Morales Méndez, 2021, [44]. Mixed Methods, Spain.	This systematic literature review explores the application of AR in STEM education, with a focus on collaboration and gamification elements specifically for geometry and geography subjects at the elementary school level.	Assessing students' spatial intelligence skills through the use of AR devices in STEAM learning.
6	Atmojo et al., 2021, [45]. Quantitative Method, Indonesia.	STEAM-based AR media has been shown to be effective in improving the quality of science learning. It enables students to build understanding independently, interact with virtual objects, and provides a more natural and authentic human-computer interaction experience.	Students' learning achievement was assessed through multiple-choice tests, while the improvement in learning quality was analyzed by comparing the results of the experimental and control groups.
7	Soroko et al., 2021, [46]. Qualitative Method, Ukraine.	Most teachers expressed their readiness to integrate virtual media technology, including AR, into STEAM teaching.	The survey results indicate that teachers are very enthusiastic about using virtual media, including AR, as a tool in STEAM learning.
8	Sabil et al., 2022, [47]. Quantitative Method, Indonesia.	The use of STEAM-based AR learning media has been shown to be effective and practical, significantly improving the quality of mathematics education at the junior high school level.	Teachers' and students' perspectives on the practicality of using AR-based learning media in STEAM education.
9	Rukayah et al., 2022, [48]. Mixed Methods.	Both teachers and students greatly benefit from AR-based media to support the STEAM learning process.	The results indicate a positive response from students regarding the use of AR media in the STEAM learning process.
10	Alkhabra et al., 2023, [49]. Quantitative Method.	Integrating AR devices with appropriate teaching methods can offer students an immersive and memorable learning experience. This approach not only enhances their interest and understanding of STEAM subjects but also supports the development of essential 21st-century skills.	This study evaluates learning retention and critical thinking skills through tests designed to measure students' knowledge and understanding of the material presented with the aid of AR technology in the context of STEAM education.
11	Delcheva & Zhelyazkova, 2023, [50]. Mixed Methods, Bulgaria.	This study revealed that students achieved a deeper understanding of the learning material when using the STEAM approach combined with AR, compared to conventional teaching methods.	The study compared two teaching approaches: the traditional method and the STEAM approach supplemented with AR.
12	Vasca, 2023, [51]. Qualitative Method, Moldova.	The use of AR technology in STEAM education significantly enriches students' learning experiences in a more interactive, engaging, and applicable manner. However, the main challenges include a lack of experts in educational project planning and limited technology training for teachers, which ultimately hinder the integration of AR into education.	Assess student learning achievements, levels of participation and teamwork, and the ability to utilize AR technology in the context of STEAM education.
13	Winarni & Purwandari, 2023, [52]. Quantitative Method, Indonesia.	This supports the concept that combining AR with the STEAM approach can significantly increase student participation and enhance their understanding of the subject matter.	This study measured key variables related to the improvement of student understanding both before and after the implementation of AR in STEAM learning.

(Continued)

Table 2. Main finding and measure variable of 19 eligible articles (Continued)

No.	Study/Type of Research	Main Finding	Variable Measure
14	Delgado-Rodríguez et al., 2023, [53]. Mixed Methods, Spain.	This research highlights the potential of AR technology in enriching STEAM education and underscores the need for follow-up studies with larger sample sizes to fully understand its impact.	This study evaluates students' attitudes toward using AR methodology through a questionnaire designed to measure their perceptions and experiences with the technology.
15	Huang et al., 2023, [54]. Quantitative Method, Taiwan.	This study emphasizes the positive influence of multisensory experiences in virtual media on students' learning achievements and provides guidance for future STEAM curriculum design.	The measurement of this variable plays a crucial role in assessing the success of the curriculum that utilizes the concept of STEAM-based virtual smart greenhouses.
16	Velarde-Camaqui et al., 2024, [55]. Mixed Methods.	The measurement of this variable plays a crucial role in assessing the success of the curriculum that utilizes the concept of STEAM-based virtual smart greenhouses.	This presents a comprehensive overview of the platform's effectiveness in promoting STEAM education through the use of AR technology.
17	Zhan et al., 2024, [56]. Mixed Methods, Mexico.	This study highlights the importance of integrating cognitive principles into Virtual Education and Training Applications (VETA) design to optimize the benefits of STEAM education for learners.	These variables play a key role in evaluating the effectiveness of VETA in enriching learning experiences within STEAM education.
18	Hidayat et al., 2024, [57]. Qualitative Method, Indonesia.	AR technology simplifies the process of delivering content, enhances interaction, and stimulates creativity, while effectively visualizing abstract concepts.	The researchers evaluated the effectiveness of AR-based learning media by examining student learning outcomes.
19	Wang et al., 2024, [58]. Qualitative Method, China.	AR modules for learning have proven their ability to significantly boost young people's interest and active participation in STEM education.	AR-based learning applications are assessed using methods such as black box testing to evaluate their performance as effective educational media.

5 RESULT AND DISCUSSION

5.1 Empirical studies covering the types and results of research on AR-based STEAM in basic education

The review of 19 relevant articles in this study reveals that all these studies utilize AR as a support tool in implementing the STEAM approach to learning. The STEAM approach is highly compatible with AR, as it offers transformative learning experiences and a flexible platform for students at the basic education level. According to the research results presented in Figure 2, 17% of the studies employed qualitative methods, 39% used quantitative methods, and 44% applied mixed methods. This data indicates that research related to AR-based STEAM is not confined to a single research approach but encompasses a variety of methodologies.

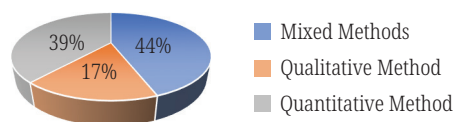


Fig. 2. Types of research on AR-based STEAM

The results of a review of research articles indicate that the application of AR-based STEAM can motivate students to learn, foster the creation of more effective and efficient learning environments, and facilitate teachers' ability to convey visual information. Additionally, this approach transforms contextual learning into direct

experiences, enhances students’ spatial abilities, and deepens their understanding of the material. As a result, learning becomes more engaging, shifting students’ focus from mere memorization to analysis [59]. Students’ curiosity also increases, which is accompanied by strengthened teamwork, improved problem-solving skills, and a greater encouragement of innovation in learning for both students and teachers. The results of this review are illustrated in Figure 3.

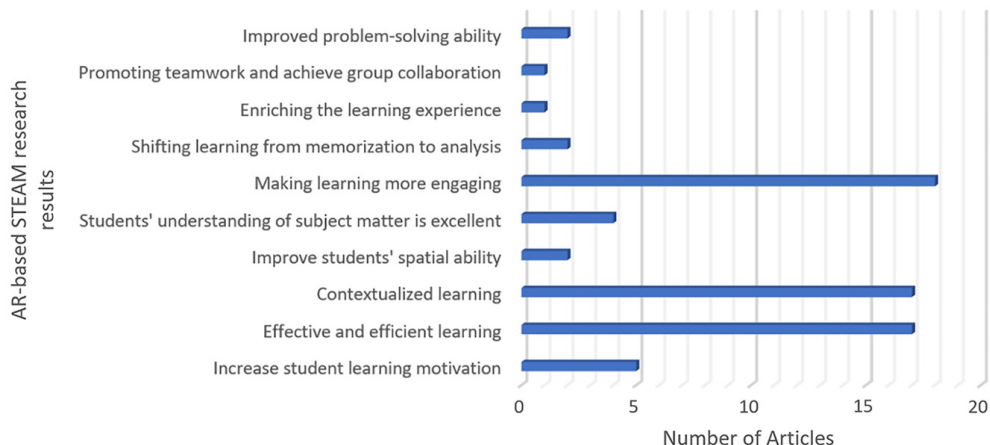


Fig. 3. Research findings regarding the application of AR-based STEAM approach in the learning process

The differences in research trends between Western and non-Western countries highlight the diversity of approaches to contemporary educational challenges, showcasing their complementary focuses. Western countries typically emphasize interactive and immersive learning experiences, the development of 21st-century technical skills, and the use of advanced technologies, such as AR and digital platforms, in STEAM education [60]. Meanwhile, non-western countries are increasingly focusing on adapting technology to fit local cultural contexts. They are working to overcome language barriers and digital divides while promoting more equitable participation among students. Both approaches provide valuable insights into the efforts to create more inclusive and effective education systems globally. These efforts consider the uniqueness of each context while still encouraging innovation in learning methods. The differences in research trends are illustrated in Figure 4.

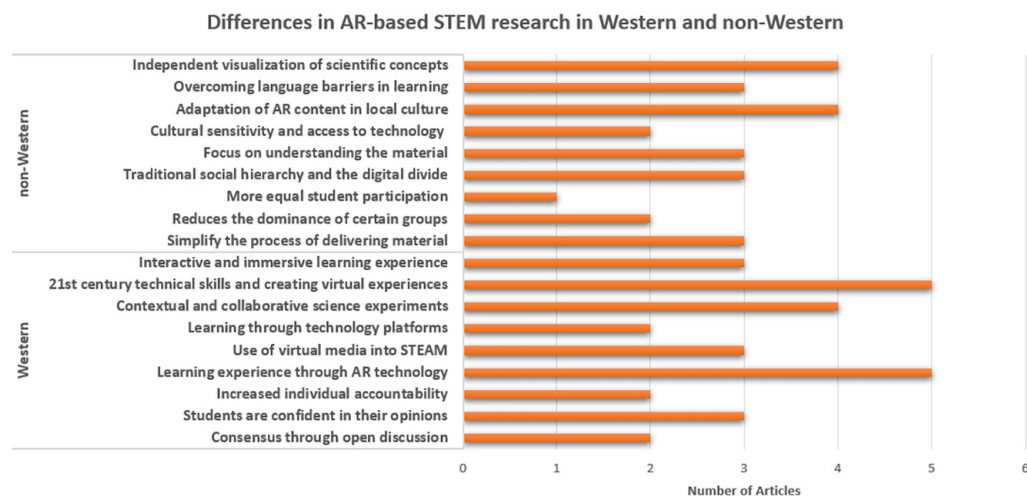


Fig. 4. Trends in research findings regarding the application of AR-based STEAM approach in the learning process in western and non-western countries

Alongside the numerous benefits associated with the implementation of AR-based STEAM education, researchers have also identified several drawbacks. Among these is the necessity for specialized training for teachers to effectively utilize AR applications within the classroom, as well as a deficiency in available supporting resources for AR materials.

5.2 The application of AR-based STEAM at the basic education level shows strong potential to improve students' collaborative abilities based on several indicators, such as communication skills, cooperation in problem-solving, responsibility, and collective decision-making

The implementation of AR-based STEAM education demonstrates significant potential for improving students' collaborative skills at the elementary level. The effectiveness of this approach is evident from the various indicators of collaboration skills identified in the 19 research articles analyzed. The findings of the study suggest that integrating AR into STEAM education can greatly enhance student collaboration, thereby laying a strong foundation for developing these skills early on.

First, the communication skills indicator demonstrates that AR-based STEAM can enhance students' understanding of the material and facilitate the effective visualization of ideas. Research conducted in Western countries has utilized AR to create virtual museum experiences, which have improved students' verbal and written communication when presenting historical artifacts [61]. In non-Western nations, AR helps bridge language barriers within STEAM education, particularly in situations where the medium of instruction differs from the students' native languages. For instance, in various Asian contexts, AR facilitates the visualization of complex scientific concepts, thereby enhancing communication skills in a second language. Overall, students in both western and non-western regions demonstrate increased confidence in articulating their ideas following learning experiences that incorporate augmented reality.

Secondly, indicators of collaboration in problem-solving suggest that AR-based STEAM learning promotes teamwork in addressing challenges. Students engaged in hands-on investigations, shared their findings, and developed collaborative strategies. In non-western countries, AR helped overcome cultural obstacles to collaboration, particularly in societies with hierarchical structures. For instance, AR facilitated more equitable participation in group discussions, reducing the impact of social norms that often restrict interaction. In both Western and non-Western contexts, AR experiences strengthened students' ability to collaborate in solving real-world problems. However, in non-western countries, cultural sensitivities and infrastructure challenges must be considered in the implementation of these technologies [62].

Third, the responsibility indicator demonstrates that the use of AR in STEAM enhances students' sense of responsibility through the assignment of specific tasks within teams. In Western countries, AR projects, such as the creation of a 3D model of a sustainable city, have shown significant increases in individual accountability [63]. Students were assigned specific responsibilities—such as green technology research, model design, and presentation—which led to increased intrinsic motivation. In non-western countries, AR helped overcome sociocultural barriers in the distribution of responsibilities. For instance, in a similar project, AR facilitated more equitable participation regardless of socioeconomic background, enhancing the sense of ownership among students who are typically less engaged. In both Western and

non-Western contexts, the use of AR promotes strong accountability. However, in non-Western countries, special considerations must be made for cultural norms and technology access, as these factors can influence the distribution of responsibilities within the group.

Fourth, the shared decision-making indicator demonstrates that AR in STEAM encourages student engagement in collaborative decision-making. In western countries, AR projects are utilized to reduce school energy consumption and enhance democratic decision-making skills. Students become more confident in expressing their opinions and reaching consensus through open discussions. In non-Western countries, AR helps bridge traditional social hierarchies in decision-making, fostering a more inclusive environment for all students. The utilization of AR visualization enables students from diverse backgrounds to participate equally in learning activities focused on energy conservation initiatives [64], thereby reducing the dominance of certain groups. In both Western and non-Western countries, AR enhances students' ability to consider multiple perspectives. However, in non-western countries, the implementation of AR must take into account cultural norms that influence group decision-making dynamics, as well as the potential digital divide that can affect equal participation in technology-based projects.

The results indicate that the effectiveness, efficiency, and innovation of learning are closely linked to collaborative skills, including communication, cooperation, accountability, and collective decision-making. In Western countries, the use of AR in STEAM has enhanced students' collaborative skills through sophisticated interdisciplinary projects. In contrast, in non-Western countries, AR helps overcome language and cultural barriers to collaboration. These skills are essential for team-based learning, as AR provides better visualization of abstract concepts, making it easier for students to work together. In Western countries, AR enhances engagement in complex projects, while in non-Western countries, it addresses limitations in accessing expensive laboratory equipment and technology. Despite its promise, research on enhancing collaboration skills through AR remains limited, particularly in non-Western contexts. Further studies are needed to explore the application of AR-based STEAM in enhancing collaboration at the elementary education level, with a focus on comparing Western and non-Western contexts to understand the impact of cultural and infrastructural factors.

5.3 A systematic review informs practical recommendations to address the challenges educators face in implementing STEAM education

For the effective implementation of AR-based STEAM practices in elementary education, several actionable insights and recommendations are essential. First, professional development and training should be prioritized. Schools should organize regular workshops and training sessions for teachers to familiarize them with AR technology and its applications in STEAM education. These workshops can include hands-on experiences with AR tools and resources [65]. Furthermore, it is essential for schools to establish peer mentoring programs in which experienced teachers, who have successfully integrated AR into their instructional practices, can provide guidance and support to their colleagues.

Second, resource allocation is critical. Schools should invest in AR tools by allocating a budget to acquire AR applications and devices, such as tablets or smartphones, which are essential for implementing AR-based STEAM activities. Furthermore, schools should encourage collaboration between educators and developers to

create customized AR content that aligns with the curriculum and enhances the learning experience.

Thirdly, curriculum integration is crucial for the successful implementation of AR in STEAM education. Teachers should design interdisciplinary projects that incorporate AR into existing STEAM curricula, allowing students to engage with real-world problems through collaborative AR experiences. Moreover, educators should utilize existing AR resources and platforms that provide ready-to-use AR content across various subjects. This approach ensures that teachers can easily integrate these tools into their lessons, enhancing the learning experience while maintaining alignment with curriculum goals [66].

Fourth, fostering a collaborative learning environment is essential for effective AR-based STEAM education. Teachers should implement team-based learning activities that allow students to collaborate on AR projects, thereby enhancing their collaboration and communication skills. Moreover, establishing AR learning stations in the classroom enables students to explore a variety of AR applications related to STEAM subjects, promoting both independent and collaborative learning experiences. Educators should regularly seek feedback from students regarding their experiences with AR-based STEAM activities to identify areas for improvement and adjust teaching strategies accordingly. Additionally, conducting assessments to evaluate the impact of AR-based STEAM practices on student learning outcomes—particularly in collaboration skills—provides valuable data for refining instructional approaches. By implementing these recommendations, educators can enhance the effectiveness of AR-based STEAM practices in their classrooms, ultimately improving students' collaborative skills and engagement in the learning process [53].

5.4 Identified gaps and recommendations for future studies

While research demonstrates significant benefits of AR-based STEAM implementation in optimizing students' learning potential and enhancing their abilities across multidisciplinary subjects, studies on its application at the elementary and junior high school levels remain limited. This limitation is primarily due to a lack of teachers' proficiency in using AR technology and an inadequate understanding of the STEAM approach within elementary education [67]. One effective approach to addressing this issue is the implementation of comprehensive and continuous training programs for teachers, specifically focusing on AR technology and the STEAM methodology. Such programs could include practical workshops, mentoring sessions, and opportunities for collaboration with experts in both technology and education. Additionally, schools can establish communities of practice where teachers can share experiences and best practices for integrating AR into the STEAM curriculum. Furthermore, action research can be conducted in pilot classes to measure the impact of teacher training on the effectiveness of AR implementation in STEAM learning. The findings from this study may serve as a foundation for the ongoing enhancement of the training program while also providing valuable insights into the existing body of educational literature.

Moreover, infrastructure limitations in many schools can pose significant barriers to the effective implementation of AR technology. Schools lacking adequate access to the necessary hardware, software, or high-speed Internet may struggle to adopt AR-based STEAM practices [68]. This disparity is especially pronounced in rural or underfunded school districts, where resources are often limited. Several practical solutions can be implemented to address this issue. First, fostering partnerships

between governments, educational NGOs, and technology companies can facilitate the provision of essential resources and infrastructure [69]. Second, it is essential to develop AR applications that can function offline or operate effectively with low bandwidth. Third, implementing device-sharing programs between schools or establishing a rotation system for device usage can enhance accessibility. Fourth, utilizing educational grants or crowdfunding can help finance necessary infrastructure improvements. Finally, focusing on creating simple AR content that can run on existing devices, such as students' smartphones, while gradually upgrading school infrastructure as budgets allow, is crucial. This approach is poised to bridge the gap between global educational trends and local practices, making AR-based STEAM education more accessible and relevant for students in non-western countries.

In conclusion, despite substantial evidence supporting the benefits of AR-based STEAM education, further research is necessary to gain a comprehensive understanding of its implementation, particularly in non-Western countries. An analysis of relevant articles reveals significant disparities between western and non-western countries regarding the implementation of AR-based STEAM education in primary schools. western countries tend to emphasize practical implementation and the integration of technology into the curriculum, while non-Western countries encounter unique challenges, including limited infrastructure, inadequate teacher training, restricted access to technology due to socio-economic factors, and gaps in policy and curriculum [70]. To address these gaps, future research should incorporate studies from diverse cultural backgrounds, investigate the impact of teacher training and infrastructure on the integration of AR, and examine non-western education systems. This approach will deepen the understanding of collaborative skills in AR-based STEAM education and contribute to more effective and inclusive educational practices.

6 CONCLUSION

Based on the findings and analysis, the application of the STEAM approach utilizing AR shows significant potential for enhancing students' collaborative skills at the primary education level. This potential is evident through several indicators, including the ability to communicate effectively, cooperate in problem-solving, demonstrate a sense of responsibility, and make collective decisions. The research findings indicate that collaboration skills encompass various elements, such as inspiring students to engage in learning, facilitating more effective and efficient educational experiences, supporting teachers in conveying visual information, transforming contextual learning into practical experiences, and enhancing students' spatial abilities and comprehension of the subject matter. Moreover, learning becomes more engaging, shifting students' understanding of material from mere memorization to analysis. Additionally, students' curiosity is heightened, fostering good teamwork and group dynamics, while also enhancing their problem-solving skills. Both teachers and students are encouraged to innovate within the learning process.

On the other hand, the methodologies employed in related studies vary, encompassing quantitative, qualitative, and mixed-methods approaches. However, there is still a need for further research on enhancing collaboration skills, as well as addressing the challenges teachers face in utilizing technology within the STEAM approach. This represents a significant challenge that must be tackled in future studies. Therefore, teachers and practitioners must demonstrate a strong commitment to implementing a technology-based STEAM approach to improve students'

collaborative skills. Educators should actively engage in incorporating AR into group projects to facilitate student interaction and promote mutual learning. Additionally, policymakers should ensure adequate technological infrastructure and provide training for teachers to enable the effective use of AR in their instruction.

Educators should actively engage in incorporating AR into group projects to enhance student interaction and promote mutual learning. Additionally, policymakers must ensure adequate technological infrastructure and provide training for teachers to facilitate the effective use of AR in their instruction. Further research is needed to explore the application of AR-based STEAM in improving collaboration at the primary education level. This study should take into account the cultural and infrastructural influences of diverse backgrounds, the impact of teacher training, and the variations in education systems. The findings of this study are expected to deepen the understanding of collaborative skills in AR-based STEAM education and to support more effective and inclusive educational practices.

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