Italian Journal of Educational Technology, 31(1): 77-88, 2023
ISSN 2532-4632 (print) – ISSN 2532-7720 (online)
DOI: 10.17471/2499-4324/1291
https://ijet.itd.cnr.it

STEM teaching and learning with innovative technologies in the upper secondary school: A scoping review

Didattica delle STEM e tecnologie digitali innovative nella scuola secondaria di II grado: una revisione della letteratura

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HOW TO CITE Roffi, A., & Cuomo, S. (2022). STEM teaching and learning with innovative technologies in the upper secondary school: A scoping review. *Italian Journal of Educational Technology,* 31(1): 77-88. doi: 10.17471/2499-4324/1291

Received: March 6, 2022; *Accepted:* June 8, 2022; *First Published:* July 8, 2022

ABSTRACT The integration of digital technologies in the school context has now become a necessary and fundamental process in daily teaching practices. In particular, innovative technologies such as the so-called X-Reality seems effective to promote student learning, to encourage the acquisition of skills and interest in scientific disciplines, although their potential and possible drawbacks are still under inquiry. Based on these premises, the purpose of this literature review is to outline the state of the art of the use of X-Reality in STEM education in the context of upper secondary school, without limitations regarding the country, to understand the benefits, the critical aspects and the challenges faced by researchers in this field. To answer these Research Questions, a scoping review was conducted based on the Scopus and ERIC databases. The results highlight how the use of X-Reality in STEM teaching offers many opportunities for learning concepts and acquiring scientific skills. At the same time, however, an accurate balance of these positive effects with the related risks is also required, in order to allow a critical and conscious use of these innovative technologies.

KEYWORDS STEM Teaching and Learning; X-Reality; Digital Technologies; Secondary School.

SOMMARIO L'integrazione delle tecnologie digitali nel contesto scolastico è diventato ormai un processo necessario e fondamentale nelle pratiche didattiche quotidiane. In particolare, le tecnologie innovative come le cosiddette X-Reality sembrano particolarmente efficaci per promuovere l'apprendimento degli studenti, per favorire l'acquisizione di competenze e promuovere l'interesse per le discipline scientifiche, anche se il loro potenziale e le criticità del settore sono ancora oggetto di studio. Sulla base di queste premesse, lo scopo di questa rassegna della letteratura è quello di delineare lo stato dell'arte dell'utilizzo delle X-Reality nell'educazione STEM nel contesto della scuola secondaria di secondo grado, senza limitazioni geografiche, per comprendere i benefici, gli aspetti critici e le sfide da affrontare in questo campo. Per rispondere a queste domande di ricerca, è stata condotta una revisione della letteratura sui database Scopus ed ERIC. I risultati di questo lavoro mettono quindi in evidenza come l'utilizzo delle X-Reality nella didattica delle STEM offra molte opportunità per l'apprendimento dei concetti e l'acquisizione delle competenze scientifiche. Al tempo stesso però è richiesto anche un accurato bilanciamento di questi effetti positivi con i rischi correlati, per poter arrivare ad un utilizzo critico e consapevole di queste tecnologie innovative.

PAROLE CHIAVE Didattica STEM; X-Reality; Tecnologie Digitali; Scuola Secondaria.

1. The use of innovative digital technologies in the school context

The integration of digital technologies in the school curricula has now become a necessary and fundamental process in the daily teaching practices. In particular, innovative technologies such as the so-called X-Reality, i.e. Augmented Reality (AR), Virtual Reality (VR), Mixed Reality (MR) or 360° video, used both in the traditional 2D and immersive 3D modality, are particularly effective to promote student learning, to encourage the acquisition of skills and to foster the interest in scientific disciplines (Roffi, Cuomo, & Ranieri, 2021; Ranieri, Bruni, & Luzzi, 2020; Shu & Huang, 2021; Chavez & Bayona, 2018; Ibáñez & Delgado-Kloos, 2018).

In fact, one of the added values of these technologies is the possibility to take advantage of the visual component for teaching scientific concepts or phenomena not easily explored in class, resulting in improved effectiveness than the traditional methods (Arici, Yildirim, Caliklar, & Yilmaz, 2019).

The positive results related to the use of these technologies, in particular in the teaching of STEM (Science, Technology, Engineering and Mathematics disciplines), have been reported both in primary and secondary schools, in terms of improving learning outcomes, attitude and motivation (Roffi, Cuomo, & Ranieri, 2021), although their potential and possible drawbacks are still under inquiry. Besides these positive effects, Fidan and Tuncel (2019) described how X-Reality is able to promote the retention of knowledge up to 3 weeks after the educational intervention. Moreover, these technologies are also able to increase the scientific aspiration in particular of female students, thus favouring the reduction of gender differences in learning STEM subjects (Makransky, Petersen, & Klingenberg, 2020).

However, despite this positive evidence, there are still many questions that require further investigation, for example whether X-Reality could be appropriate for each teaching context and for all students. In this regard, a recent review of the literature (Pellas, Kazanidis, & Palaigeorgiou, 2020) highlighted that in secondary education the use of MR learning environments leads to benefits in terms of student learning outcomes, but in the context of primary school this improvement is limited to student participation and involvement.

Moving to teaching strategies, Inquiry Based Learning (IBL) was found to be the most used for STEM teaching also in virtual contexts (Pedaste et al., 2015; Ibáñez & Delgado-Kloos, 2018; Arici et al., 2019). IBL is an educational strategy that promotes the discovery of knowledge through the formulation of hypotheses and subsequent verification through experiments or observations (Pedaste et al., 2015). Students are involved in reproducing methods and practices similar to those of the scientific method, focusing on the characteristics of scientific thinking, and drawing inspiration from the principles of Situated Cognition (Brown, Collins, & Duguid, 1989) and experiential learning (Kolb, 1984). However, this teaching strategy presents some challenges for students and teachers, especially in the design phase (e.g. in relation to dependent and independent variables; Arnold, Kremer, & Mayer, 2014). Digital technologies could therefore provide support to overcome the above mentioned difficulties (Kyza, Constantinou, & Spanoudis, 2011). In particular, X-Reality can support situated and experiential learning, simulating the real context where knowledge is applied and integrating authentic activities even when access to real situations is not possible. Coiro, Castek and Quinn (2016) have developed a framework that integrates the IBL strategies with the use of digital technologies, called Personal Digital Inquire (PDI), providing suggestions for teachers on how to structure educational interventions that involve the use of PDI to meet the student's needs (Ranieri, 2022).

Another aspect that requires careful consideration is the digital well-being of students and teachers (Luzzi, Cuomo, Roffi, & Ranieri, 2022; Melo et al., 2020). In fact, the use of these environments requires an appropriate balance between opportunities and risks (Melo et al., 2020) and must be addressed from a multidisciplinary point of view. Following the model proposed by Cuomo and collaborators (2022) related to the educational context, digital well-being in immersive environments can be declined according to 4 perspectives: the cognitive perspective, considering the implications deriving from isolation during the immersive experience, the physiological perspective, considering the physical implications (nausea, headache) deriving from the use of wearable devices, the social perspective, considering the relational dimension especially in teaching activities in groups, and the educational perspective, which considers the learning opportunities that these innovative technologies offer.

Therefore, it is not only necessary to promote the use of new digital technologies in STEM education, but it is equally important to take into account the dimensions of digital well-being, allowing critical use of these tools. Furthermore, from a technical point of view, usability and the possible cognitive overload are the main challenges for the correct design and implementation of X-Reality in education (Altmeyer et al., 2020).

Finally, it is also necessary to consider aspects related to the digital skills of teachers and students, which can constitute a barrier to the integration of these technologies in the classroom. The pandemic has certainly brought to light the difficulties of teachers in terms of these skills, underlining the lack of training regarding the adoption of digital technologies in the daily teaching practices (Carretero Gomez et al., 2021). In fact, the recent literature relating to the didactic changes introduced in the pandemic period highlights how the main difficulties encountered by teachers during online teaching can be related with the lack of competence needed to re-design teaching with the use of digital technologies (Carretero Gomez et al., 2021).

Based on these premises, the purpose of this literature review is to outline the state of the art of the use of X-Reality in STEM education in the context of upper secondary schools, to understand the benefits, the critical aspects and the challenges to be faced in this field.

In particular, the following Research Questions (RQs) have been formulated:

- RQ1: What are the characteristics of the published studies in the field of STEM teaching with technologies using X-Reality in the upper secondary schools?
- RQ2: What are the disciplines involved, the teaching strategies and the innovative digital technologies used for STEM learning in the upper secondary schools?
- RQ3: What are the benefits, critical aspects and challenges for teachers and students in using these technologies for STEM learning?

2. Methodology

To answer the RQs, a scoping review (Grant & Booth, 2009) has been conducted in accordance with the PRISMA guidelines (Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009), except for those items that are specific of meta-analyses. In fact, although it is not a systematic review, the scoping review shares the characteristics of transparency, reproducibility and systematicity (Grant & Booth, 2009).

The review has been conducted on the Scopus and ERIC (Education Resources Information Center) databases with the following search string: (stem OR steam OR science OR technolog* OR engineering OR mathematics) AND (education OR learning OR teaching) AND ("digital technolog*" OR "mixed realit*" OR "virtual reality" OR "augmented reality") AND ("secondary education" OR "secondary school"). The papers published in the last 5 years have been considered due to the rapidly changing technological scenarios.

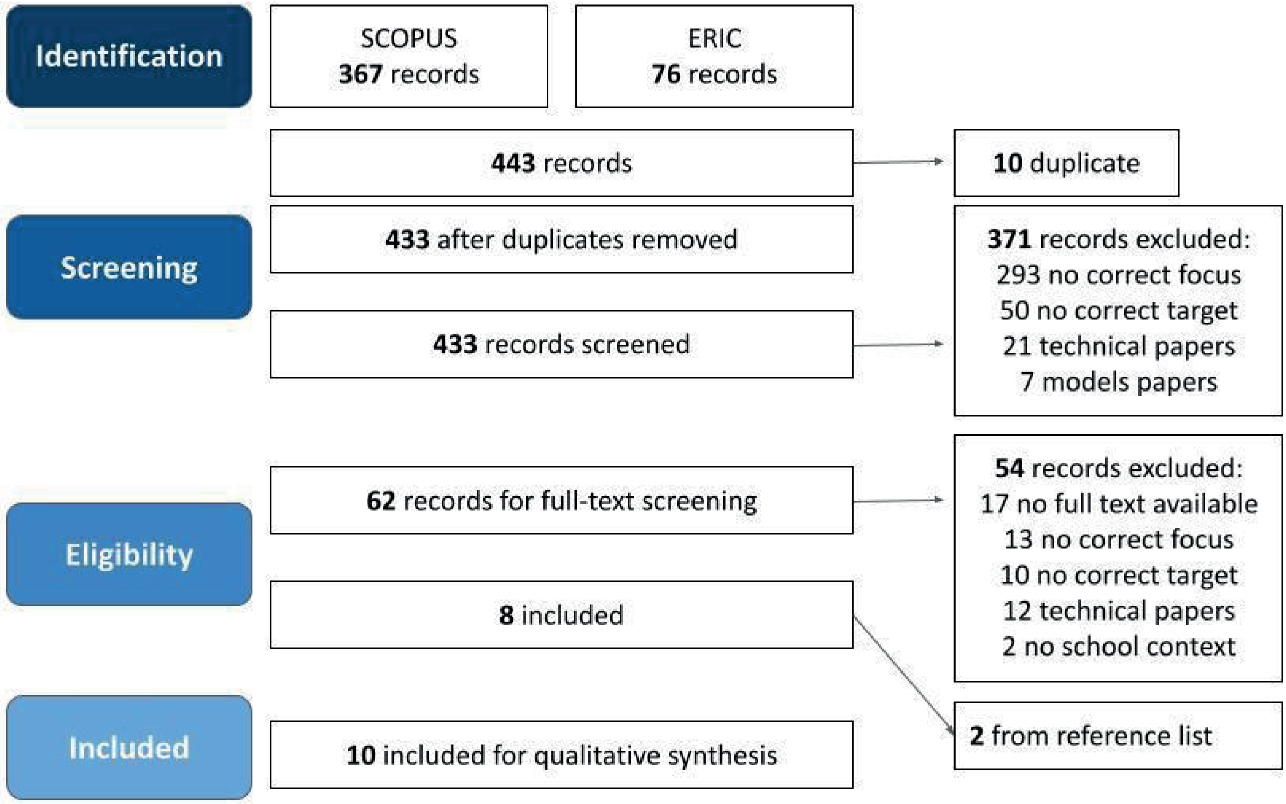

Figure 1. Workflow for papers selection according to PRISMA.

A summary of the inclusion and exclusion criteria is shown in Table 1. After the selection of papers by title and abstracts screening, the complete available full text has been analyzed and the useful information was extracted. Reference lists of selected papers were also searched for further relevant articles. Initially, 443 papers were found, of which only 10 were included, due to the strict criteria of inclusion and exclusion and aimed at selecting papers specifically focus on STEM teaching in upper secondary school. As we can see in the Figure 1, about 300 have been excluded because although the STEM and digital technologies were mentioned in the title and in the abstract the focus of the paper was out of the scope of this literature review. For the analysis of the papers, a coding table has been designed in order to identify the categories for the study description. According to the research questions, 4 categories have been identified with the relative sub-categories, as shown in Table 2.

3. Results

3.1. RQ1: What are the characteristics of the published studies in the field of STEM teaching with technologies using X-Reality in the upper secondary schools?

As for the year of publication, most of the papers were published in 2021 (7/10), the rest in 2020 (2/10) and in 2019 (1/10).

The selected papers presented researches conducted in different geographical areas: 3 in China, 1 in Greece, 1 in Taiwan, 1 in Cyprus, 1 in Bulgaria, 1 in Finland, 1 in Spain and 1 in Indonesia.

Table 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Papers on STEM teaching with digital technologies	Technical papers (i.e. describing software or app development without application phase in the classroom)
Peer-reviewed journals	Papers not dealing with the school context
Papers in English	Papers with an exclusive focus on the usability of digital technology
Books, book chapters, conference proceedings, empirical papers	Papers with an exclusive focus on didactic models
Upper secondary school	Other targets (teachers, primary and lower secondary students, universities)

Table 2. Coding table for papers description.

Categories	Subcategories
Characteristics of publications	Authors Year Title Journal Geographical Area
Technical information	Technology type Technology equipment
Research Design	Study Design Teaching Strategy Duration of educational intervention Subject Training before experience
Results	Learning outcomes Learners' reactions Benefits and drawbacks

Regarding the type of X-Reality technology used in STEM teaching, 7/10 articles describe the use of AR and 3/10 of VR. No articles describing experiences with MR or 360 video for STEM education. For this reason, in the current analysis we will explicitly refer to the technology used (AR or VR) instead of using the general term X-Reality.

Even if the papers analyzed refer to different school systems, the target of each article is the upper secondary school, in accordance with the criteria for inclusion of the research, with different ages ranging from 14 to 19 years old. Moving to the types of experimental designs, 3/10 articles have a quasi-experimental design, 3/10 experimental, 3/10 a pre-experimental design, and 1/10 a case study. A synthesis of these data has been reported in Table 2.

Table 3. Characteristics of the studies.

Authors	Year	Technology used	Experimental design
Cai, Liu, Wang, Liu, & Liang	2021	AR	Experimental
Del Cerro Velázquez & Morales Méndez	2021	AR	Quasi-experimental
Georgiou, Tsivitanidou & Ioannou	2021	VR	Pre-experimental
Liu, Yu, Chen, Wang & Xu	2021	AR	Experimental
Ling, Zhu & Yu	2021	AR	Quasi-experimental
Niittymaki, Christopoulos & Laakso	2021	VR	Case study
Shu & Huang	2021	VR	Experimental
Petrov & Atanasova	2020	AR	Pre-experimental
Weng, Otanga,Christianto & Chu	2020	AR	Quasi-experimental
Tomara & Gouscos	2019	AR	Pre-experimental

3.2. RQ2: What are the disciplines involved, the teaching strategies and the innovative digital technologies used for STEM learning in the upper secondary schools?

As for the disciplines involved in the educational experience with AR/VR, Physics is the most represented (4/10), followed by Biology (3/10), Chemistry (1/10), Information and Communication Technologies (1/10), and Mathematics (1/10), as shown in Figure 2.

The teaching strategies used are various, 3/10 describe the use of collaborative educational strategies, 2/10 report the experience with AR to guide learning processes by discovery, in groups or individually, and 1/10 uses a directive strategy.

Another aspect to be analyzed is related to the duration of the educational interventions, which represents a variable parameter in the analyzed papers: in 4 studies the experimental design foresees only one lesson lasting about one hour, while in 5 studies they refer to sequence of lessons over a time lapse of a few weeks or even months.

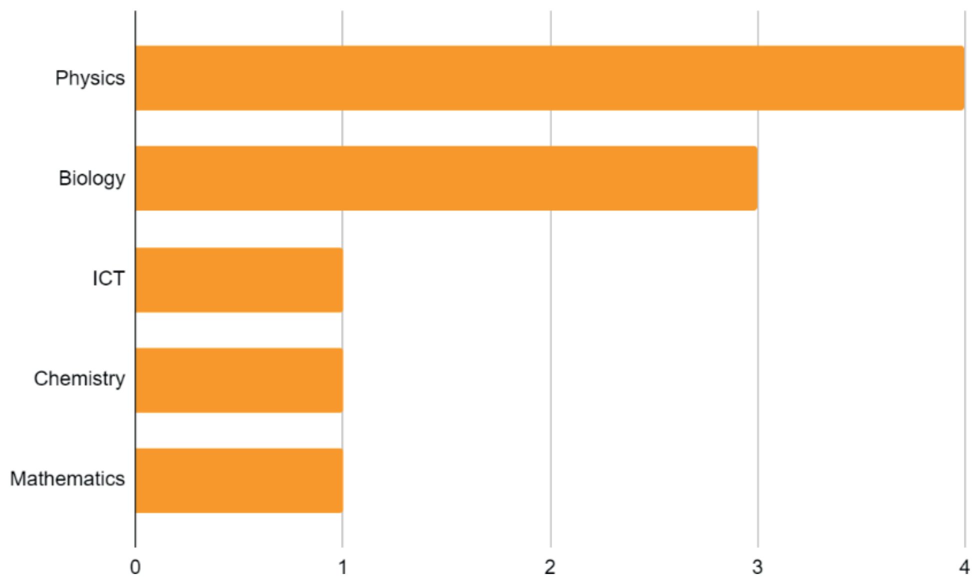

Figure 2. Frequency of STEM disciplines in the papers analysed.

The use of digital technologies, especially the immersive ones, which require the use of a special headset that alienates the user from the surrounding world, can lead to the novelty effect on students, in particular for those who do not regularly use these technologies (Liu et al., 2021). This bias could prevent the effectiveness of the educational intervention supported by innovative technologies and therefore it is an aspect that needs to be considered. Only two articles deal with this aspect: one by devoting some training time before the actual learning intervention, to allow students to improve their confidence with the technology used, the other by choosing a target of students already confident with X-Reality.

3.3. RQ3: What are the benefits, critical aspects and challenges for teachers and students in using these technologies for STEM learning?

The effects of using the technologies identified for this literature review (AR and VR) in teaching practice are reported below, highlighting benefits, critical aspects, and future challenges.

3.3.1. Attitude, motivation and interest

As concerns the use of AR in teaching practice, one of the positive effects is related to the improvement of attitude towards STEM disciplines, as demonstrated by Weng and collaborators (Weng et al., 2020). The results achieved by the research team demonstrate how this innovative technology can make biology's learning interesting and fun. Similarly, Petrov and Atanasova (2020) describe the use of AR in a biology lesson, making the learning process simple and at the same time interesting and motivating. Always within the sphere of interest and motivation, VR is also able to promote them. In particular, the research by Niittymäki, Christopoulos and Laakso (2021) has shown that VR positively impacts on interest, motivation and attention to details in biology teaching. However, it is important to pay attention to the level of difficulty of the proposed topics when planning educational interventions, as well as the number of activities to be completed. This is needed to avoid negative impact on motivation and interest which could in turn hinder performance (Niittymäki, Christopoulos, & Laakso, 2021).

3.3.2. Learning and knowledge retention

AR and VR also offer benefits in terms of knowledge retention and improving the learning of STEM disciplines. Liu and collaborators (2021) described significant improvements in students learning in the field of physics: these have been larger with the use of AR compared to 3D animations and traditional study materials (such as real magnets and other objects to explore magnetism) with long-lasting learning outcomes (Ling, Zhu, & Yu, 2021) and better visuo-spatial skills (del Cerro Velázquez & Morales Méndez, 2021). On the other hand, it has also been shown that these positive learning outcomes seem to be limited to the analytical dimension, thus not involving the memory and understanding dimensions (Weng, Otanga, Christianto, & Chu, 2020). Finally, not all students can benefit from the use of AR technologies for learning, as reported by Ling and collaborators (2021): their research highlights that "high foundation of learning"[1] and excellent visual-spatial skills are characteristics that would allow students to use AR effectively, reaching long-lasting learning outcomes. On the contrary,

[1] The author defines this term as an important representation of previous content knowledge.

students with poor pre-existing competence and visual-spatial skills, the use of AR for learning is not effective, even if there is a good attitude towards this technology.

Similarly, VR used in the teaching of physics has proven effective in achieving significant learning outcomes. Furthermore, the students underlined how the realism of the immersive experience combined with the process of knowledge construction have increased their involvement in learning (Georgiou, Tsivitanidou, & Ioannou, 2021).

3.3.3. Cognitive load

Liu et al. (2021) described a lower mental load in learning physics with the use of AR, also accompanied by a lower mental effort that makes students able to better process the complexity of experimental activities.

3.3.4. Improvement of understanding

Still in the field of physics, it has been documented (Cai et al., 2021) that the use of AR promotes an improvement in self-efficacy in students, makes them better able to reach high levels of understanding of complex concepts and thus stimulates their motivation for deeper learning.

Improving understanding of study material is another positive aspect of using AR: Petrov and Atanasova (2020) reveal that AR use improves students' understanding of study material compared to traditional materials based on texts and graphics.

3.3.5. Technological aspects

The novelty of X-Reality applications implies a relative technological immaturity that may cause critical aspects and barriers to their adoption. Cai and colleagues (2021) underlined some drawbacks related to the software prototypical status and in particular to an exceedingly slow response of the applications. In the case of VR, the main aspect that requires further reflection concerns the poor quality of the experience that caused a decrease in enthusiasm, as mentioned by Niittymaki and collaborators (2021). According to the authors, these critical aspects are attributable to the use of low-cost equipment. In addition, in this research, two students were not included in the experiment due to the incompatibility of the VR software with the operating system of their mobile phones. Finally, a further drawback underlined (even if not directly linked to the technology itself) is the language barrier due to a software interface in English, which is considered difficult by many non-native English students.

4. Discussion

This scoping review has analyzed the use of so-called X-Reality (AR, VR, MR and 360° Video) in STEM teaching in the context of upper secondary schools, identifying 10 relevant papers that focus on the use of AR and VR technologies. It should be noted that the lack of papers on MR and 360° Video is probably due to the relative novelty of these technologies; in particular with regard to 360° Videos, even if their use in educational practice is increasing, especially in higher education (Ranieri, Luzzi, Cuomo, & Bruni, 2022).

The studies published in the field (RQ1) describe experiences in different geographical areas, with China most represented. Seven articles (7/10) focus on research on the use of AR in the teaching of scientific disciplines and 3/10 on VR. As for the research designs, more than 50% of the articles have an experimental (3/10) or quasi-experimental (3/10) design, underlining the research effort aimed at understanding the benefits and critical aspects of these innovative technologies in comparison with long-established educational strategies with traditional school materials.

Only 6 out of 10 articles specifically indicate the educational strategy used in interventions supported by AR or VR and, among these, the collaborative strategies and IBL are the most represented. Physics and Biology are the disciplines most frequently dealt with in the papers. In this regard, in fact, Cai and colleagues (2021) underlined how physics education is going through a period of change towards a more active dimension of students involvement in the scientific investigation process and in the acquisition of knowledge through self-directed processes, and at the same time how some topics (for example optics, electrical forces - Tomara & Gouscos, 2019 or magnetism - Liu et al., 2021) require complex equipment for demonstrations that would be difficult to use in the classroom or laboratory. In this context, X-Reality provides a valid support to the IBL process, making abstract concepts visible and interactive (Cai et al., 2021). Similarly, the use of these technologies can also offer benefits in the context of biology learning, a discipline more effectively taught with technologies due to the need to visualize invisible aspects (Weng et al., 2020).

The dimension of time is another important point to be considered: this literature review showed experiences involving individual lessons or several ones over some weeks, depending on the type of discipline and the teaching strategy used. In particular, it is necessary to pay attention to the duration of the experience with X-Reality in terms of digital well-being, according to the 4 perspectives identified by the model of Cuomo et al. (2022) previously described. In this perspective, the distracting effect of X-Reality on students, which occurs by introducing immersive technologies not frequently used in daily teaching practices (novelty effect) (Liu et al., 2021) should be countered since it hinders the effectiveness of the educational intervention itself. Few articles (2/10) have taken this aspect into consideration, implementing strategies to mitigate this effect (a short training phase before the teaching experience) or selecting a target with a good degree of confidence with this type of technology.

As for the learning outcomes derived from the use of X-Reality in STEM teaching (QR3), it can be said that the benefits are multiple and linked to different aspects. First, positive effects have been reported on attitude towards discipline, interest, and motivation, as well as on learning and knowledge retention, although further research is needed in order to prove the long-term effect.

Secondly, a further benefit is related to the impact on cognitive load, in particular for AR. It has been reported that the use of X-Reality has led to a decrease in mental load, promoting in turn a better processing of the complexity of the experimental activities. Moving to the reactions of the students, in general the use of X-Reality in STEM teaching has been appreciated, with a request to extend its use in other scientific subjects. However, it should also be considered that the positive effects of X-Reality are not simply generalizable and could be influenced by the characteristics of students. Indeed, Ling and collaborators (2021) investigated the relationship between levels of foundation of learning and visual-spatial skills, and the use of AR and its effect on learning, identifying that a solid competence base and excellent visual-spatial skills are characteristics that would make possible to use AR effectively, reaching long-lasting learning outcomes. Also in this case, further research is needed to deepen the issue of when using X-Reality in STEM teaching is appropriate and when it is not, by striking a balance between, on one hand, the characteristics of the students, and on the other, their training needs.

Finally, two reflections arise on the technical dimension, concerning the limitations that can affect the effectiveness of these technologies in the educational context (the proper operation of devices and applications) and the need to make sure students have the necessary equipment to conduct learning activities with these innovative technologies. The former has to do with difficulties regarding interactivity due to the typical slow response time of the software, which had a negative impact on the learning outcomes. It is therefore necessary to take into account this aspect in the design phase of STEM learning by including, for example, a test-phase before their use.

The latter concerns the equipment needed for conducting educational interventions with this type of innovative technologies. In the articles considered, tablets, PCs or smartphones and, in some cases, wearable devices (head-mounted displays) were used for a complete immersive experience, showing that these innovative technologies do not always require technologically sophisticated equipment. Nonetheless for a wider adoption of X-reality in school curricula, and particularly for the immersive technologies, careful consideration must be given to the strong dependence from technological devices and their fast obsolescence, as well as the difficulties that some students, especially those with some impairments, may have in using these devices, thus limiting the full exploitation of the potential of the technology.

5. Conclusions

The results of this literature review highlight how the use of X-Reality technologies in STEM teaching, and in particular AR and VR, offers many opportunities for effective learning and acquiring scientific skills by promoting interest, engagement and knowledge retention. At the same time, however, some drawbacks are reported, particularly related to the immaturity of the technology, that should be overcome to allow a wide adoption in upper secondary school curricula.

In terms of future research perspectives, some points can be underlined from a pedagogical point of view. Firstly, it is important to further investigate the long-term effect of the use of X-Reality for STEM education, especially in relation to the implication on knowledge retention. Secondly, it is also necessary to deepen the knowledge on when the use of X-Reality in STEM teaching is appropriate and when it is not, taking into account the characteristics of the students and their training needs. Thirdly, particular attention should be given to the inclusiveness of these technologies so that their use does not create a boundary between the students with the effect of excluding the disadvantaged or impaired ones. These aspects, at present not completely addressed in the literature, can be seen as a relevant research perspective in the next future. Finally, from a technological point of view, it is necessary to carefully consider the phase of testing after the development of these digital environments, in order to limit any possible technical problem resulting in a negative impact on students' learning.

6. Authors' contributions

This contribution can be attributed for paragraphs 1, 2, 3 to Alice Roffi and for paragraphs 4 and 5 to Stefano Cuomo.

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