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The role of extended reality technologies in hygiene education and training: a systematic review of applications, benefits, and challenges

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Abstract

Background The emergence of the Metaverse and Extended Reality (XR) technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has created innovative opportunities for healthcare education and training. These immersive technologies show promise in enhancing infection prevention and control, especially during infectious disease outbreaks.

Objectives This systematic review aims to evaluate the current application of XR technologies in infection control education, identifying key trends, benefits, and limitations of VR and AR-based interventions.

Methods A comprehensive literature search was conducted on January 12, 2025, for the Web of Science and PubMed databases using keywords related to hygiene, infection prevention, and XR technologies. An initial pool of 162 articles was screened, resulting in 38 studies that met inclusion criteria. These studies were descriptively analyzed to assess their contributions, focus areas, and outcomes.

Results The review indicates most studies show XR tools effectively improve practical skills, behaviors, or attitudes, while a smaller number reveal limited or no significant gains, especially in knowledge and compliance. This result shows that XR tools have the potential to improve knowledge retention, practical skills, and provide real-time feedback, outperforming traditional training methods. XR tools specifically enhanced hand hygiene, proper use of personal protective equipment, and emergency response training, areas critical during outbreaks like COVID-19. Nevertheless, widespread adoption remains limited due to the need for more long-term efficacy data and strategies for integrating XR into standard curricula. To fully realize this potential, it is essential to address existing limitations related to cost, safety, and validation, while establishing robust frameworks for curriculum integration and policy implementation.

Conclusion XR technologies play a crucial role in advancing infection control education by offering potential benefits for healthcare training and education. Future research should prioritize evaluating long-term outcomes and

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developing effective implementation strategies to facilitate broader adoption, maximize their educational impact and, and mitigate potential barriers.

Clinical trial number Not applicable.

Keywords Augmented reality, Extended Reality, Hand hygiene, Healthcare worker, Immersive, Infection control, Infection prevention, Metaverse, Training, Virtual reality

Introduction

Virtual reality (VR) technology is rapidly advancing and offers numerous educational opportunities. As an innovative technological tool, VR is cost-effective and allows users to interact with realistic 3D computer-generated environments in real-time, engaging their natural senses and abilities [1–3]. Through VR applications, users can manipulate virtual objects and collaborate with others within immersive three-dimensional (3D) environments that are digitally created [4–6]. Augmented reality (AR) enhances real-world settings by overlaying digital elements onto physical environments through visual displays. AR creates a "smart environment" that leverages location-based and network-based technologies, often using immersive or semi-transparent headgear to project real-time images of the physical world with digital augmentations [6, 7]. Hence, unlike VR, which immerses users entirely in a virtual realm, AR enriches real-world interactions by integrating digital information directly into the physical environment, facilitating more practical and accessible learning experiences [1–3, 8–13]. Mixed Reality (MR) combines real and virtual elements interactively. In other words, AR provides overlays without deep interaction, while MR allows for more natural and interactive experiences between real and virtual objects. MR creates a more integrated and immersive experience, often with 3D spatial mapping, whereas AR is typically simpler and less spatially aware [14, 15]. Extended reality (XR) is an umbrella term for AR, VR, and MR. The Metaverse is a 3D-based VR platform enabling users to interact through virtual avatars across different locations, creating mirror images of the physical world via real-virtual environments; while its use in education remains limited compared to gaming and entertainment, its features such as 3D simulations hold significant potential for enhancing gamification, learning activities, and real-time decision-making through immersive XR, remote sensing, and simulation technologies [16].

The integration of XR into healthcare is expanding rapidly, opening new avenues for medical training, patient care, and infection prevention. These technologies enable real-time, multidimensional experiences that foster social, economic, and cultural exchange, especially through the concept of the metaverse—a convergence of virtual and physical worlds [17, 18]. With technological progress, health education and training have undergone significant transformation. Modern methods facilitate innovative approaches to treatment and skill development, particularly in infection control practices [1, 2]. One critical application area for XR is infection prevention and control (IPC). To combat the global burden of infectious diseases, fundamental practices such as hand hygiene, proper use of personal protective equipment (PPE), and surgical site infection prevention are essential [2]. The critical importance of effective infection prevention is underscored by data from the World Health Organization (WHO) and the International Council of Nurses (ICN), which report that an estimated 115.000 healthcare workers worldwide succumbed to COVID-19 between January 2020 and May 2021. These figures highlight the lethal risks associated with infection transmission in healthcare settings and underscore the urgent need for proper infection control measures, including hand hygiene and correct PPE use [19, 20]. Improper sequences or lapses in PPE protocols can significantly elevate contamination risks, leading to severe outcomes, including death. However, traditional training methods often fall short in ensuring long-term retention and consistent application of these practices. Emerging research indicates that AR- and VR-based training programs can significantly enhance knowledge retention and practical skills [3]. For example, VR-supported hand hygiene training provides real-time visual and auditory feedback, allowing users to recognize and correct mistakes instantly, thereby reinforcing proper techniques [1]. Similarly, AR applications assist healthcare professionals by offering real-time guidance, making hands-on training more accessible and effective [21]. Both VR and AR can be crucial during emergency responses to infectious diseases and pandemics, as they support remote and virtual training solutions—an aspect highlighted during the COVID-19 pandemic when many health systems relied heavily on virtual training methods [22, 23]. The visualization capabilities of these technologies, particularly their ability to depict concepts in three dimensions, have proven especially effective in improving knowledge retention and skill acquisition [24, 25]. This approach underscores the importance of hand hygiene among healthcare personnel and demonstrates correct handwashing techniques [26–28]. Building on this foundation, the present study conducted a systematic review of literature retrieved from the Web of Science and PubMed

databases to comprehensively explore VR applications in hand hygiene education and training.

Method

Search strategy

Studies written in English were selected from Web-of Science and PubMed libraries on January 12, 2025. The following search term was used to select the related articles from PubMed.

((“hygiene”[MeSH Terms] OR “hygiene”[All Fields] OR “hygienic”[All Fields] OR “hygienical”[All Fields] OR “hygienically”[All Fields] OR “hygienics”[All Fields] OR “hygienization”[All Fields] OR “infection prevention”[All Fields]) AND (“educability”[All Fields] OR “educable”[All Fields] OR “educates”[All Fields] OR “education”[MeSH Subheading] OR “education”[All Fields] OR “educational status”[MeSH Terms] OR (“educational”[All Fields] AND “status”[All Fields]) OR “educational status”[All Fields] OR “education”[MeSH Terms] OR “education s”[All Fields] OR “educational”[All Fields] OR “educative”[All Fields] OR “educator”[All Fields] OR “educator s”[All Fields] OR “educators”[All Fields] OR “teaching”[MeSH Terms] OR “teaching”[All Fields] OR “educate”[All Fields] OR “educated”[All Fields] OR “educating”[All Fields] OR “educations”[All Fields] OR (“education”[MeSH Subheading] OR “education”[All Fields] OR “training”[All Fields] OR “education”[MeSH Terms] OR “train”[All Fields] OR “train s”[All Fields] OR “trained”[All Fields] OR “training s”[All Fields] OR “trainings”[All Fields] OR “trains”[All Fields])) AND (“virtual reality”[All Fields] OR “augmented reality”[All Fields] OR “immersive”[All Fields] OR “Metaverse”[All Fields])) AND (english[Filter]))

The query is appled with the following syntax in the Web of Science database:

(((((((TS = Hygiene) OR (TS = infection prevention)) AND ((TS = education) OR (TS = training))) AND ((((TS = virtual reality) OR (TS = augmented reality)) OR (TS = immersive)) OR (TS = Metaverse))) AND (TS = all fields)) AND (TS = Article)) OR ((((TS = Review Article) AND (TS = Document Types)) AND (TS = English)) AND (TS = Languages)))

Preregistration of this systematic review was not conducted. This was due to logistical constraints that prevented timely preregistration prior to the start of the review. We acknowledge that the absence of preregistration introduces the potential for increased flexibility in analysis decisions, which could introduce bias. To mitigate this, we have developed and strictly adhered to a detailed, fixed protocol for this review, which has been documented and followed throughout the process. Prisma 2020 criteria [29] was applied for the study and a checklist is given in the Appendix-C.

Inclusion and exclusion criteria

Inclusion criteria: (1) studies published in English language (2) studies published in journals (3) studies related to hygiene education or training (IPC training for healthcare personnel -hand hygiene, PPE, surgical site infection prevention, NICU infection control-, oral hygiene education for patients and the general public (toothbrushing behavior, plaque/gingival indices), K–12 and public studies (4) studies including any of the VR, AR or XR technologies (5) all educational environments were included not limiting to the healthcare learners (6) Review and opinion articles were also included

Exclusion criteria: (1) Studies not in English Language (2) Conference articles (3) studies not related to hygiene education or training (4) studies do not include any of the target technologies namely VR, AR or XR

Study selection

Following a comprehensive search for relevant research, three qualified reviewers independently examined the full texts, abstracts, and titles of all identified articles. Throughout the review process, the reviewers discussed and resolved any discrepancies, consulting outside experts when necessary. Only articles that met the inclusion criteria after thorough evaluation were incorporated into the final analysis. Duplicate studies were avoided by ensuring each original research article was included only once, and papers lacking original data were excluded. All selected studies were managed and organized using Mendeley software.

Data extraction

Three reviewers independently screened all titles and abstracts for eligibility based on predefined inclusion and exclusion criteria. Articles that appeared relevant or were unclear at this stage were subsequently subjected to full-text review. During the full-text screening, the same independent approach was maintained. Any discrepancies between the reviewers’ assessments were discussed jointly to reach consensus. If disagreements could not be resolved through discussion, a third reviewer was consulted to make the final decision. Interrater agreement was assessed using Cohen’s kappa coefficient, which was calculated to quantify the level of agreement between reviewers. A kappa value of 0.75 indicated substantial agreement.

Quality assessment

The reviewed studies encompass a range of research designs, primarily quasi-experimental, observational, and review methods, with varying levels of bias risk from low to moderate. As seen from the summary of bias and quality in tech-based interventions table given in Appendix-A, many studies used pre- and post-intervention assessments, often relying on self-reported data and immediate outcomes, which limits understanding of long-term effects. While several studies employed randomized or controlled designs to strengthen validity, issues such as small sample sizes, lack of detailed fidelity measures, potential confounders, and absence of long-term follow-up introduce biases. Overall, these studies suggest positive impacts of interventions like VR, AR, and educational modules on knowledge, attitudes, and behaviors in healthcare and education settings, but limitations in design and reporting restrict the strength of causal inferences.

Results

Study selection

The Prisma flow diagram for the search and creation of the corpus is given in Fig. 1. As seen from Fig. 1, 162 articles (104 from Web of Science, 58 from PubMed) were identified after the application of the search term into the database. Among them 38 duplicate records were removed. Among the 126 screened articles, 88 were

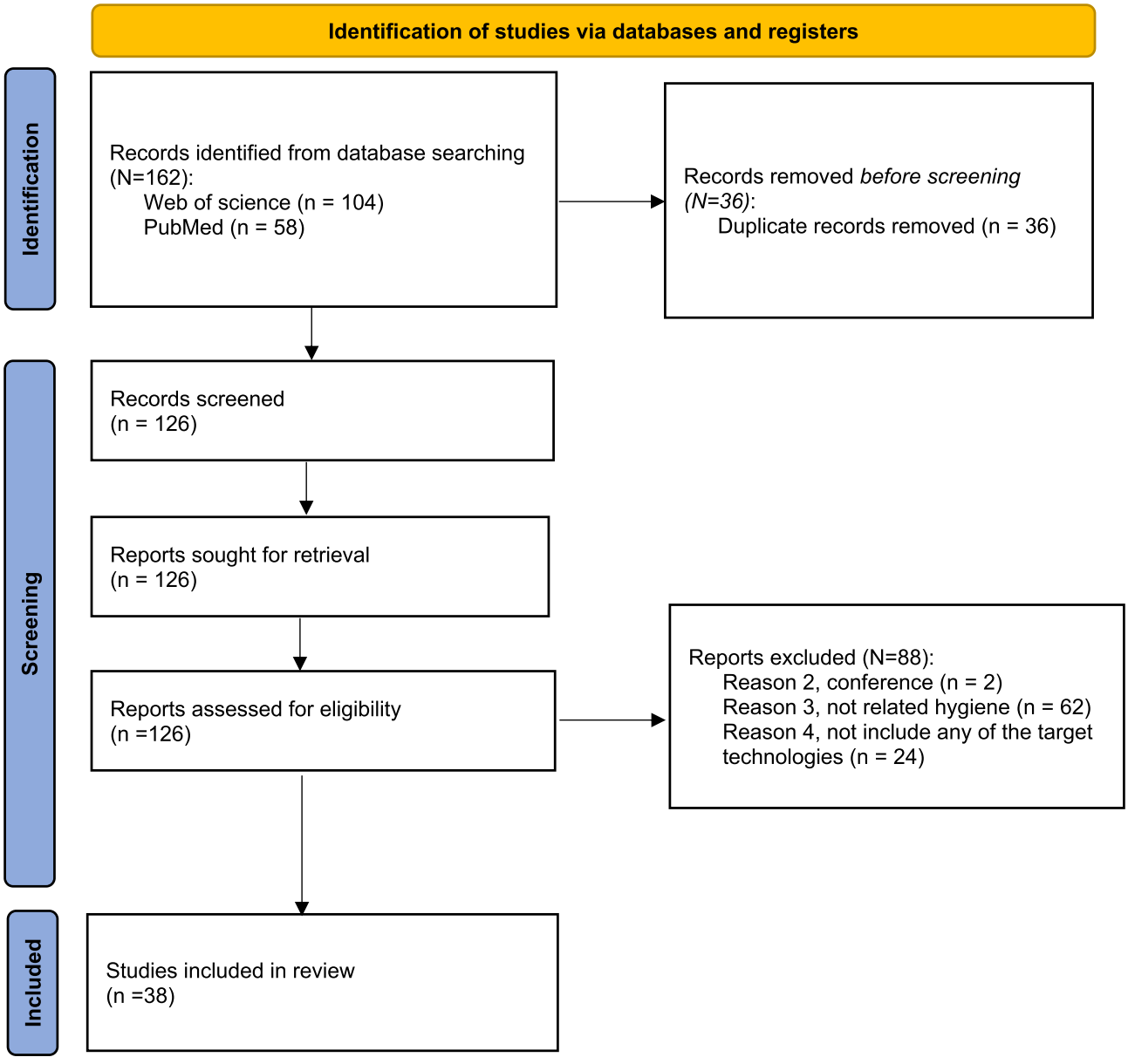


Fig. 1 The PRISMA flowchart for selecting articles by January 12, 2025

moved (2 of them were conference articles, 62 of them were not related to hygiene education or training and 24 studies were not including any of the VR, AR or XR technologies). After this screening process 38 articles were included in the corpus of this study.

Most of the articles published in 2024 ($n = 10$, 26.32%) (Fig. 2). This indicates the researchers' increasing interest in the topic. Additionally, an increasing trend can be expected for the next few years.

Characteristics of the included studies

The source title of the articles is shown in Table 1.

The articles in this study's corpus were analyzed according to several classification criteria: the types of VR technologies utilized, the target populations studied, and any specific special groups targeted, the skills addressed, and the benefits and challenges. The classification of special groups, such as individuals with intellectual disabilities, elderly individuals, and women, is conducted based on the necessity to address their unique needs and challenges in hygiene education and infection prevention.

Focusing on these groups allows for an assessment of how effectively immersive technologies can be adapted to diverse cognitive, physical, and demographic characteristics, ensuring interventions are accessible, engaging, and culturally sensitive. This categorization also helps identify research gaps and underscores the importance of designing inclusive, tailored solutions that can significantly improve health outcomes in high-risk or underserved populations, ultimately supporting more targeted and effective public health strategies. When an article met multiple criteria, it was categorized accordingly across all relevant categories. The percentages presented in the tables were calculated based on the total number of articles in the corpus ($n = 38$). A summary of the findings based on these classifications is provided below.

Utilized VR and AR technologies in the articles

As seen from Table 2, most of the articles in the corpus of this study were created fully immersive environments with headsets ($n = 20$, 53%). Some studies evaluated the possible impact of different technologies such as AR and VR. AR environments created through Kinect technology or smartphones were the second most common technology ($n = 11$, 29%).

Target groups overview

The articles were classified according to their target groups as given in Table 3. As seen from this table there were seven review/opinion/curriculum/survey articles identified in the corpus of this current study. Among them, a scoping review examining the use of VR in hand hygiene training for healthcare providers and students found that while VR enhances learning and engagement, most studies lacked a theoretical foundation [1]. The review emphasized the need for further research,

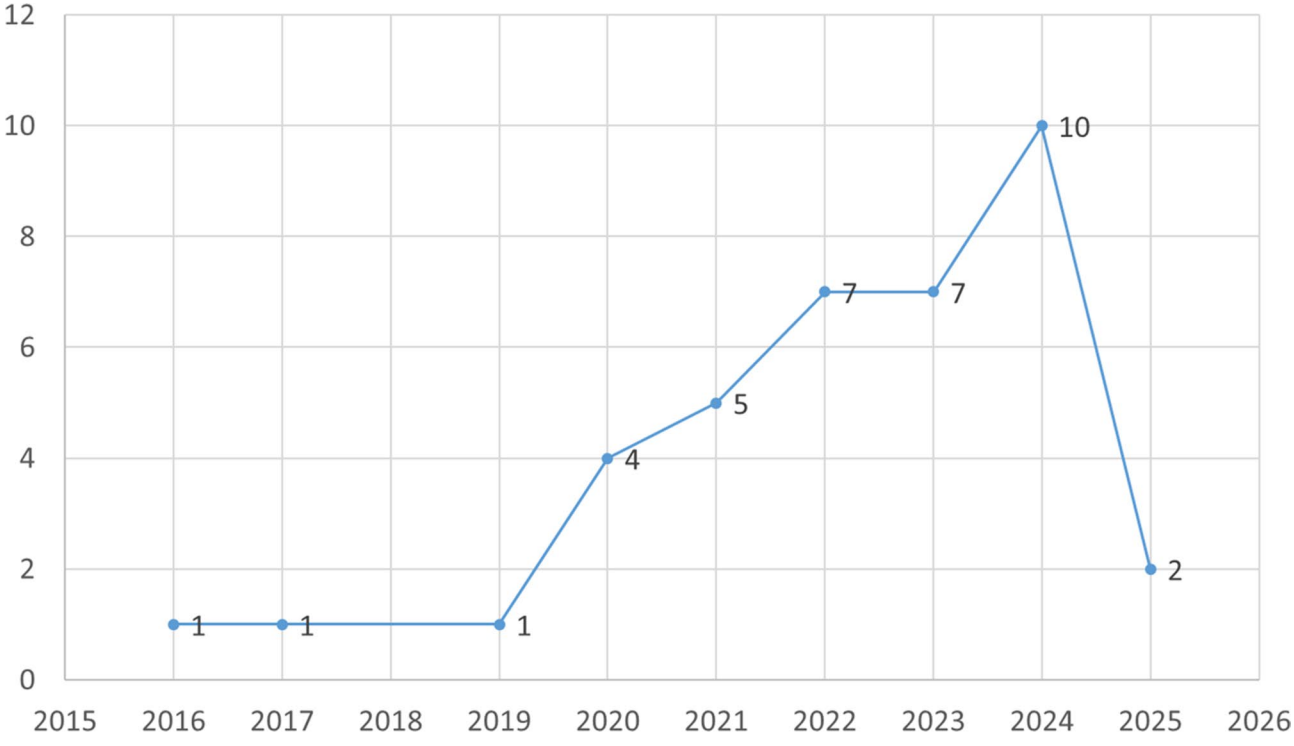


Fig. 2 Annual distribution of published articles (Note: data was collected up to January 12, 2025; therefore, the figure reflects publication trends through 2025)

Table 1 Source titles of the articles

Source Title	n	Article
American Journal of Infection Control	2	[26, 30]
BMC Medical Education	2	[1, 31]
Journal of the American Medical Informatics Association	2	[27, 32]
Antimicrobial Resistance and Infection Control	1	[10]
Asian Nursing Research	1	[21]
BMC Medical Informatics and Decision Making	1	[13]
BMC Oral Health	1	[25]
BMJ Open	1	[33]
Digital Health	1	[34]
Education And Information Technologies	1	[9]
Family Medicine and Primary Care Review	1	[12]
Frontiers In Digital Health	1	[3]
Frontiers In Education	1	[35]
Frontiers In Virtual Reality	1	[22]
Health & Social Care in The Community	1	[36]
Healthcare	1	[37]
Infection Control & Hospital Epidemiology	1	[38]
International Journal of Dental Sciences	1	[39]
International Journal of Dentistry	1	[8]
International Journal of Environmental Health Research	1	[28]
International Journal of Integrated Engineering	1	[40]
International Journal of Medical Dentistry	1	[41]
JMIR Research Protocols	1	[42]
Journal of Advanced Oral Research	1	[43]
Journal of allied health	1	[24]
Journal of Applied Research in Intellectual Disabilities	1	[44]
Journal of Chemical Education	1	[45]
Journal of Personalized Medicine	1	[46]
MededPortal	1	[47]
Multimedia Tools and Applications	1	[48]
Pesquisa Brasileira Em Odontopediatria E Clinica Integrada	1	[49]
Plos One	1	[2]
Simulation In Healthcare	1	[11]
Teaching And Learning in Nursing	1	[23]
Virtual Reality	1	[50]
Total	38	

Table 2 Type of VR technology used in the studies

Type of VR Technology	n	%
VR fully immersive headset [10, 21–23, 25–28, 30, 31, 33, 34, 36, 38, 39, 41, 45, 46, 48, 50]	20	52.63
AR [9, 12, 27, 34, 36, 37, 40, 42–44, 49]	11	28.95
Smartphone (Mobile apps) [9, 13, 27, 36, 40, 41, 48]	7	18.42
Optical 3D glasses [22, 34, 46]	3	7.89
VR-non immersive computer [11, 13, 27]	3	7.89
Kinect [42, 44]	2	5.26
Automatic Virtual Environment (CAVE) [46]	1	2.63
Total	47	

Note: The total percentage exceeds 100% because multiple VR technologies were used in some studies. Each technology is counted independently, representing overlapping results rather than mutually exclusive categories

Table 3 Target groups overview studied in the articles

Target Groups Overview	Articles	n	%
Healthcare Staff			
Healthcare workers	[9–13, 22, 23, 31, 36, 50]	10	26.32
Nurses	[21, 25, 35]	3	7.89
Care home workers	[27, 34]	2	5.26
Students			
Medical students	[26, 30, 33, 38, 46]	5	13.16
K-12 students	[39, 41–45, 48, 49]	8	21.05
Other Groups			
Food handlers	[28]	1	2.63
General population	[37, 40]	2	5.26
Review/opinion/curriculum/survey	[1–3, 8, 24, 32, 47]	7	18.42
Total		38	

cost-effectiveness analysis, and a robust evaluation framework to fully understand its impact [1]. Similarly, a systematic review aimed to consolidate scientific evidence on technologies used to teach hand hygiene in hospital settings [2]. It analyzed original quantitative research studies from multiple databases and assessed their methodological quality [2]. An opinion paper highlighted the importance of safely resuming VR-based learning while identifying previously unrecognized infection risks [3]. The paper suggested that future head-mounted display (HMD) designs should incorporate IPC principles to mitigate these risks [3].

Another review addressed the existing gap in comprehensive studies on metaverse-based oral health education, underscoring the need for further exploration in this area [8]. A systematic review reported that despite the innovative engagement methods offered by VR/AR, the majority of hand hygiene training apps lacked essential functionality and failed to meet basic quality standards [32]. The review recommended that future hand hygiene apps be developed in collaboration with infection prevention experts and aligned with best practices. Additionally, it emphasized the necessity of further research to assess their effectiveness, particularly in healthcare settings [32].

A separate study proposed an interprofessional education curriculum designed to equip oral health learners with the essential skills to collaborate with interpreters. The study found that the curriculum was highly effective and flexible, significantly improving communication with patients who have Limited English Proficiency (LEP) [47]. Another study explored dental hygiene students' understanding of informed consent when working with LEP patients. Using pre- and post-surveys in an immersive learning experience, the study reported significant improvements in students' knowledge, perceptions, and

attitudes. The findings highlighted the positive impact of training on their approach to informed consent in such clinical settings [24].

As shown in Table 3, healthcare workers ($n = 10$, 26.32%) and K-12 students ($n = 8$, 21.05%) are the most studied groups. The inclusion of K-12 populations reflects the universal importance of infection prevention principles and the value of early hygiene education in fostering lifelong health behaviors. Examining these groups allows for assessing the adaptability and effectiveness of XR-based training across diverse educational settings, supporting the development of scalable, age-appropriate strategies for broader public health education and infection control. Below their findings are summarized according to the classifications given in Table 3.

The study groups targeted in the articles were further groups such as Healthcare Staff, students and other groups. Studies conducted under each group are summarized below.

Healthcare Workers: Training healthcare workers in hand hygiene is challenging due to microorganism invisibility. A VR-based COVID-19 IPC curriculum in Uganda showed superior outcomes in skill, speed, and retention compared to traditional methods, with participant feedback noting effectiveness, feasibility, and broader applicability [31]. Similarly, AR/VR training, initially for healthcare workers, has been adapted for care home staff, emphasizing interactive learning, real-time feedback, and task realism to improve outcomes [36]. Research indicates VR simulations remain effective even for trainees with low initial tech acceptance, highlighting their practical potential [50]. VR also enhances awareness of the 5 Moments for Hand Hygiene, reinforcing its educational value [23]. Mobile AR applications enable healthcare workers to develop and maintain hand hygiene skills independently, and integrating self-directed training with assessments can improve standards [9]. Healthcare workers prefer VR over traditional lectures, with 48 VR sessions versus 33 lectures for hand hygiene education [10]. In resource-limited settings, low-fidelity simulation-based IPC modules improved confidence and competence among healthcare professionals treating Ebola patients [11]. AI-powered AR virtual assistants are emerging as tools to support infection control teams, while digital IPC systems improve response adaptability and training methods [12, 13]. A gamified VR simulation for COVID-19 testing demonstrated enhanced skill transfer and training efficiency [22].

Nurses: A study highlights VR's potential as a low-cost, standardized tool for IPC training among African nurses, addressing re-training challenges and cultural considerations in diverse settings [35]. Another pilot study found that VR simulation significantly enhances nursing students' knowledge, attitudes, and self-efficacy in geriatric oral healthcare, strengthening nursing education [25]. Additionally, VR simulation improves self-efficacy and satisfaction in high-risk neonatal infection control training, especially where access to Neonatal Intensive Care Units (NICUs) is limited [21].

Care home workers: Frontline healthcare assistants, working in nursing homes, care facilities, and private homes, are vital in caring for the elderly. A study found that AR/VR simulation training significantly improves their knowledge, self-efficacy, and skills in geriatric oral care [34]. Similarly, VR and AR training for care home workers has been well accepted and led to notable improvements in hand hygiene techniques, with success attributed to repeated practice, task realism, real-time feedback, and interactivity [27].

Medical students: Studies show that VR training enhances medical and dental education. A study with first-year medical students found that a "summary" visualization of pathogen transmission during VR hand hygiene training improved both performance and immersion, while "real-time" visualization had a negative effect [38]. Medical students who received VR-based training in hand hygiene and PPE techniques performed significantly better than those who underwent traditional lectures [30]. Similarly, a study comparing VR simulations to conventional methods across three universities for teaching surgical site infection prevention highlighted VR's potential in medical training [33]. An immersive 360° VR education system also significantly improved hand hygiene practices among medical students, increasing alcohol-based hand rub use compared to video lectures [26]. Medical Students' knowledge, attitudes, self-efficacy, and intents to provide oral healthcare to older people with disabilities were all positively impacted by VR instruction [46].

K-12 Students: Multiple studies demonstrate the effectiveness of VR and AR in teaching oral hygiene and health behaviors to children. A study with 300 students aged nine to twelve showed that immersive virtual reality (IVR) effectively teaches dental hygiene, with participants engaging through drawings and improving brushing and flossing habits [39]. Another study found significant improvements in brushing scores, plaque index, and plaque percentage compared to traditional methods [48]. An AR-based serious game aims to motivate children to maintain good dental hygiene [42]. Research on 6–8-year-olds supports AR-assisted toothbrushing as more effective than conventional techniques, promoting positive oral health behaviors in K-12 education [49]. VR offers interactive, realistic laboratory experience for teaching glove hygiene and safety protocols [45]. AR-assisted toothbrushing has also proven to reduce bacterial counts and improve plaque control in K-12 children [43]. For female high school students, VR-based oral

health education resulted in greater reductions in plaque and gingival indices compared to traditional methods [41]. Additionally, AR gamified handwashing activities effectively improved independent hand hygiene skills in children with intellectual disabilities, highlighting its potential in K-12 education [44].

Food handlers: A study evaluating VR training for food handlers found that participants who underwent VR showed the greatest improvements in handwashing duration, adherence to the WHO 11-step process, and accuracy in performing each step. Compared to Glo-Germ and traditional training methods, VR proved to be a highly effective tool for enhancing hygiene practices in foodservice settings [28].

General population: AR training has shown promise for delivering personalized oral care in residential care settings, improving healthcare education tailored to individuals [37]. Moreover, a mobile AR application aimed at educating urban and rural communities on proper handwashing techniques for COVID-19 prevention improved adherence to handwashing steps and movements [40]. However, it did not significantly affect handwashing duration. The study indicates that such AR applications could support the Malaysian health department's community education efforts [40].

Targeted special groups

The studies also targeted some special groups. These special target groups were analyzed under this section.

Intellectual disabled

Some special groups were targeted in some studies (Table 4). Among them, three articles targeted people with intellectual disabilities. A study found that gamified hand washing activities effectively improve hand hygiene skills in children with intellectual disabilities, helping them perform the task independently [44]. They have reported an increase in correct task steps among all participants and parental approval of the video game's effectiveness in teaching hand hygiene, while the conclusion suggested that although the game is well-accepted for school use, improving its technical robustness could enhance motivation and task accuracy [44].

The results indicated an increase in correct task steps among all participants and parental approval of the video game's effectiveness in teaching hand hygiene, while the conclusion suggested that although the game is well-accepted for school use, improving its technical robustness could enhance motivation and task accuracy.

Similarly, VR training has been reported to significantly enhance oral hygiene students' knowledge, attitudes, and self-efficacy in providing oral care to elderly individuals with intellectual disabilities [46]. A feasibility study conducted in Korea assessed the effectiveness of AR-based tooth-brushing training with a smart toothbrush for individuals with intellectual disabilities. The study found that AR training significantly improved tooth-brushing performance and oral hygiene care compared to traditional visual material training, positioning AR as a promising tool for personalized oral hygiene instruction in residential care settings [37].

Table 4 Target skills overview studied in the reviewed articles

Target Skills Overview	Articles	n	%
Hand hygiene	[1–3, 9, 10, 23, 26–28, 30–32, 36, 38, 40, 44, 50]	17	44.74
Oral hygiene	[8, 24, 25, 34, 37, 39, 41–43, 46, 48, 49]	12	31.58
IPC	[11–13, 35]	4	10.53
Curriculum development	[47]	1	2.63
Glove hygiene	[45]	1	2.63
High-risk Neonatal Infection Control	[21]	1	2.63
Surgical site infections (SSI)	[33]	1	2.63
PPE	[22]	1	2.63
Total		38	

Table 5 Targeted special groups

Special Groups	Articles	n	%
Intellectual Disabled	[37, 44, 46]	3	7.89
Elder People	[22, 34, 46]	3	7.89
Female	[41]	1	2.63
Total		7	

Elderly People: Three studies reported impact of immersive technologies on better understanding hygiene for elderly people [22, 34, 46].

Female: One study identified female students indicating that VR-based oral health education significantly improves dental hygiene in female high school students, reducing plaque and gingival indices more effectively than verbal methods [41].

Target skills overview studied in the reviewed articles

Most of the articles targeted skills on hand hygiene and oral hygiene (in total 76%) (Table 5).

Hand hygiene: Several studies highlight the potential of VR and AR for hand hygiene and infection control training. VR-based programs, focusing on COVID-19 patient management, PPE use, and hand hygiene, emphasize feedback, reminders, realism, and repeated practice to enhance skills [31, 36, 50]. VR training can improve hospital hygiene practices and is adaptable across languages, supporting global education efforts [23]. However, traditional training often lacks sufficient repetition and feedback, with some studies showing minimal behavioral change, such as unchanged hand rub consumption [9, 10]. AR and VR have demonstrated effectiveness in promoting hygiene in various settings, including foodservice and care homes, with high usability and significant

skill improvements when using repeated practice, task realism, and feedback [27, 28, 40]. Specifically, gamified AR handwashing improved skills in children with intellectual disabilities, though it did not affect duration [44]. Fully IVR systems have increased hand-rub alcohol use, indicating improved compliance [26]. Beyond healthcare, VR has been effective in food safety training, outperforming other methods [28]. Systematic reviews support the overall efficacy of VR, gamification, and audiovisual tools in improving hand hygiene compliance and education for patients and staff [1, 2]. Nonetheless, safety guidelines for VR use are needed, considering contact points with HMDs and controllers, requiring collaboration among experts and organizations to ensure safe practices [3]. Additionally, a review of hand hygiene apps revealed many lack adherence to best practices or infection control expert involvement [32].

Oral hygiene: VR and AR are promising tools for dental education, especially for young patients. VR-based learning is more effective than traditional methods in improving children's oral hygiene [39, 48], with AR serious games making toothbrushing fun and interactive, leading to significant reductions in plaque and gingival bleeding among 6- to 8-year-olds [42, 49]. AR-assisted gamified brushing also reduces plaque and bacteria more effectively than manual brushing [46]. VR education has further improved dental hygiene by lowering plaque and gingival indices more than verbal instructions [41].

Beyond pediatric care, VR simulation enhances nursing and dental students' knowledge, attitudes, and self-efficacy in geriatric oral health, including proper tool use and promoting dental visits [25, 46]. AR/VR training for healthcare assistants improves their knowledge, self-efficacy, and behavioral intentions in providing oral care to older adults [34], with AR-based training leading to better brushing performance than traditional visual materials [37]. A review highlights the potential of metaverse technology to boost engagement and awareness in children's oral health education [8]. Additionally, IVR exercises improve dental students' understanding of informed consent, increasing awareness of state-specific requirements by 8%, demonstrating VR's positive impact on knowledge and perceptions [24].

IPC: The widespread availability of the IPC module via laptops and tablets can significantly reduce disease transmission in West Africa by using high-frequency, low-fidelity simulations to boost healthcare workers' confidence and skills in Ebola care [11]. Future developments in hospital information technology systems are expected to create integrated solutions that offer continuous, personalized support to infection control teams, staff, patients, and families, enhancing safety [12]. A digital emergency IPC system has improved knowledge and operational skills among healthcare workers in psychiatric hospitals, increasing their preparedness [13]. Additionally, VR is recognized as a low-cost, standardized educational tool that can address cultural and resource barriers, providing equitable infection control training for nurses in Africa [35].

Curriculum development: A study developed a 3.5-hour simulation-based training program aimed at improving communication between oral health and interpreting learners when working with LEP patients [47]. The curriculum incorporated immersive simulations, virtual scenarios, and reflection discussions, and was implemented across multiple dental disciplines [47]. The program was found to effectively address communication gaps and enhance interprofessional collaboration, ultimately benefiting patient safety and improving the overall quality of care [47].

Glove hygiene: One study identified VR as an active learning tool to teach proper glove hygiene in laboratory settings, addressing the transfer of chemicals and contaminants during experiments [45].

High-risk Neonatal Infection Control: One study in the corpus identified reporting that VR simulation significantly enhances Korean nursing students' self-efficacy and satisfaction in high-risk neonatal infection control, providing a valuable alternative when direct access to NICUs is limited [21].

Surgical site infections (SSI): One study identified SSI on VR simulation compared with conventional education to teach medical students SSI prevention measures, focusing on improving compliance with IPC practices in the operating room [33].

PPE: A VR-based medical simulation was developed to train healthcare professionals in COVID-19 swab testing and proper use of personal protective equipment, enhancing skill transfer through a gamified learning approach [22].

Benefits and challenges

When the articles in the corpus of this study were analyzed in terms of the benefits derived from these technologies, several key findings emerged. The studies report improvements in practical skills and performance on hand hygiene [2, 26–28, 40, 44, 50], PPE donning/doffing [30, 31], oral hygiene [24, 42, 46], improvement in lab safety, glove hygiene and contamination transfer [45], and geriatric oral care [25]. Some studies also report increased motivation in oral health education [39] as well as learner engagement and satisfaction [50]. On the other hand some studies also report no significant difference in oral health knowledge after VR training [39] or minimal knowledge gain [27] and no significant effect on handwashing duration time [40] (see Appendix-B). An earlier review which is also in the corpus of this study also reports some no significant differences [1].

The articles in the corpus of this study also highlight some challenges of XR technologies. For instance, technical and infrastructure challenges addresses the requirements for specialized hardware, manages lag, and needs robust support, which pose significant logistical barriers [27, 39, 50]. Cybersickness and Comfort is another challenge related with the headset fit, flickering screens, and latency which can cause cybersickness, discomfort, and nausea, reducing acceptance [27, 45, 50]. High cost of equipment is another challenge reported by the articles. The content development (~$12k–$100k), and maintenance limit scalability, especially in low-resource settings [27, 30–32, 48]. Variability in headset quality, tracking accuracy, and hardware compatibility is reported as a challenge which affect training quality and immersion [1, 22, 33, 41]. Users need time to familiarize themselves with these technologies. Some may experience cognitive overload, distraction, or discomfort, impacting engagement and effectiveness [44, 45, 50]. Another challenge is the development of realistic, guideline-based scenarios which is reported as a complex process and the limited content and lack of expert involvement affect efficacy [2, 11, 41, 42] of the education systems. Additionally very few studies validate long-term skill transfer or real-world outcomes; small sample sizes and methodological issues hinder generalizability [2, 23, 24]. Managing large groups, space requirements, and technical maintenance challenge widespread adoption [47, 48, 50]. Non-disposable headsets pose infection risks, especially during pandemics, requiring redesign for safety [3]. Finally, cognitive and physical discomfort is reported as a challenge, where motion sickness, fatigue, and cognitive load can impair learning and user comfort [41, 45, 50].

Discussions

This review consolidates evidence from 38 studies demonstrating that immersive technologies, primarily VR and AR, are increasingly employed to enhance hygiene training across diverse populations, including healthcare professionals, students, and vulnerable groups. Fully IVR environments utilizing HMDs feature prominently, with over half of the studies employing this modality. Other technologies, such as AR via smartphones or Kinect sensors, also demonstrate promise, particularly in engaging younger populations and resource-limited settings. The findings consistently show that XR interventions improve knowledge, skills, and behavioral adherence related to hand hygiene, oral health, and infection prevention. However, the results also reveal that while XR technologies can enhance practical skills, motivation, and engagement in various health-related tasks, some studies report minimal or no significant improvements in knowledge or behavior, indicating mixed evidence of their effectiveness. This review highlights the versatility of XR tools across populations and settings, including low-resource environments, care homes, and pediatric populations, demonstrating adaptability. Despite these promising developments, challenges remain. The challenges of XR technologies include technical and infrastructure requirements, high costs, hardware variability, user discomfort and cybersickness, content development difficulties, limited long-term validation, and logistical issues such as space, maintenance, and safety concerns. These findings are parallel to the earlier research results indicating that while most studies report positive outcomes, some evidence suggests that behavioral improvements may require ongoing reinforcement and broader incorporation into training curricula to sustain benefits over time [51]. For instance, an earlier findings show that the metaverse can, in fact, be a helpful and efficient educational tool whose technological complexity is not a barrier to medical teaching, depending on the appropriate design and user experience features [52]. Hence, there is a need for the development of rigorous theoretical frameworks to guide intervention design and integration. Additionally, comprehensive cost-effectiveness analysis is essential to justify widespread implementation, alongside safety considerations related to head-mounted devices. A recent systematic review [27] has similarly emphasized the advantages of immersive simulation in infection control, yet often pointed to a paucity of high-quality, longitudinal data evaluating sustained behavioral outcomes and cost-effectiveness. Compared to earlier reviews [53, 54], which primarily highlighted the potential of VR for medical education, this review underscores a broader trend: XR's capacity not only to enhance engagement but also to facilitate skill retention and behavior change in the context of hygiene education and training.

The results of this study may have several implications for Policy, Curriculum, and Practice. To harness XR's full potential, policy frameworks should encourage standardization, safety protocols, and integration into national infection control curricula. Regulatory oversight is essential to ensure safety, efficacy, and ethical use, especially concerning shared hardware and data privacy. Investment in infrastructure and training is vital; governments and funding bodies should consider subsidizing equipment and content development, particularly

for low-resource settings. XR tools should complement, not replace, traditional training modalities. Embedding immersive modules within existing curricula can reinforce procedural competence, especially for critical skills like PPE donning/doffing and hand hygiene. Development of evidence-based, theory-driven curricula is necessary to maximize learning transfer and behavioral sustainability. Incorporating behavior change models can guide effective design. For practitioners, XR-based simulation offers a safe, realistic environment for ongoing skills reinforcement, especially in high-stakes areas like neonatal or surgical infection control. - Routine use can foster habitual compliance, reduce errors, and ultimately decrease healthcare-associated infections. Implementing standardized scenarios aligned with WHO and Center for Disease Control (CDC) guidelines can ensure consistency.

High-quality, longitudinal studies are needed to evaluate sustained behavior change, real-world infection rates, and cost-effectiveness of XR interventions. Rigorous validation of skills in clinical environments should be prioritized. Technological advances should focus on creating disposable or easily sanitizable hardware to address infection risks. Efforts to develop more affordable, user-friendly devices will enhance scalability. Integrating behavioral science models into intervention design can improve efficacy and durability of learning outcomes. Establishing international standards and accreditation for XR-based training modules can promote widespread acceptance and integration into health education systems.

Conclusion

Immersive XR technologies hold potential promises for revolutionizing hygiene education and infection prevention training. Their capacity to create engaging, realistic, and repeatable learning experiences can lead to immediate improvements in knowledge and skills, with potential for sustained behavioral change. However, realizing this potential requires addressing current limitations such as the cost, safety, validation, and developing robust frameworks for curriculum integration and policy support. Strategic, evidence-based adoption of XR can contribute substantially to global efforts in reducing healthcare-associated infections and enhancing public health resilience.

To advance the field and ensure the effective translation of evidence into practice, several key actions can be taken. First, future research should employ a formal evidence-to-practice translation model to systematically bridge the gap between research findings and real-world application. This approach can facilitate more structured implementation strategies and improve outcomes. Second, there is a pressing need for the adoption of standardized outcome measures across studies. Standardization will enable more accurate comparisons, meta-analyses, and the development of best practices. Consistent metrics will also support the identification of what works best in different contexts and populations. Third, long-term follow-up studies are essential to assess the sustainability and enduring impact of interventions. Such longitudinal data can inform adjustments, ensure continued effectiveness, and support policy development. Overall, by addressing these areas, future research can enhance the applicability, reliability, and long-term success of initiatives within the field.

This review has several limitations. First, the literature search was restricted to two databases—Web of Science and PubMed—which may have resulted in the omission of relevant studies available in other sources. Second, the included studies exhibited significant heterogeneity in their outcomes, interventions, and assessment methods, which limited the ability to perform a quantitative synthesis or meta-analysis. Consequently, the findings are primarily descriptive and may not fully capture the overall effectiveness of XR technologies in hygiene education. Future research with more standardized outcome measures and broader database searches is needed to strengthen the evidence base.

Appendix-A

Summary of bias and quality in tech-based interventions

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[27]-1	Quasi-experimental/ Feasibility study	Low risk (care staff recruited from multiple care homes)	Adequate, with reported usability and acceptability measures	Validated questionnaires, observations, videos, interviews	Short-term follow-up: no long-term outcomes reported	Not explicitly controlled for confounders	Some concerns/Moderate	The study reports high usability and acceptability but limited long-term efficacy data. Potential selection bias due to voluntary participation.
[39]-2	Quasi-experimental/Pre-post intervention	Moderate risk (all pupils received intervention; selection likely systematic within schools)	Not explicitly reported; assumed consistent VR delivery	Outcomes measured via self-reported behavior (e.g., flossing, brushing) and drawings/comments; statistical tests applied	Short-term assessment: no long-term follow-up reported	Potential confounders such as prior oral health education or socioeconomic status not controlled	Some concerns/Moderate	The study demonstrates positive changes in oral hygiene behaviors with VR but lacks detailed reporting on intervention administration and potential confounders.
[50]-3	Exploratory pre-post observational study	Low to moderate risk (medical students recruited; representativeness not detailed)	Adequately described VR levels and assessments	Performance scores based on task completion; behavioral intention via questionnaires; engagement measures	Immediate post-training assessments; no long-term follow-up	Not explicitly controlled; prior experience or motivation may influence results	Some concerns/Moderate	The study shows improvements in performance and associations with acceptance and engagement, but limited information on sample representativeness and confounders.
[1]-4	Scoping review	Low risk (comprehensive search across multiple databases)	Data extracted systematically; descriptive analysis	Summary of existing studies; no primary data collection	Not consistently applied; only 2 studies included theories/concepts		Some concerns/Moderate	The review provides an overview of current research but highlights gaps such as lack of theoretical support and cost-effectiveness analysis.
[23]-5	Pilot observational study	Moderate risk (small sample size; convenience sampling)	Not detailed; assumes consistent VR experience	Self-reported questionnaires and direct observation; high compliance rates	VR sickness reported; some participants experienced mild to moderate symptoms		Some concerns/Moderate	The study suggests positive educational utility, but limitations include small sample size, potential bias in self-reporting, and lack of control group.
[36]-6	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet		AR and VR hand hygiene training has been developed for healthcare workers, but has not yet	AR and VR hand hygiene training has been developed for healthcare workers, but has not yet

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[9]-7	Prospective cohort study	Moderate risk (small sample size, 47 participants)	Likely consistent; based on detailed design and weekly assessments	Objective electronic assessments and human inspections; high proficiency achievement	Follow-up over 4 weeks with weekly assessments; retention appears adequate		Some concerns/Moderate	Promising results for mobile AR training; lack of control group and randomization limits causal inference
[35]-8	Conceptual/ Implementation study	High risk (focus on design and implementation, not empirical research)	Variable; dependent on context-specific adaptation and support	Not applicable	Not applicable		N/A (not empirical)	Addresses cultural and resource considerations for VR implementation in Africa; lacks empirical outcome data
[37]-9	Quasi-experimental comparative study	Low risk (randomly assigned groups, equal group sizes)	Likely adequate; interventions are well-defined (AR-based vs visual material)	Objective measures of tooth-brushing performance and oral hygiene; significant differences reported	Not specified; presumably immediate post-intervention assessment		Some concerns/Moderate	Small sample size (30 total), but controlled comparison enhances validity; limited long-term follow-up info
[46]-10	RCT	Low risk (randomization of participants)	Likely adequate; structured VR interventions with repeated sessions	Self-administered questionnaires; validated measures of knowledge, attitude, self-efficacy, and intentions	Follow-up at 6 weeks; data collected immediately after interventions		Low	Small sample size (23 total), but RCT design enhances internal validity; short follow-up period
[34]-11	RCT	Low risk (randomly assigned HCAs to groups)	Likely adequate; structured AR/VR training sessions described	Self-administered questionnaires measuring knowledge, self-efficacy, and intention	Not specified; pre- and post-training assessments suggest immediate or short-term evaluation		Low	Sample size (80 participants) is moderate; the use of standardized measures and appropriate analysis supports validity
[22]-12	Descriptive/ Developmental study with usability testing	Not applicable (descriptive/ technological development)	Likely adequate; detailed algorithms, models, and architecture provided	Usability and performance compared to traditional methods; details from referenced study	Not specified; focus on usability and performance in simulated settings		Moderate to Low	The study emphasizes system development and usability; lacks randomized evaluation but demonstrates technical feasibility and user satisfaction
[31]-13	Comparative observational study with quantitative and qualitative components	Moderate; comparison with historical cohorts may introduce selection bias	Likely adequate; VR content developed specifically for IPC training	Knowledge acquisition assessed via comparison metrics; qualitative feedback gathered	Not specified; focus on immediate learning outcomes and participant feedback		Moderate	Comparison with previous cohorts introduces potential confounding; qualitative data adds richness but subjective; randomized controlled design not reported

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[28]-14	RCT with pre- and post-intervention assessments	Low; randomization likely minimized selection bias	High; standardized training procedures for VR, Glo-Germ, and face-to-face methods	Objective observations of handwashing practices and microbiological swabs; statistically analyzed	Not specified; immediate post-intervention outcomes assessed		Low	Well-designed RCT with objective outcome measures; randomization reduces bias; follow-up details limited but outcomes are immediate
[48]-15	Longitudinal mixed-methods study with comparative assessments	Moderate; selection of school children may introduce some bias if not randomized	Likely adequate; intervention (VR vs. traditional education) appears standardized	Quantitative measures (plaque index, plaque percentage, brushing score); statistical significance reported	Not specified; focus on pre- and post-intervention measures		Moderate	No mention of randomization; potential selection bias; outcome measures are objective, but follow-up details are limited
[42]-16	Protocol for a developmental and evaluative study with planned assessments	Not applicable at this stage (development protocol)	Planned; involves design of an AR serious game with defined technological features	Future evaluation plans include questionnaires and efficacy analysis; no results yet	Not applicable (study is in development phase)		Not applicable (study is a protocol)	This is a developmental protocol outlining methodology; actual bias assessment depends on implementation and evaluation outcomes
[38]-17	RCT evaluating different visualization timings in VR hand hygiene training	Low; randomized allocation of participants to different setups	Presumed adequate; different visualization setups are clearly defined	Objective measure of pathogen transmissions (contaminations) and user immersion via questionnaires	Not specified; likely immediate post-intervention assessment		Moderate; potential bias if allocation concealment or blinding not described	Randomization strengthens internal validity; outcome measures are objective, but lack of details on blinding/concealment could introduce bias
[10]-18	Prospective, cross-controlled trial comparing VR training to conventional lecture	Moderate; allocation appears based on intervention type, but details on randomization or allocation concealment are not specified	Presumed adequate; interventions are well-defined (VR vs lecture)	Outcomes include HCW satisfaction (subjective), hand rub consumption, and compliance observed directly	Follow-up appears immediate; no long-term follow-up reported		Moderate; potential bias if allocation was not randomized or blinded, and subjective outcomes may be influenced by participant preferences	Lack of detailed randomization or blinding procedures limits bias assessment; satisfaction is subjective, but compliance is objectively measured
[49]-19	Concurrent parallel examiner-blinded interventional study	Moderate; allocation to groups appears based on intervention, but randomization process is not specified	Presumed adequate; specific interventions (manual vs AR toothbrush) are well-described	Objective measures (plaque and gingival bleeding scores) assessed at baseline and follow-up	Follow-up duration of two weeks; completeness assumed but not explicitly stated		Moderate; potential bias if allocation was not randomized or concealed, and blinding details are limited	Randomization process not detailed; blinding of examiners is noted, reducing detection bias

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[45]-20	Descriptive development and feasibility study of a VR instructional module	Not applicable; this is a developmental and conceptual report rather than a comparative study	Moderate; development process described, but fidelity of implementation and standardization not fully detailed	Not applicable; primarily descriptive and qualitative insights	Not applicable; no follow-up data reported		Low to Moderate; primarily a descriptive project, so traditional bias assessment is limited	Focuses on development and potential rather than empirical effectiveness; lacks comparative or controlled outcome data
[43]-21	RCT (assumed based on two groups)	Moderate; allocation method not specified	Presumed adequate; clear description of interventions, but adherence not detailed	Objective measures (fluorescence lesion scores and bacterial counts) assessed pre- and post-intervention	Follow-up duration of two weeks; completeness not explicitly stated		Moderate; lack of detail on randomization and blinding, which could influence bias	
[30]-22	RCT (assumed based on two groups)	Moderate; group allocation method not specified	Presumed adequate; both groups received the same content, but details on adherence are lacking	Objective OSCE scores and self-reported questionnaires; standardized assessments	Not specified; follow-up appears immediate post-training		Moderate; potential bias due to lack of detail on randomization and blinding	
[3]-23	Observational study/guideline development and implementation	Low; comprehensive stakeholder engagement and clear inclusion criteria	Moderate; adherence to developed guidelines not quantitatively assessed	Qualitative feedback, infection rates, and compliance audits	Not applicable; focus on guideline development and initial implementation		Moderate; potential bias due to lack of control group and long-term outcome data. The study effectively describes the guideline development process; however, outcome data on infection rates and adherence are limited, affecting bias assessment.	
[41]-24	Randomized controlled field trial	Low; random selection of schools and participants, with clear inclusion criteria	Moderate; intervention procedures (VR and verbal education) described, but adherence and consistency not quantitatively verified	Low; clinical indices (GI and PI) measured using standard, validated methods	Adequate; re-examination conducted one month post-intervention	Not explicitly addressed; potential influence of baseline differences or external factors not discussed	Low to Moderate; potential bias due to lack of blinding and short follow-up period	The study employs randomization and validated outcome measures, but lacks details on blinding and long-term follow-up, which could influence bias assessment.

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[40]-25	Quasi-experimental study with intervention and comparison	Moderate; participants categorized by age, but no mention of randomization or selection procedures	Low; the mobile app intervention described, but adherence and proper usage weren't detailed	Moderate; outcomes measured using statistical analysis (ANOVA), but specific measures of handwashing quality are not detailed	Not specified; appears to be a single assessment post-intervention	Not explicitly addressed; demographic differences such as gender not compared, which could influence results	Moderate; potential biases due to lack of randomization, unclear follow-up, and unaddressed confounders	The study used standard statistical methods, but lacked details on participant selection, adherence to intervention, and potential confounding variables, affecting bias assessment.
[25]-26	Randomized controlled pilot study	Low; random assignment of nursing students to experimental and control groups	Moderate; intervention (VR training) described, but adherence and consistency details are limited	Low; outcomes assessed via validated questionnaires on knowledge, attitude, self-efficacy, and intention, with repeated measures over time	Moderate assessments conducted at multiple time points (weeks 1, 2, 4), but long-term follow-up not specified	Not explicitly addressed; potential for baseline differences in knowledge or motivation between groups	Low to Moderate; randomization reduces bias, but possible limitations in intervention, fidelity and follow-up duration	The study employed randomized assignments and validated measures; however, details on adherence to VR sessions and long-term effects are limited, affecting bias certainty.
[44]-27	Single-subject, non-concurrent multiple baseline design	Very low; small sample of four children with specific inclusion, no randomization	Moderate; intervention involved a Kinect-based game, but technical variability & error-proneness noted	Low; outcome based on task step correctness, with parental social validity assessments	Short; no long-term follow-up reported	Not addressed; small sample and individualized design limit control of confounders	Moderate; appropriate for pilot/small study but limited generalizability and potential measurement errors	The design is suitable for preliminary evaluation, but technical issues and small sample size impact bias risk.
[11]-28	Development and implementation of an educational module with evaluation components	Low; participants appear to be healthcare workers involved in Ebola response, but specific selection details are not provided	Moderate; rapid development using Scrum and gamification suggests potential variability in content delivery and engagement, though core content is structured	Moderate outcomes include self-reported confidence and competence, with possible analytics tracking, but detailed measurement methods are not specified	Not specified; short-term assessment implied, but long-term retention or impact not detailed	Not addressed; potential confounders include prior experience and varying outbreak contexts	Moderate; innovative rapid development approach with some measurement limitations; generalizability may be limited	The agile methodology supports rapid development, but the absence of detailed outcome measures and follow-up limits bias certainty.
[33]-29	Multicenter RCT	Low; randomization of students across three universities aims to reduce selection bias	Moderate; VR intervention and conventional education may vary in implementation; fidelity depends on standardization	Low; primary outcome is a standardized exam score across countries, reducing measurement bias	Moderate; follow-up at end of year, but potential variability in retention and engagement across sites	Potential confounders include prior knowledge, variation between institutions, and differing teaching quality	Moderate; randomized design with multicenter approach enhances validity, but intervention fidelity and cross-country differences may introduce bias	The study employs rigorous RCT methodology, but intervention fidelity and cross-cultural implementation may impact bias risk.
[12]-30	Conceptual/Review study on emerging IT solutions	Not applicable; theoretical discussion	Not applicable; no intervention implemented	Not applicable; no empirical outcome measurement	Not applicable	Not applicable	Not applicable; as a conceptual review, bias assessment is limited	The abstract discusses potential future applications of IT in hospital infection control but lacks empirical data or intervention testing.

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[26]-31	RCT	Low; randomization of participants into VR and video groups reduces selection bias	Moderate; intervention involves IVR, which may vary in implementation fidelity; adherence and engagement are not detailed	Low; primary outcome measured via quantifiable alcohol use, reducing measurement bias	Short follow-up (2 weeks), sufficient for immediate behavior change assessment	Possible confounders include baseline hand hygiene habits, prior familiarity with VR, and motivation levels	Moderate; RCT design supports validity, but small sample size and potential variability in intervention delivery may impact bias risk	The study employs a robust RCT approach, but limited sample size and intervention standardization considerations are noted.
[21]-32	Quasi-experimental non-randomized control group	Moderate; non-random assignment may introduce selection bias	Moderate; intervention involves IVR with technology that may vary in implementation; details on standardization are limited	Moderate outcomes include self-reported performance efficacy and satisfaction, which are subjective and may be biased	Short-term, immediate post-intervention assessment; no long-term follow-up reported	Potential confounders include baseline knowledge, motivation, prior experience with VR, and differences in clinical exposure	Moderate; lack of randomization and potential variability in intervention delivery may introduce bias, but control group enhances comparability	The study design does not involve randomization, which may limit internal validity, but control group comparison provides some level of evidence.
[2]-33	Systematic review of primary studies	Variable: dependent on included studies, some may have selection bias	Variable; depends on individual studies' implementation fidelity	Variable: depends on the original studies' measurement tools, which may vary in validity and reliability	Not applicable; synthesis of existing studies	Heterogeneity among included studies regarding populations, interventions, and outcomes	Moderate to high; quality depends on the methodological rigor of the included studies, which the review assesses critically	Overall bias risk reflects the quality and heterogeneity of the primary studies included. Rigorous selection and quality assessment improve confidence.
[13]-34	Quasi-experimental before-and-after study	Low to moderate; all participants from a single institution, no control group specified	High; system implementation and training appear standardized, but variation in user engagement possible	Moderate; outcomes include self-reported knowledge and skills, and system performance metrics, which are subject to measurement bias	Short-term follow-up (12 months); no long-term data reported	Potential confounders include prior IPC knowledge and varying levels of engagement among staff	Moderate; lack of a control group limits causal inference, but pre- and post-assessment strengthens internal validity	Demonstrates positive effects of the digital system, but the absence of a control group reduces robustness of conclusions.

Table (continued)

Ref.	Design Type	Selection Bias	Intervention Fidelity	Outcome Measurement	Follow-up	Confounding Factors	Overall Risk of Bias	Comments
[8]-35	Narrative or scoping review of existing studies	Not applicable; as a review, selection bias depends on search strategy and inclusion criteria	Not applicable; it depends on the comprehensiveness of included studies	Not applicable; based on secondary data, but the quality depends on the original studies' validity and reliability	Not applicable; no primary data collection	Potential publication bias, especially if unpublished or negative studies are underrepresented	Moderate; quality depends on the search strategy, inclusion/exclusion criteria, and critical appraisal of included studies	The review synthesizes current evidence but may be limited by the quality and scope of available primary studies.
[32]-37	Cross-sectional descriptive study	Low; comprehensive search of app stores with clear inclusion criteria	Moderate; evaluation based on standardized scales (IMS and MARS), but variability in app development quality	Moderate; app quality and features assessed via established scales, but subjective elements in ratings	Not applicable; no longitudinal follow-up or testing of app effectiveness	Limited; primarily descriptive assessment, no analysis of user engagement or actual behavior change	Moderate; assessment of app quality but no evaluation of real-world effectiveness or user outcomes	The study provides a snapshot of app features and quality but does not assess behavioral impact or effectiveness in practice.
[47]-38	Quasi-experimental pre-post study	Low; participants included a broad range of students across multiple disciplines	Moderate; curriculum included varied methods (didactic, simulation, reflection), but standardization supported by a toolkit	High; outcomes measured via pre- and post-surveys with statistically significant improvements, using validated statistical tests	Not applicable; immediate post-intervention assessments, no long-term follow-up	Limited; potential confounding from concurrent educational activities or prior experience, but not explicitly controlled	Moderate; significant improvements suggest positive impact, but lack of control group limits causal inference	The study demonstrates effective educational outcomes but is limited in establishing causality without a control group.
[24]-39	Quasi-experimental pre-post study	Low; all participants were senior dental hygiene students from a single institution, with voluntary participation	Moderate intervention included lectures, immersive role-play, & discussions, but fidelity depends on consistent implementation across groups	High; knowledge, perceptions, and attitudes assessed via pre- and post-surveys with statistical analysis indicating changes	Not applicable; immediate post-intervention assessments, no long-term follow-up reported	Limited; potential confounders include prior knowledge or experience, but not controlled	Moderate; positive changes observed, but lack of control group limits causal conclusions	The study provides evidence of educational impact but cannot definitively attribute changes solely to the intervention.

RCT: Randomized controlled trial, VR: Virtual Reality, AR: Augmented Reality, IVR: Immersive Virtual Reality

Appendix-B

Study characteristics table

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[27]-1	Care home staff in Northwest England; total participants: 48 (including care assistants and senior carers), with a mean age of 38.1 years (range 18–67), 85% female, 25% from Black, Asian, or mixed ethnicities.	• AR smartphone application (SureWash) • Fully IVR headset with Tork VR Clean Hands Training app • Non-IVR training on a computer (standalone laptop) for comparison	• AR smartphone application (used as a non-immersive alternative) • Non-IVR training on a computer (used as a control/comparison to IVR and AR)	• Hand hygiene techniques aligned with WHO guidelines • Knowledge of hand hygiene practices and IPC • Repetition and practice of hand hygiene poses and techniques	Feasibility and implementation (uptake, session completion, engagement) Usability (System Usability Scale scores) Acceptability (learner satisfaction, tolerability) Efficacy (improvement in hand hygiene knowledge, confidence, and technique assessed via video and performance scores) Mechanisms for learning (task realism, interactivity, feedback, and repeated practice)	• AR and immersive VR apps demonstrated good usability, high acceptability, and improved hand hygiene technique. • Knowledge gains were minimal, but self-reported confidence increased overall. • The non-IVR was less usable, acceptable, and effective, indicating inequity in training opportunities. • Overall, AR and IVR are feasible and potentially effective, with mechanisms supporting learning. Future research is needed to confirm long-term benefits and comparative effectiveness.
[39]-2	300 pupils aged 9 to 12 years from public schools in Brazil.	• Oculus Go VR glasses (Facebook Technologies) • A virtual environment called "Inside the Mouth," which included 3D visualizations of oral cavity structures, biofilm, brushing and flossing techniques, and interactive animations.	The study primarily evaluated the effect of VR-based instruction; there was no explicit control group, but pre- and post-intervention questionnaires served as comparison measures.	• Oral hygiene education, including proper tooth brushing, tongue cleaning, and flossing techniques • Understanding of oral cavity structures and biofilm removal • Motivation to adopt better oral health habits	• Change in oral hygiene habits (e.g., increased use of dental floss, tongue brushing, and toothbrushing frequency) • Oral hygiene knowledge (assessed via questionnaires before and after intervention) • Participant opinions and drawings related to oral hygiene (qualitative assessment) • Statistical significance of changes in oral hygiene practices (Chi-square and Fisher's exact tests, significance level 5%)	• Significant increase in the use of dental floss, tongue brushing, and daily toothbrushing frequency after VR intervention ($p < 0.001$ for flossing, tongue brushing, and brushing frequency). • No significant change in oral hygiene knowledge scores ($p = 0.550$). • Participants produced positive drawings and comments, indicating engagement and motivation. • VR was effective as an educational tool, promoting behavior change through an interactive and playful experience, especially beneficial for children.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[50]-3	Forty-three medical students (mean age 23 years) from a medical school at the University Hospital of Zürich, Switzerland.	• VR hand hygiene training system using HTC Vive pro helmet and Valve Index controllers. • A simulated hospital environment replicating a real clinical setting, with interactive tasks such as greeting patients, auscultation, temperature measurement, and documentation. • The VR system included three levels of increasing difficulty, with virtual pathogens and infection scenarios.	No control group or traditional training used; the study focused on pre- and post-training performance within the VR environment and predictors of performance and behavioral intention.	• Hand hygiene procedures, including proper disinfection and pathogen management • Understanding of infection transmission and environmental contamination • Behavioral intention to further engage with VR-based medical training	• Performance scores in level-3 of the VR training (measured as accuracy and task completion time) • Technology acceptance, including performance expectancy, effort expectancy, and behavioral intention (measured pre- and post-training) • In-training engagement (adapted questionnaires assessing focus, usability, and motivation) • Predictors of VR performance and future behavioral intention (via linear regression models)	• Significant improvement in hand hygiene performance from level-1 to level-3 ($p < 0.001$). • Performance in level-3 was positively predicted by prior performance expectancy and in-training engagement, and negatively by effort expectancy. • The intention to further use VR training was positively predicted by prior effort expectancy and in-training engagement. • Results suggest that both engagement and prior acceptance influence VR training outcomes. • The findings support VR as a promising tool for medical procedure training, with engagement playing a critical role, though further research is needed on long-term transferability and effectiveness in real clinical settings.
[1]-4	The review encompasses studies involving healthcare professionals, medical students, nursing students, and college students, with sample sizes ranging from 17 to 150 participants across various studies.	NA	Most studies compared immersive technology-based training (VR/AR/MR) to traditional methods such as lectures, videos, or standard training. Some used control groups or pre- and post-assessment designs, while others lacked a comparator.	• Hand hygiene procedures, including proper disinfection and infection control • Knowledge of pathogen transmission and infection prevention • Motivation and engagement in hand hygiene practices among healthcare providers and students	• Hand hygiene performance scores (via assessments like OSCE, questionnaires, or task performance) • User satisfaction, usability, and acceptance measured through scales such as SUS, USEQ, ASQ, and SSQ • Motivation, engagement, and attitude toward immersive learning • Perceived usefulness and realism of the VR/AR experiences • Cybersickness and side effects (visual fatigue, dizziness, motion sickness)	• Immersive technologies, primarily VR, generally improved hand hygiene performance and motivation. • Participants reported high satisfaction, engagement, and perceived usefulness of VR/AR in hand hygiene training. • Some studies found no significant differences compared to traditional methods, but overall, immersive tech was viewed as effective and engaging. • Participants felt that VR could enhance infection control education, with many expressing interest in continued use. • Challenges such as cybersickness and limited pedagogical frameworks were noted, emphasizing the need for further research.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[23]-5	Twenty-five healthcare providers (nurses and nursing aids) with ages over 20 years participated in the study.	• Fully immersive 360-degree VR clips developed for educational purposes. • Oculus Quest 2TM (Meta Platforms, Inc.) HMD for delivering the VR content. • Two types of VR clips: one depicting transmission of microorganisms for doctors, and another for nurses, illustrating undetectable microorganisms during daily care.	No control group: the study was a pilot assessing the utility and safety of VR content. Performance was evaluated through direct observation post-VR exposure without comparison to traditional training methods.	• Hand hygiene practices aligned with the "5 Moments for Hand Hygiene." • Recognition of high-frequency contact surfaces and infection transmission risks during patient care.	• Participants' feedback on the VR experience gathered through questionnaires (perceived usefulness, awareness, VR sickness). • Hand hygiene compliance assessed via direct observation during a nursing-care scenario, focusing on adherence to the "5 Moments" and proper practices. • Safety and feasibility of VR content for educational use.	• The majority of participants found the VR clips helpful in increasing awareness of hand hygiene practices. • Hand hygiene compliance was high among participants, with observed adherence rates exceeding 85% in all moments. • Most participants reported no significant VR sickness, indicating safety of the digital content. • The study suggests VR has potential as an educational tool to improve infection prevention practices, though causality and long-term effects remain to be established.
[36]-6	Care home workers, including carers and managers, across residential and nursing homes in Northern England. The study involved 25 participants with varying ages, genders, and years of experience.	• AR and VR applications delivered via smartphones and HMDs (e.g., VR headsets). • Examples include the Tork VR Clean Hands Training app (VR scenario) and the SureWash hand hygiene app (AR gamification with gesture recognition).	No control group: the study was qualitative and exploratory, focusing on participants' perceptions, theories, and contextual considerations regarding AR/VR training.	• Hand hygiene practices aligned with IPC guidelines. • Use of AR/VR to promote repeated practice, interactive learning, feedback, reminders, and task realism to improve hand hygiene skills.	• Participants' perceptions of how and in what contexts AR/VR might work in care homes. • Theoretical insights into mechanisms such as realism, interactivity, repeated practice, feedback, and environment. • Qualitative feedback on acceptability, feasibility, and potential barriers or facilitators to implementation.	• Care home workers believed AR/VR could refresh hand hygiene practices by enabling repeated, interactive, and realistic practice scenarios. • Perceived mechanisms included increased understanding, learner satisfaction, and improved skills. • Contextual factors such as policies, staff preferences, infrastructure, costs, and comfort with technology influenced perceived feasibility. • Overall, participants viewed AR/VR as a promising tool, but noted the importance of addressing implementation challenges for successful adoption.
[9]-7	Healthcare workers, including nurses and other clinical staff, involved in patient care, with a sample size of 47 participants in the study.	A mobile AR training application designed for smartphones, utilizing the front-facing "selfie" camera to track hand motions, with multiple levels of difficulty and real-time feedback features.	Traditional hand hygiene training methods, such as annual classroom sessions, demonstrations, and observational assessments, without the use of AR or mobile self-directed practice.	Development of the WHO 6-step hand hygiene technique, emphasizing psychomotor skills through deliberate practice, repetition, feedback, and assessment to improve proficiency and retention.	• Number of practice sessions required to achieve proficiency (performance in the 6-step technique). • Hand hygiene proficiency assessed electronically via automated systems and through human inspection. • Engagement and practice frequency over the 4-week period. • Correlation of training sessions to demographic variables such as gender, age, and prior training.	• The study demonstrated that a mobile AR training tool could effectively enable learners to develop hand hygiene skills independently, with 81% reaching proficiency after an average of 24 practice sessions. The approach supports self-directed, deliberate practice leading to improved skills, suggesting potential for enhanced infection control and efficiency in healthcare training.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[35]-8	Nursing students in African universities, aiming to enhance IPC competencies. The exact population size is not specified, but the focus is on the regional scale involving multiple countries and institutions across Africa.	VR simulation applications designed for low-cost, mobile or desktop platforms. These VR tools are intended to be low-resource, self-paced, and accessible via links or downloads, incorporating real-time feedback and standardized training modules.	Traditional, institution-based clinical skills training and simulation laboratories, often resource-rich but unevenly distributed across African educational institutions. The comparison also considers the absence of standardized, inclusive, and scalable VR-based training programs currently in use.	IPC principles and practices, including hand hygiene, use of personal protective equipment, and other critical infection control procedures. The focus is on developing critical thinking, clinical reasoning, and practical competence through immersive, standardized simulation.	• Development of standardized IPC competencies among nursing students. • Engagement levels with VR simulation (e.g., access, frequency, practice time). • Self-reported confidence and critical thinking related to IPC practices. • Comparative assessment of IPC skills before and after VR intervention, including automated feedback and peer/instructor evaluations. • Cultural relevance and acceptance of VR technology within diverse African contexts.	• The implementation of culturally adapted low-cost VR simulation has the potential to improve IPC training by providing equitable, standardized, and inclusive educational experiences. It is expected to foster competence, critical thinking, and confidence in infection control practices among nursing students, thereby positively impacting healthcare quality and infection indicators across Africa.
[37]-9	People with intellectual disabilities residing in residential care facilities, with an estimated population size of approximately 30 individuals involved in this feasibility study.	AR training applications integrated with a smart toothbrush (e.g., Brush Monster), providing real-time visual feedback and gamified tooth-brushing guidance through mobile or tablet devices.	Traditional tooth-brushing training using visual educational materials, such as printed or video-based instructions, without AR or smart device integration.	Oral hygiene care, specifically improving tooth-brushing techniques, performance, and consistency among individuals with intellectual disabilities. The focus is on establishing correct brushing habits, enhancing motivation, and increasing effective oral hygiene practices.	• Changes in tooth-brushing performance, measured by performance scores and brushing time. • Improvement in oral hygiene status, assessed through indices such as debris and calculus levels. • Participant engagement, motivation, and ability to perform proper brushing techniques, tracked through observational checklists and performance reports. • Statistical significance of improvements pre- and post-intervention.	• The application of AR-based training using a smart toothbrush is expected to significantly enhance tooth-brushing performance and oral hygiene among individuals with intellectual disabilities, surpassing traditional visual material-based training in effectiveness.
[46]-10	Oral hygiene students ($n=23$) enrolled in a university program, participating in a RCT to evaluate VR training effectiveness.	IVR system utilizing stereoscopic displays, motion-tracking technology, and full-body immersion via VR goggles and controllers (e.g., PVIX CAVE VR system). The system simulates oral healthcare scenarios for disabled elderly persons, allowing self-practice and interactive learning. Optical 3D Glasses	No VR-based intervention; students in the control group received standard education without VR training.	Providing oral healthcare to disabled elderly persons, including knowledge of oral health, attitude towards patient care, self-efficacy in performing oral health procedures, and behavioral intentions to assist with specific oral care tasks such as interdental cleaning, soft tissue cleaning, and regular dental visits.	• Oral care-related knowledge (measured via questionnaire of 20 items). • Attitude towards oral healthcare (Likert scale). • Self-efficacy in providing oral care (Likert scale). • Behavioral intentions to assist in specific oral care activities (Likert scale). • System usability and student satisfaction (SUS score). • Effect sizes and statistical significance of changes over time, evaluated at baseline and multiple follow-ups (2, 4, and 6 weeks).	• VR training positively influences students' knowledge, attitudes, self-efficacy, and intentions toward providing oral healthcare to disabled elderly persons, with significant improvements observed compared to the control group.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[34]-11	Healthcare assistants (HCAs) ($n=80$) working in long-term care facilities, aged 65 years or older, with a focus on improving geriatric oral care performance through simulation training.	Combined AR and VR: **AR system:** Digitalized oral care procedures, including the Bass brushing technique, using optical tracking and wireless toothbrushes for self-assessment and real-time feedback. **VR system:** Scenario-based immersive training simulating various physical and oral health conditions in older adults, with animated videos, interactive modules, and automatic assessments. Participants used optical 3D glasses, controllers, and AR/VR headsets during training sessions.	Control group receiving no intervention or traditional training methods (not specified but implied as standard or no AR/VR training).	• Geriatric oral healthcare knowledge (e.g., proper brushing techniques, oral hygiene tools). • Self-efficacy in performing oral care procedures on older adults with diverse health conditions. • Behavioral intentions to perform and promote oral care activities, including denture cleaning, soft tissue cleaning, and encouraging regular dental visits.	• Increase in oral care-related knowledge (measured via questionnaire, scoring correct responses). • Self-efficacy in delivering oral care (Likert scale assessments). • Behavioral intention to perform oral care activities (Likert scale assessments). • Effect sizes (Cohen's d) indicating the magnitude of change. • Statistical significance of pre- and post-intervention differences analyzed via generalized estimating equations.	• The AR/VR simulation training significantly improved HCAs' oral care knowledge, self-efficacy, and behavioral intentions for geriatric oral healthcare compared to controls, indicating effective enhancement of skills and confidence.
[22]-12	Medical students ($n=29$) in years 3–6 at the University of Bern, Switzerland, participating in a usability and effectiveness study of the "Covid-19 VR Strikes Back" (CVRSB) application.	**Hardware:** Oculus Rift S HMD and hand controllers, Optical 3D Glasses **Software:** The CVRSB VR application built on the MAGES SDK, supporting SteamVR-compatible headsets and mobile HMDs. **Features:** Multiplayer collaboration, analytics engine, virtual whiteboard, avatar customization, reflective mirror, and realistic interaction mechanics designed to avoid the Uncanny Valley.	Traditional training methods involve printed instructions, instructional videos on PPE donning/doffing, and formal demonstration by an experienced physician.	• Proper performance of nasopharyngeal swab sampling for COVID-19 testing. • Correct donning and doffing of Personal Protective Equipment (PPE). • Hand hygiene protocols. • Developing psychomotor skills and cognitive understanding of infection control procedures through immersive simulation.	**Usability:** System Usability Scale (SUS). **User Satisfaction:** After-Scenario Questionnaire (ASQ) and User Satisfaction Evaluation Questionnaire (USEQ). **Simulator Sickness:** Assessed with the Simulator Sickness Questionnaire (SSQ). **Presence & immersion:** Assessed via Slater-Usoh-Steed questionnaire. **Workload & emotional response:** NASA-Task Load Index and Self-Assessment Manikin (SAM). **Performance improvements:** Measured via pre- and post-training assessments, including hand disinfection and PPE use, with corroborative fluorescent markers and UV-light scanning in follow-up studies.	• The VR training application demonstrated high usability, satisfaction, and immersion, with users performing significantly better in key infection control tasks post-training. The VR approach matched or exceeded traditional methods in training effectiveness, with high tolerability and engagement.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[31]-13	Frontline health workers in Uganda, including nurses, clinical officers, laboratory officers, medical officers, pharmacists, and epidemiologists. The pilot involved a cohort of 52 trained participants, with a diverse mix in gender, age, and professional background.	**Hardware:** HTC Vive Pro HMD with room-scale tracking, base stations, and controllers. **Software:** Custom VR content created using platforms like Enduvo, Humulo, and SOMA (for 360° videos). The curriculum included animated simulations, 360° videos, voice-over narrations, and interactive modules.	Traditional classroom-based training for IPC, including in-person lectures, demonstrations, and printed materials.	• Proper donning and doffing of Personal Protective Equipment (PPE). • COVID-19 case management procedures. • Hand hygiene practices. • Building practical skills and knowledge related to IPC in the context of COVID-19.	• Knowledge acquisition and retention, compared to previous classroom cohorts (statistically significant improvements, P-value = 4.0e-09). • Participant feedback on experience, including ratings of course satisfaction, perceived effectiveness, and willingness to recommend. • Skill performance, assessed through scores and practical demonstrations.	• VR-based training demonstrated better performance outcomes, faster learning, higher retention, and positive participant feedback, indicating it is a feasible, effective, and scalable approach for IPC training in low-resource settings during a pandemic.
[28]-14	129 foodservice workers aged 18–64, including cooks, waiters, and other food handlers, from various institutions.	**Hardware:** HTC Vive VR headset, VR gloves (Manus Prime II), and room-scale tracking system. **Software:** Custom VR application simulating the WHO 11-step handwashing process, combined with 360° videos and interactive modules.	Three training methods: **Classical (CT):** PowerPoint presentation with face-to-face instruction. **Glo-Germ demonstration (GT):** UV light revealing residual contamination after handwashing. **VR:** Interactive IVR training using headsets and gloves.	• Proper handwashing technique according to WHO 11-step protocol. • Improving handwashing duration and adherence to the steps. • Reducing microbial contamination on hands. • Enhancing compliance with hygiene practices in foodservice.	Behavioral: Handwashing duration, number of steps correctly performed, adherence to WHO steps (pre- and post-intervention). Microbiological: Total bacterial colony counts (log10 CFU) on hands before and after handwashing. Statistical analysis: Comparison of improvements among the three groups using appropriate tests (e.g., Kruskal-Wallis, Wilcoxon, ANOVA).	• All groups showed improvements post-training, but the VR group demonstrated the most significant enhancements: • Longer handwashing times. • Higher number of correctly performed WHO steps. • Greater reduction in bacterial contamination. • The findings suggest VR training is highly effective in promoting thorough hand hygiene practices.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[48]-15	School children aged 10–18 years old in Riyadh, Saudi Arabia, with a total sample size of approximately 2150 students after initial recruitment, with 1285 included in the final analysis.	**Hardware:** VR headsets and mobile app interactive dental health simulations. **Software:** Custom VR platform providing immersive, gamified dental health education, including interactive lessons, virtual dental clinics, and self-directed learning resources.	**Traditional Method:** Classroom-based lectures and demonstrations on oral hygiene and dental health practices. **VR Method:** IVR tools providing visual and hands-on experiences for students.	• Improving students' oral hygiene practices, specifically brushing techniques. • Enhancing dental health literacy regarding caries, proper brushing, and oral health maintenance. • Reducing plaque accumulation as measured by plaque index scores and plaque percentage.	**Quantitative:** Changes in plaque index scores, plaque percentage, and brushing scores before and after intervention. **Qualitative:** Observations of brushing technique adherence and student engagement. **Results:** Significant improvements in oral health indicators and brushing techniques in the VR group compared to the traditional group.	• Use of VR technology significantly improved students' oral health status, as evidenced by lower plaque indices and improved brushing techniques post-intervention. • Students reported higher engagement and interest with VR, and it was perceived as more effective and enjoyable than traditional methods.
[42]-16	Children aged 6 to 10 years; sample size approximately 50–100 participants.	AR combined with Kinect motion-sensing technology within Unity 3D environment.	Standard oral health education methods, such as verbal instructions and static demonstrations.	• Enhanced toothbrushing technique, error correction in brushing movements, and increased oral health awareness.	• Precision and correctness of brushing movements. • Reduction in brushing errors. • Plaque removal efficacy measured via residue scores. • User engagement and usability ratings. • Behavioral changes in oral hygiene practices.	• Expected to be positive, indicating improvements in brushing technique, error reduction, and increased motivation among children.
[38]-17	First-year medical students at the University of Zurich; total of 173 participants.	VR hand hygiene trainer with pathogen visualization in "real-time" or "summary" modes.	Three different visualization set-ups: **Set-up 1** ("on-off-off"): real-time visualization only at level 1, summary at levels 2 and 3. **Set-up 2** ("off-on-off"): real-time at level 2, summary at levels 1 and 3. **Set-up 3** ("off-off-off"): no real-time visualization, only summary at the end of each level.	Hand hygiene performance, specifically reducing pathogen transmission events (contaminations and colonizations) during simulated patient care.	• Number of pathogen contamination events in level 3. • Number of patient colonizations. • Time to complete the training level. • User's immersive experience (immersion, fidelity, engagement). • User's perception and acceptance of the VR technology.	• Participants with "summary" visualization at all levels performed best, with fewer contaminations. • "Summary" visualization also resulted in higher immersion scores. • "Real-time" pathogen visualization during tasks may negatively impact performance and immersion, suggesting that immediate feedback could be distracting or less effective for novice learners.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[10]-18	Healthcare workers (HCWs) at three wards in a tertiary care hospital in Germany; total of 81 trainings (48 VR, 33 lecture).	VR training using Oculus Go headsets and the "VR Clean Hands" application, simulating hand hygiene scenarios. The comparison was made with traditional lecture-based education.	Conventional face-to-face lecture with slide show presentation on hand hygiene indications and techniques.	• Correct hand disinfection technique according to WHO guidelines. • Compliance with hand hygiene indications. • Knowledge transfer from training to practice. • User satisfaction and acceptance of training modalities.	**Primary ourcomes** • HCW satisfaction assessed via Likert-scale questionnaire. • Hand rub consumption measured continuously (per patient-day). • Compliance with WHO hand hygiene indications observed before and after interventions (minimum 50 observations per period). • Adverse effects of VR (e.g., dizziness, nausea). • Feedback on usability, technical issues, and hygiene concerns related to VR devices.	• High acceptance and satisfaction with VR, with most HCWs preferring VR over traditional lectures. • Slightly higher compliance observed after traditional lecture (95%) compared to VR training (87%), with statistical significance only for the lecture. • No significant difference in hand rub consumption across groups. • VR considered a promising, engaging, and feasible supplement to traditional training but did not demonstrate superior impact on hand hygiene compliance or disinfectant use.
[49]-19	Children aged 6–8 years attending the Department of Pediatric and Preventive Dentistry, JSS Dental College & Hospital, India. The study involved 32 participants divided into two groups.	AR assisted toothbrush supported by an interactive mobile application and sensor-based toothbrush, designed to guide children in proper toothbrushing techniques.	Conventional toothbrushing using a manual toothbrush and standard oral hygiene instructions.	• Improving toothbrushing technique and oral hygiene practices among children. • Reducing plaque accumulation and gingival bleeding. • Enhancing motivation and engagement in oral health behaviors.	• Reduction in plaque scores (modified Quigley-Hein Index). • Reduction in gingival bleeding scores (Loe and Silness Index). • Feedback on acceptance, ease of use, motivation, and perceived cleaning efficiency of AR-assisted brushing. • Participant and parent satisfaction via feedback questionnaires. • Adherence to brushing instructions over two weeks.	• Significant reduction in plaque and gingival bleeding scores in the AR-assisted group compared to the conventional group ($p < 0.0001$). • Higher motivation and engagement reported by children and parents in the AR group. • AR-guided toothbrushing demonstrated an effective and engaging method for improving oral hygiene behaviors in children.
[45]-20	Undergraduate chemistry students at the University of Southern California, with cohorts of approximately 30–200 students across multiple semesters.	VR applications developed using Unity, deployed on Oculus Quest standalone headsets. The VR environment simulates a laboratory setting to teach glove hygiene and safety practices.	Traditional laboratory safety training methods, including verbal instructions, videos, and written manuals.	• Proper glove use and hygiene in laboratory settings. • Visualizing and understanding how chemicals and contaminants transfer via gloves. • Active learning to reinforce safety protocols and reduce cross-contamination.	• Student feedback on usability, comfort, and educational value of the VR module. • Effectiveness in improving awareness of glove contamination and safety practices, assessed via pre- and post-experience questionnaires. • Observation of student actions and engagement during the VR simulation. • Incidence of nausea or discomfort experienced by students during VR use. • Feasibility of deploying VR in academic library spaces to accommodate large student groups. • Technological challenges and suggestions for future improvements.	• The VR module demonstrated potential for active learning in lab safety, especially in teaching glove hygiene and contamination transfer. • Student enthusiasm was notable, though nausea remained a challenge. • The environment was effective in visualizing invisible chemical spread, likely reinforcing safety concepts better than traditional methods. • Deployment through library spaces was feasible and scalable for large classes.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[43]-21	Children aged 6–8 years, with a total sample size of 32 participants, divided equally into two groups (16 children per group).	AR-assisted toothbrushes combined with a smartphone application and sensor-assisted toothbrushes, utilizing AR technology to overlay virtual content onto the real-world environment.	Conventional manual toothbrushing technique without AR assistance.	• Improving children's motivation and engagement in effective toothbrushing. • Educating children on proper brushing techniques through gamified AR interactions. • Enhancing understanding of oral health and plaque control.	• Reduction in fluorescence lesion area scores, indicating decreased carious activity assessed via fluorescence imaging. • Decrease in plaque Streptococcus mutans bacterial counts, measured microbiologically before and after intervention. • Changes in clinical and microbiological oral hygiene indicators over two weeks.	• The AR-assisted brushing demonstrated a significantly greater improvement in oral hygiene markers, including lower fluorescence scores and bacterial counts, indicating enhanced effectiveness in motivating children and improving their oral health behaviors.
[30]-22	Fourth-year medical students at a Japanese university; total of 42 students (21 in VR group and 21 in lecture group).	• Fully immersive 360-degree VR using HMDs (goggles). • VR content created with a 360-degree camera, delivering scenarios from both doctor's and patient's viewpoints. • Cloud-based VR delivery system developed by Jolly Good Inc.	Lecture-style learning using PowerPoint slides with narration, text, photos, and tables.	• Infection control procedures: hand hygiene, proper donning and doffing of PPE, and environmental management to prevent infection spread. • Improving adherence to infection control protocols and increasing motivation and engagement in learning.	• Objective Structured Clinical Examination (OSCE) scores assessing infection control practices, including hand hygiene, PPE use, and overall compliance. • Hand hygiene compliance rates before and after learning, measured via observation. • Student responses on questionnaires evaluating understanding, enjoyment, perceived usefulness, realism, immersion, and willingness to recommend VR.	• Both groups showed improvement post-learning, but the VR group demonstrated significantly higher post-test scores and greater satisfaction. • VR experience increased motivation, engagement, and adherence to infection control practices, with students reporting higher enjoyment and perceived realism.
[3]-23	Healthcare professionals, including clinicians, students, and educators involved in clinical education within New South Wales, Australia. The article does not specify exact numbers but implies a broad group of VR users in healthcare training settings.	NA	Traditional face-to-face clinical education and simulation training methods. The article discusses the transition from conventional in-person training to VR-based methods during the COVID-19 pandemic.	Development of technical and non-technical clinical skills through simulation, including advanced life support, crisis response, and reflective practice. The primary focus is on ensuring safe and effective delivery of VR-based education while mitigating infection risks.	• Establishment and implementation of a standardized cleaning and disinfection guideline for VR HMDs. • Ensuring IPC, reducing the risk of pathogen transmission between users. • Facilitating safe resumption of VR-based clinical education during COVID-19. • Practical adherence to cleaning protocols, safety, and operational feasibility of VR equipment.	• The implementation of a targeted, standardized cleaning and disinfection protocol for VR HMDs effectively minimizes infection risks, thereby enabling the safe continuation and scaling of VR-based clinical education during and beyond the pandemic.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[41]-24	Female high school students in Birjand, Iran. Sample size: 90 students divided into three groups of 30 each (VR, verbal, control).	VR simulation with mobile HMDs. VR content included 3D videos demonstrating oral health techniques. Compared to traditional verbal education and no intervention.	• Verbal oral health education (traditional method). • Control group receiving no training during the initial phase.	Improving oral hygiene behaviors, specifically reducing dental plaque (PI) and gingival inflammation (GI). Teaching proper tooth brushing and flossing techniques via VR simulation versus verbal instruction.	• Changes in Gingival Index (GI) and Plaque Index (PI) scores measured clinically before and after intervention. • Statistically significant reductions in GI and PI in VR and verbal groups, with VR showing superior effectiveness. • Follow-up at one month post-intervention to assess the impact of the education.	• VR-based oral health education significantly reduces GI and PI scores more effectively than verbal education or no intervention, indicating improved oral hygiene and health outcomes.
[40]-25	Community members across different age groups (urban and rural populations). **Specific Target Groups:** Young adults (ages 15–35) Middle-aged adults (ages 36–55) Older adults (older than 56) **Sample Size:** 83 participants (Young adults: 28, Middle-aged: 28, Older adults: 27)	• Mobile application incorporating AR • Mobile AR • Hand gesture recognition through camera-based hand tracking • Marker-based AR system that detects hand movements and gestures in real-time	• The study compares pre- and post-intervention handwashing skills and behaviors within the same participants. • No explicit mention of a traditional control group; the comparison is based on the participants' performance before and after using the Mobile AR Hw application.	Proper handwashing steps following WHO guidelines Hand movement accuracy (circular, forward, backward motions) Duration of handwashing (aiming for 20–30 seconds) Correct sequence of steps in handwashing The focus is on improving accuracy, effectiveness, and adherence to recommended handwashing techniques among different age groups.	**Quantitative Measures:** • Improvement in handwashing movement accuracy (statistically significant with $p = 0.028$ and $p < 0.001$) • Duration of handwashing (not statistically significant, $p = 0.07$) • Proper step adherence (significant improvement, $F(5,27) = 32.21$, $p < 0.001$) **User Acceptance and Usability:** • Ease of use and understanding (measured via user acceptance test and mean scores) • Perceived interest and engagement levels (percentage of participants rating the app as easy and interesting) **Behavioral Metrics:** • Changes in handwashing behavior before and after intervention	• The mobile AR application positively affected participants' handwashing skills, particularly in movement accuracy and step adherence. • No significant effect was observed on handwashing duration time. • Overall, the intervention improved handwashing techniques and was well-accepted by most participants, especially younger adults.
[25]-26	Undergraduate nursing students in Taiwan. 50 students total	VR-based Oral Health Care Learning System (Pvix VR, eped Inc., Taiwan), • VR head-mounted devices with 3D glasses and remote control • Virtual interactive simulation environment for practicing geriatric oral health care procedures	The control group did not receive the VR-based training intervention; they only completed repeated questionnaires without exposure to the VR system. The experimental group received two rounds of VR simulation training at two-week intervals.	• Greet older adult patients and explain oral health care procedures • Inspect environment for safety and adequacy • Assist in cleaning dentures and natural teeth using appropriate tools and products • Recognize and respond to geriatric oral health needs • Build confidence and self-efficacy in geriatric oral health care	**Knowledge**: Assessed via a 10-item scale, higher scores indicate better geriatric oral health knowledge. **Attitudes**: Measured through a 7-item Likert scale, higher scores reflect more positive attitudes toward geriatric oral health. **Self-efficacy**: Evaluated with a 10-item scale, higher scores denote greater confidence in providing oral health care. **Behavioral Intentions**: Assessed via a 10-item scale, higher scores indicate increased intention to assist older adults with oral health. **Satisfaction**: Participant satisfaction with the VR system measured through the System Usability Scale (SUS), score range 0–100.	• The VR-based simulation training significantly improved nursing students' knowledge, attitudes, self-efficacy, and behavioral intentions regarding geriatric oral health care. • Repeated VR training (twice over 4 weeks) was more effective in enhancing attitudes and intentions than a single session. • Participants reported high satisfaction with the VR system, indicating positive acceptance and usability.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[44]-27	Four Children with intellectual disabilities (ID) in elementary school	Kinect V2 sensor combined with a computer game called *Soap and Water!* creating an AR environment Motion-controlled gesture recognition technology 3D interactive game environment developed with Unity 3D Video recording for performance assessment	The study used a **non-concurrent multiple baseline design**, with baseline (pre-intervention) data collected before introducing the game intervention. No mention of a separate control group; each child's progress was compared across phases (baseline, intervention, maintenance).	• Performing the 15-step hand washing task independently • Recognizing and executing each step correctly during hand hygiene routines • Learning to wash hands thoroughly and independently, including specific steps like turning on water, applying soap, scrubbing, rinsing, drying.	**Task Performance:** Percentage of individual steps completed independently, recorded via video analysis. **Progress:** All four children showed increased independent performance, with improvements ranging from around 63% to 219%. **Social Validity:** Parental and teacher feedback regarding usefulness, motivation, and progress; high satisfaction reported. **Error Rate:** The game was effective but error-prone, with technical issues like loss of motion tracking affecting performance.	• The intervention significantly improved the children's ability to perform hand washing steps independently. • The progress was maintained during the follow-up (maintenance phase), indicating effective skill acquisition. • Parents and teachers viewed the game as a useful, motivating, and acceptable training tool, with positive perceptions about learning and independence gains.
[11]-28	Healthcare workers in Liberia involved in IPC, particularly during the Ebola outbreak. Involved development and testing of a prototype module; specific participant numbers are not detailed in the excerpt, but it focuses on a broad healthcare workforce in a resource-limited setting.	VR platform utilizing 3D immersive environments, accessible via laptops or tablets. • Distributed simulation combining VR with lightweight, portable hardware • Use of 3D graphics, avatars, animations, voiceovers, gamification mechanics (leaderboards, badges, challenges) • Interactive environment with real-time feedback, self-assessment, hazard perception modules	The development centered on creating a rapid, adaptive training tool rather than a traditional comparison study. The methodology emphasizes iterative development, stakeholder feedback, and continuous improvement rather than a direct control vs. intervention comparison.	• IPC principles • Proper donning and doffing of PPE • Hazard identification and perception in clinical settings • learning theories (motivational features, contextual relevance, clear goals) • Practical skills (e.g., PPE protocols) • Critical thinking and hazard recognition	• Development of an adaptable, rapid-response virtual training module • Incorporation of simulation features like deliberate practice, feedback, self-assessment, gamification, hazard exposure • Potential Evaluation Metrics (implied): • User engagement and satisfaction • Confidence and competence in PPE use and hazard recognition • Learning retention and behavioral change (though specific metrics are not detailed in the excerpt) • Data analytics for tracking progress and performance	• The project demonstrates that high-frequency, low-fidelity simulations can be rapidly designed and deployed using Scrum agile methodology. • The virtual module, with embedded analytics, has the potential to improve healthcare workers' confidence and competence in IPC measures during Ebola outbreaks. • The approach suggests broad applicability for rapid response training in various disaster or emerging health crises, emphasizing accessibility, adaptability, and effectiveness.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[33]-29	Third-year medical students across three universities in France, the UK, and Germany. Approximately 55 students per group per university, totaling about 110 students per university, with a total estimated sample size of around 330 students.	VR simulation environment with headsets and immersive scenarios. • Fully IVR scenarios replicating the operating room environment. • Real-life videos integrated into VR. • Interactive tasks based on IPC measures.	**Control Group:** Students receiving conventional teaching, including a 1-hour slide-based lecture and two real-life videos about hand hygiene and gloving in the OR. **Comparison:** The primary comparison is between VR-based education versus traditional classroom-based instruction.	• Knowledge of surgical site infection (SSI) prevention measures. • Appropriate behaviors in the operating room (e.g., limiting movements, hand hygiene, proper gowning/gloving). • Recognition of infection control practices in a surgical setting.	• Difference in scores on the IPC exam at the end of the academic year between the two groups. • The exam assesses knowledge of SSI prevention measures, with questions aligned across three countries. • Student satisfaction and progression within the VR group, measured through questionnaires and usability scales. • Engagement, errors, and time spent during VR sessions.	• The hypothesis is that VR-based training will lead to improved exam scores compared to conventional teaching. • The study also aims to assess student satisfaction and engagement, with expectations that VR will enhance learning experience and confidence. • Overall, the expectation is that VR will be an effective, innovative educational tool that surpasses traditional methods in imparting IPC knowledge and appropriate behaviors in the OR.
[12]-30	Hospital ICT, medical staff, hospitalized patients, and accompanying persons in Polish hospitals. The study and projected applications are relevant across hospital staff involved in infection prevention, antibiotic stewardship, vaccination, and epidemiological monitoring.	Emerging IT solutions including machine learning (ML), artificial intelligence (AI), AR, large language models (LLMs) like ChatGPT, and virtual assistants. • AI-based virtual assistants for medical staff. • AR tools for training and operational support. • Multi-modal integration of wireless broadband, big data, and interconnected hospital IT systems.	The study compares current conventional hospital IT systems and manual practices against the capabilities and potential of advanced, AI-driven, and AR-enhanced solutions. The projections suggest a future where all hospital IT tools are integrated into a unified, holistic system.	• Hospital hygiene improvement. • Antibiotic stewardship adherence. • Vaccination promotion and compliance. • Infection control monitoring and data analysis. • Decision support for epidemiological tasks. • Data collection, processing, and reporting for infection control activities.	• Identification and potential implementation of IT solutions to improve infection control activities. • Enhanced decision-making, surveillance, and reporting capabilities through AI and AR tools. • A fully integrated hospital IT ecosystem providing personalized, continuous, and omnipresent support to healthcare staff and patients. • Revolutionization of hospital epidemiology practices.	• Identification and potential implementation of IT solutions to improve infection control activities. • Enhanced decision-making, surveillance, and reporting capabilities through AI and AR tools. • Long-term Projections: A fully integrated hospital IT ecosystem providing personalized, continuous, and omnipresent support to healthcare staff and patients. Revolutionization of hospital epidemiology practices.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[26]-31	22 healthcare trainees including 18 medical students and 4 residents at Okayama University Hospital, Japan	Fully immersive 360° VR system (VIVE Pro Eye) with HMD, sensing gloves, and tracking system. • Fully IVR environment simulating a patient room. • Interactive tasks: Environmental Cleaning, Gauze Exchange, and Urine Collection. • Visualized virtual microorganisms as small colored dots adhering to surfaces and hands.	**Control Group:** Participants received a 15-minute online video lecture on hand hygiene. **Intervention Group:** Participants trained using the IVR system, with interactive tasks designed to promote hand hygiene practices. **Comparison**: Effectiveness of VR training versus traditional video-based education.	• Hand hygiene compliance, specifically the amount of alcohol used for hand rubbing. • Recognition of contamination and microorganism spread. • Behavioral change related to IPC.	• Quantity of portable hand-rubbing alcohol used before and after intervention, measured in grams. • Residual viral load in VR tasks (simulated virus spread and disinfection effectiveness). • Changes in hand hygiene behavior, assessed via alcohol usage and residual virus data.	• The VR education system is expected to significantly enhance hand hygiene practices, evidenced by increased alcohol usage post-intervention in the VR group. • The immersive and interactive nature of VR is anticipated to lead to better recognition of contamination and improved compliance with hand hygiene protocols.
[21]-32	50 senior Korean nursing students	IVR system using HMD (VIVE Pro) with hand-tracking (Leap Motion Controller™). Fully IVR environment simulating neonatal NICU. Three scenarios: Basic care, feeding management, skin care and environmental management for infection prevention. Sensory stimuli include visual and touch interactions, visualizing infection control procedures in a virtual neonatal setting.	**Control Group:** Participants engaged in routine clinical practice in the NICU, supplemented with lectures. **Intervention Group:** Participants used the VR simulation program in addition to routine practice. **Comparison:** Effectiveness of VR simulation versus traditional NICU practice plus lectures in enhancing knowledge, self-efficacy, and satisfaction.	• Neonatal infection control knowledge. • Self-efficacy in performing infection control procedures. • Learner satisfaction with the educational method. • Practical skills in infection prevention such as basic care, feeding, skin care, and environmental management.	• Knowledge measured via the High-Risk Neonatal Infection Control Competency Scale Knowledge (HirNICCS_K). • Self-efficacy in infection control performance measured by a modified self-efficacy scale. • Learner satisfaction assessed via Likert-scale items. • No significant difference in knowledge between groups post-intervention. • Significant improvements in self-efficacy and learner satisfaction in the VR group compared to control.	• The VR simulation program significantly increased nursing students' performance self-efficacy and learner satisfaction. • Although knowledge did not differ significantly, the IVR environment likely contributed to enhanced confidence and satisfaction, fostering better practical engagement and problem-solving in infection control.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[2]-33	Healthcare professionals, patients, visitors, family members, and caregivers of all ages.	NA	• Traditional education (e.g., printed materials, illustrations, leaflets) • No intervention or baseline compliance measurement • Different educational tools (e.g., videos vs. traditional materials)	• Knowledge of proper hand hygiene procedures • Technique accuracy and quality of handwashing • Attitudes and intentions towards hand hygiene • Compliance rates among healthcare workers, patients, visitors, and family members • Behavioral reinforcement through feedback and reminders	• Increased hand hygiene compliance (HHC) rates • Improved technique and knowledge scores • Higher acceptability, usability, and satisfaction with the technological tools • Changes in behavioral intentions and actual practice in clinical or real-world settings • Findings: • Technologies such as electronic reminders, gamification, and VR significantly improve HH performance and compliance. • Some systems, like wearable devices, increase the duration and volume of handrub applications but may not significantly alter compliance rates.	• Use of educational technologies substantially enhances hand hygiene knowledge, technique, compliance, and learner/patient engagement. • These tools facilitate repetitive, accessible, and evidence-based learning, thus promoting better infection control behaviors among healthcare professionals and the general population.
[13]-34	Medical staff at a class A tertiary mental health center, including 116 employees (medical staff, nurses, caregivers, cleaners, administrators).	• Cloud computing (PaaS platform using Docker containers) • Mobile or desktop applications • Big data analytics • Streaming media technology • Knowledge graph technology	Pre-Implementation: Traditional text-based emergency plans, manual operations, and limited digital support. Post-Implementation: Use of the D-B_EPCS system for training, emergency response, and resource management, compared to prior manual practices.	• Emergency infectious disease response knowledge • Use of personal protective equipment (PPE) • Operation of emergency plans and decision-making • Resource allocation and management during crises • Practical skills in disease control measures	• System performance: functionality, practicality, reliability, efficiency, accuracy, assessability (all > 3, with efficiency and practicality > 4) • Staff emergency knowledge (significant improvement, $\chi2 = 37.69$, $p < 0.001$) • PPE wearing and removal skills (significant improvement, $p < 0.001$) • System usability and training effectiveness • After 12 months, marked improvements in emergency knowledge and operational skills. • Enhanced system adaptability and staff proficiency.	The digital-based emergency IPC system significantly enhances staff knowledge and operational skills for infectious disease control in psychiatric hospitals. It improves response efficiency, resource management, and training methodologies, facilitating better preparedness for future public health crises.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[8]-35	Children aged 5–12 years, along with their parents, educators, and dental professionals.	NA	Traditional Methods: Physical demonstrations printed educational materials, storybooks, videos, and standard classroom education. Digital Approaches: Metaverse-based interactive and immersive experiences aiming to enhance engagement and effectiveness.	• Oral hygiene practices (brushing, flossing) • Dental trauma awareness and emergency response • Reducing dental anxiety and fear • Promoting lifelong healthy oral habits • Enhancing motor coordination related to oral care	• Increased oral health knowledge and awareness • Improved brushing and oral hygiene behaviors • Reduced dental anxiety and pain perception • Enhanced engagement and motivation to practice oral care • Cost-efficiency and accessibility of education • Metaverse approaches are engaging, customizable, and potentially more effective in reaching children, especially those hard to reach or fearful of dental visits.	• Metaverse-based oral health promotion effectively enhances children's engagement, knowledge, and positive behaviors regarding oral health. • It offers interactive, personalized, and accessible education, with potential to improve long-term oral health outcomes.
[32]-37	Adults in general, including healthcare providers and the public.	NA	**Traditional Interventions:** Educational campaigns, workshops, posters, and performance feedback. **Digital Interventions:** Smartphone apps with behavior change techniques, aiming to improve adherence and technique in hand hygiene.	• Education on hand hygiene importance and techniques. • Reminders to prompt handwashing. • Tracking handwashing instances and performance feedback. • Promoting behavior change via personalization and prompts. • Incorporating best practice guidelines, such as WHO and CDC hand hygiene steps.	• Content quality, accuracy, and comprehensiveness regarding hand hygiene guidelines. • Technical features, innovation, and usability. • Functionality scores based on IMS criteria. • App quality assessed via MARS. • Evidence of testing or trialing of apps. • Most apps were free, with variable quality and limited expert involvement. • Only a few apps used innovative engagement techniques. • Few apps had been empirically tested for effectiveness.	• Current apps are generally simple, with limited functions and often lacking alignment with best practice guidelines. • Innovative features can enhance engagement, self-efficacy, and awareness. • There is significant potential for improvement through collaboration with infection prevention experts and robust evaluation. • Future apps should aim for higher quality, evidence-based content, and sustainable user engagement.

Table (continued)

Ref.	Population	Technology Used	Comparator	Targeted Skills/Focus	Outcomes/Metrics	Principal Effect Direction
[47]-38	Oral health students (dental, dental hygiene, dental therapy) and interpreting students.	• Simulation-based training including immersive simulated encounters with standardized patients • Use of virtual scenarios, videos, and role-play to practice communication skills. • Tools like start-stop-rewind techniques, fishbowl observation, and debriefing sessions.	• Traditional Approaches: Didactic lectures, uniprofessional training, and ad hoc communication strategies. • Innovative Approach: Interprofessional simulation training designed to improve teamwork, communication, and cultural competence in interpreter-mediated encounters.	• Effective team coordination between providers and interpreters. • Cultural competence and understanding of legal/ethical issues. • Use of frameworks like INTERPRET to improve communication. • Reflection on power dynamics, professional roles, and patient-centered care. • Interpretation of dental terminology in the patient's spoken language (for interpreters). • Ethical and legal implications of working without trained interpreters.	• Changes in learner familiarity with best practices, legal protections, and disparities. • Increased confidence in leading and employing effective communication with LEP patients. • Learner self-reports of increased knowledge, skills, and awareness. • Reflection and feedback during simulation to promote mindfulness and team cohesion. • Findings: Significant improvements in learners' self-assessed competencies, awareness, and confidence after training.	• The curriculum effectively enhances interprofessional teamwork, communication, and cultural competence skills. • It fosters mindful practice, improves understanding of roles, and addresses power disparities. • The approach promotes safe, patient-centered care, ultimately aiming to improve outcomes for LEP patients across health care settings.
[24]-39	Second-year dental hygiene students at Idaho State University.	• Simulation-based immersive encounters with trained interpreters and mock LEP patients. • Use of role-play, discussion, and reflection to enhance understanding.	• Pre- and Post-Assessment: The study compared students' knowledge, perceptions, and attitudes before and after the immersive experience. • Traditional Learning: Implicit comparison to the lack of prior specific training or interprofessional experiences in handling LEP informed consent.	• Understanding of federal and state guidelines on interpretation and informed consent. • Ethical considerations and best practices for working with LEP patients. • Recognizing the importance of professional interpreters over family members or ad hoc interpreters. • Developing confidence in explaining and obtaining informed consent in a cross-linguistic context. • Critical thinking about cultural and linguistic barriers to effective communication.	• hanges in students' knowledge of legal and ethical guidelines. • Shifts in perceptions about the appropriateness of using family members as interpreters. • Increased confidence in explaining treatment plans to LEP patients. • Attitudinal changes measured through Likert-scale responses. • Open-ended responses highlighting perceptions and suggestions for improvement. • Significant increases in awareness of federal guidelines and state requirements. • Decreased acceptance of using family members as interpreters. • Enhanced student confidence in clinical communication with LEP patients.	• The immersive, interprofessional experience positively impacted student knowledge, perceptions, and attitudes regarding informed consent on dental hygiene with LEP patients. • It increased confidence and understanding of ethical, legal, and communication issues. • The study supports integrating experiential, interprofessional training into health professions education to improve culturally and linguistically competent care.

AR: Augmented Reality, HMDs: Head-Mounted Display, HW: Hardware, IVR: Immersive virtual reality, IPC: infection prevention and control, IT: Information Technology, MARS: Mobile App Rating Scale, VR: Virtual Reality, XR: extended reality, NICU: Neonatal Intensive Care Units

Appendix-C

PRISMA 2020 checklist for "the role of extended reality technologies in Hygiene education and training"

PRISMA 2020 Item	Description	Location in Manuscript	Page/Section
Title	Identify as a systematic review.	Title	Page 1
Abstract	Structured summary including background, objectives, methods, results, conclusions.	Abstract	Page 2
Introduction	Rationale and objectives.	Introduction	Pages 3–4
Methods			
Protocol and Registration	Indicate if protocol exists.	Methods	Page 4 (state no preregistration)
Eligibility Criteria	Define inclusion/exclusion criteria.	Methods	Pages 4–5
Information Sources	List databases searched.	Methods	Page 5
Search Strategy	Provide full search strings.	Methods	Page 5–6 (detailed in Methods)
Selection Process	Describe screening process.	Methods	Page 6
Data Collection Process	Describe data extraction procedures.	Methods	Page 6
Data Items	Outcomes and variables extracted.	Methods	Page 6–7
Risk of Bias Assessment	State tools/methods used.	Methods	Page 7 (or Appendix-A summary)
Synthesis Methods	Describe how data was synthesized.	Methods	Page 7
Results			
Study Selection	Flow diagram and numbers at each stage.	Results	Page 8, Fig. 1
Study Characteristics	Summary table of included studies.	Results	Pages 9–15
Risk of Bias Within Studies	Summary of bias assessments.	Results	Appendix-A
Results of Syntheses	Main findings, tables, figures.	Results	Pages 16–20
Discussion	Main findings, limitations, implications.	Discussion	Pages 21–25
Other Information			
Registration and Protocol	State registration status.	Methods	Page 4 (no preregistration)
Funding	Declare funding sources or none.	Declarations	Page 26
Conflicts of Interest	Declare potential conflicts.	Declarations	Page 26

Abbreviations

AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
CDC	Center for Disease Control
HMD	head-mounted display
ICN	International Council of Nurses
IVR	Immersive Virtual Reality
IPC	Infection Prevention and Control
LEP	Limited English Proficiency
MR	Mixed Reality
NICU	Neonatal Intensive Care Units
PPE	Personal Protective Equipment
SSI	Surgical Site Infections
VR	Virtual Reality
WHO	World Health Organization
XR	Extended Reality

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Emine Alp Meşe (EAM): Formulated the research objectives, conducted literature searches and screening, and wrote and reviewed the manuscript. Fulya Basmacı (FB): Contributed to literature screening and manuscript writing. Ali Can Bulut (ACB): Assisted with literature searches and quality evaluation. Damla Topallı (DT): Participated in literature screening and contributed to manuscript writing. Figen Şenel (FŞ): Assisted with literature screening and manuscript review. Nergiz Ercil Cagiltay (NEC): Formulated the research objectives, conducted literature searches and screening, and wrote and reviewed the manuscript.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This study does not involve ethical issues and therefore does not require approval from the ethics committee.

Consent for publication
This study is based on published research and does not contain data from any individual person, therefore the consent for publication is not applicable.

Competing interests
The authors declare no competing interests.

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