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The application of immersive technologies for education and training in advanced manufacturing: a systematic review

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Purpose: This study aims to systematically review empirical research on the application of immersive technologies, augmented reality (AR), virtual reality (VR), mixed reality (MR), extended reality (XR), and serious games for education and training in advanced manufacturing settings.

Methodology: A domain-based systematic review was conducted following the PRISMA guidelines. Five databases (ACM, IEEE, ScienceDirect, Scopus, and Web of Science) were searched for peer-reviewed studies published between 2015 and 2025. After screening 1,421 records, 38 empirical studies were included and analyzed to identify the types of technologies used, industrial contexts, operational domains, and reported outcomes.

Findings: The reviewed studies indicate that immersive technologies are predominantly applied in assembly, maintenance, safety, and logistics across diverse Advanced manufacturing sectors, with AR and VR receiving the most attention. Positive association reported around improvements in knowledge transfer, task performance, accuracy, efficiency, and hazard awareness. Serious games were comparatively underrepresented and mainly used for broader conceptual or managerial training. Key challenges included high implementation costs, hardware and software limitations, workforce readiness, privacy concerns, and physical discomfort during prolonged use.

Originality: This review provides a comprehensive synthesis of immersive technologies across advanced manufacturing contexts, addressing gaps in prior reviews by examining technologies collectively and highlighting underexplored areas, particularly serious games and co-designed training approaches.

KEYWORDS

advanced manufacturing, gamification, immersive technologies, serious games, systematic review, workforce training

Introduction

Extended reality (XR) is advancing at a rapid pace. XR serves as an umbrella term encompassing all immersive technologies, including augmented reality (AR), virtual reality (VR), and mixed reality (MR). Immersive technologies comprise a set of methods and tools designed to engage users in virtual environments by stimulating their senses through audiovisual effects and interactive content. In recent years, XR has been employed across a

wide range of contexts, from medical practice (e.g., [Andrews et al., 2019](#)) to construction training ([Li et al., 2024](#)), to assist with aspects such as knowledge transfer and skill development. Among these, the advanced manufacturing sector has been one of the adopters of XR. For instance, VR headsets have been used to instruct assembly-line workers on the required components and the sequence in which they should be assembled to produce the final product ([Devagiri et al., 2022](#); [Mula et al., 2024](#)).

In addition to XR, serious games have received traction in the advanced manufacturing sector. Serious games leverage digital platforms such as smartphones, computers, and other smart devices to deliver gamified training experiences. These games frame learning through structured gameplay, enabling users to acquire knowledge and skills in an engaging and motivating manner ([Andari et al., 2022](#)). For example, a game that simulates the role of a sustainability manager within an industrial context (e.g., overseeing operations, managing resources, and controlling costs) allows players to become familiar with the industry, understand potential challenges, and practice strategies for addressing them (e.g., [Perini et al., 2017](#)).

XR and serious games have been employed in advanced manufacturing contexts in recent years with the aim of supporting workforce training. Training of workers in industrial contexts is a central component in developing high-performing employees, teams, and organizations. Effective workplace training could make knowledge more accessible to workers, provide authentic hands-on experiences, enhance employees' self-efficacy (confidence), foster growth and innovation, strengthen perceptions of organizational support and job satisfaction, and reduce turnover, early retirement, and attrition (see [Mehner et al., 2025](#); [Percival et al., 2013](#); [Shiri et al., 2023](#)). Moreover, it has potential to improve employee performance, decrease workplace errors and operational costs, and enhance industrial profitability and sustainability (see [Jehanzeb and Beshir, 2013](#); [Mehner et al., 2025](#); [Percival et al., 2013](#); [Schmidt, 2007](#); [Shiri et al., 2023](#)). For example, [Abidi et al. \(2019\)](#) reported that participants trained using VR completed assembly tasks approximately 60%–72% faster and made approximately 73%–91% fewer errors compared with those receiving traditional training. Similarly, [Rakesh et al. \(2024\)](#) reported a 34% reduction in welding task completion time upon VR training. Moreover, [Obermair et al. \(2024\)](#) reported that participants trained using VR completed a wiring task approximately 10% faster than those receiving traditional training and achieved 0% error rate completing the task.

Delivering effective training, however, presents several challenges. Traditional workforce training sometimes requires substantial resources, including equipment and materials, a team of skilled trainers, dedicated physical spaces, and engaging instructional content. Despite these investments, such training programs may not always be efficient, and learners may not consistently perceive them as motivating or practical. Moreover, the process could be time-consuming and may differ in important ways from real working environments and the challenges encountered within them. These constraints highlight the need for supplementary approaches that could accelerate learning and improve training efficiency ([Abro et al., 2025](#); [Devagiri et al., 2022](#); [Hoedt et al., 2016](#); [Mula et al., 2024](#); [Yang et al., 2023](#)).

The use of XR and serious games in advanced manufacturing has been a response to the rapid evolution of industry and the growing need for high-quality, efficient training of individuals in the workplace ([Andari et al., 2022](#); [Devagiri et al., 2022](#); [Di Sabato and Savov, 2024](#); [Mula et al., 2024](#)). Industry requirements continue to evolve, driven by the constant demand for greater productivity and efficiency. Consequently, workforce upskilling and training have become essential for enhancing both individual performance and overall organizational effectiveness. By providing realistic simulations and gamified learning and practice environments, immersive technologies have the potential to shorten the transition from training to active workforce participation. These technologies may provide opportunities for employees to develop skills and confidence within low-risk environments and at an appropriate pace of learning ([Andari et al., 2022](#); [Devagiri et al., 2022](#); [Mula et al., 2024](#)). For example, XR technologies can enable entry-level workers in the welding industry to practice welding in a safe environment (e.g., without exposure to heat, magnetic forces, or ultraviolet radiation), prepare for real-world work in a shorter period, and develop both theoretical understanding and practical skills while building their confidence (e.g., [Shankhwar et al., 2022](#)).

While XR technologies and serious games are often studied as different streams of research in workforce training, they share an important educational characteristic that justifies their joint consideration in this review. Both approaches seek to create immersive learning experiences that encourage active engagement and participation. In other words, although their mechanisms differ, both aim to achieve immersion as a means of enhancing learning. Immersion in XR technologies is typically driven by spatial and sensory experiences ([Lee, 2025](#); [Zhang, 2020](#)), whereas serious games focus primarily on cognitive immersion ([Starks, 2014](#)). Therefore, the focus of this review is not on a single category of technology but rather on immersive technology-enabled approaches to training. Within the context of advanced manufacturing, these approaches are predominantly represented by XR technologies and serious games.

Following the application of XR and serious games in advanced manufacturing for training purposes, research in this area has grown considerably in recent years, and several empirical investigations have been conducted (e.g., [Abidi et al., 2019](#); [Laviola et al., 2022](#); [Maio et al., 2023](#); [Perini et al., 2017](#); [Pilati et al., 2020](#); [Rakesh et al., 2024](#); [Tangjitsitharoen and Lawankowit, 2024](#); [Tobiskova et al., 2024](#)). To synthesize and discuss these empirical findings, a limited number of conceptual, commentary, and review articles have been published (see [Table 1](#)). These studies suggest that immersive technologies have the potential to transform industrial training and serve as effective tools for fostering experiential learning, improving decision-making during work, and reducing errors, while also decreasing reliance on physical prototypes and enhancing efficiency and worker engagement (e.g., see [Boopathy et al., 2024](#); [Javaid et al., 2021](#)). For instance, a serious game on clothing production has the potential to help individuals understand and practice cutting, sewing, and coloring tasks ([Andari et al., 2022](#)). Similarly, virtual assembly training for an airplane turbine engine using VR can enable individuals to practice turbine assembly by following on-screen, step-by-step instructions in a safe (low-risk and low-cost) and user-friendly manner ([Ahmad et al., 2015](#)).

TABLE 1 The conceptual, preceptive, commentary, and review articles.

Author(s)	Objective(s)	Technology (ies)	Context	Findings
Andari et al. (2022)	Designing a model for a serious game to enhance understanding of reconfigurable manufacturing systems (RMS)	Serious game	RMS; clothing production	Suggested how serious games could foster systems thinking, cooperative problem-solving, and decision-making in a risk-free environment leading to improving comprehension of RMS concepts and support learning through experiential engagement
Ahmad et al. (2015)	Demonstrating the advantages of a VR model for verifying an assembly process	VR	Aerospace industry; airplane turbine engine assembling	Highlighted the potential benefits of VR models in aerospace industry, such as reduced time to market, early testing opportunities, and the ability to perform costly or otherwise impractical tests. Additional advantages included reduced reliance on physical prototypes, improved operator safety and comfort, elimination of geographic barriers, lower development costs, increased organizational agility, minimized engineering changes, and enhanced stakeholder participation
Hoedt et al. (2016)	Proposing an evaluation framework to compare virtual training systems in mixed-model assembly environments	VR	Assembly	The review highlighted VR's potential to enhance operator efficiency and task comprehension
Abro et al. (2025)	Evaluating the acceptance and effectiveness of VR and AR for industrial operator training	AR/VR	Work efficiency, troubleshooting capabilities	Highlighted VR and AR as transformative tools for operator training, offering safe, flexible, and cost-effective simulation-based learning compared with traditional methods. Challenges to overcome for acceptance included high implementation costs, technical demands for hardware and software, adoption barriers due to user unfamiliarity or discomfort, and difficulties in creating suitable training content
Yang et al. (2023)	Explored studies on VR-assisted manufacturing education	VR	Manufacturing education	Highlighted VR's ability in delivering high-quality graphics, immersion, and interactivity. Suggested that common usages include introductory knowledge and basic operations in fields such as automobile manufacturing, design, sustainability, and additive manufacturing. Suggested that VR enhances learning satisfaction and outcomes, although limitations remain regarding scalability, content development, and long-term impact assessment

(Continued)

TABLE 1 Continued

Author(s)	Objective(s)	Technology (ies)	Context	Findings
Lagorio et al. (2022)	Exploring the role of AR in logistics under the industry 4.0 paradigm, particularly around workforce-related implications, including skills, competence, and ethical and social concerns	AR	Industry 4.0/Logistics	AR was suggested to support and augment operators by improving efficiency and task execution. However, disadvantages such as technical limitations, user-related barriers, and human factors were also highlighted, underscoring both the potential and the challenges of AR adoption in logistics
Mula et al. (2024)	Evaluating research on XR and metaverse technologies, structured around three pillars: industrial training, safety, and social interaction	XR	Training, safety, and social interaction	Highlighted the potential of XR and metaverse technologies to enhance knowledge acquisition, occupational safety, worker wellbeing, and social engagement in industrial settings. Noted that current applications primarily focus on training, though there is growing interest in accident prevention and promoting a proactive safety culture. The review noted that integrating XR with digital twin (DT) and AI technologies offers new opportunities for production, logistics, and supply chain management. Challenges were also highlighted, particularly concerning privacy issues, perceived reductions in worker autonomy, and the need for tailored policies for adoption and implementation
Devagiri et al. (2022)	A systematic review of recent advances, tools, techniques, and platforms that integrate AI with AR in industry	AR	Industrial environments; training (e.g., assembly, servicing)	Suggested that advances in the technology will enable processors that are cheaper, faster, and more energy efficient, supporting the expansion of AR applications in the future. Coupled with AI, these developments have potential to enhance industrial productivity, workforce training, manufacturing efficiency, error detection, assembly, and packaging
Leder et al. (2022)	Providing a design guide for the digitalization of work instructions in the context of industry 4.0 and cyber-physical production systems	AR	Industry 4.0; cyber-physical production systems; industrial environments	AR-based work instructions formats enhance understanding and adaptability, although they demand greater preparation and hardware robustness. AR holds particular promise but faces limitations in harsh environments and under variable lighting or climatic conditions
Javaid et al. (2021)	Exploring the role of dentistry 4.0 in addressing challenges in oral healthcare during the COVID-19 pandemic. The paper identified how XR, and smart systems, can transform both learning and patient care	XR	Dentistry 4.0; pedagogy and innovative care; COVID-19	The article identified key benefits across education and clinical care in the areas of learning, decision making, administrative, and information management areas among others

(Continued)

TABLE 1 Continued

Author(s)	Objective(s)	Technology (ies)	Context	Findings
Boopathy et al. (2024)	An overview of the metaverse in relation to industry 5.0, focusing on its role in enabling immersive experiences and technological integration	XR	Industry 5.0; productivity and efficiency; workers, experts, and students	Highlighted diverse applications of metaverse, including agriculture (crop monitoring, disease prediction, precision harvesting), supply chain management (training, simulation, assembly), healthcare (personalized treatment, holographic modeling, clinical data monitoring), education (digital learning, virtual tours, virtual campuses), and transportation (electronic payments, real-time travel experiences). Key challenges such as ensuring data security, addressing ethical concerns, and aligning technological adoption with sustainable development goals were also noted

Despite these opportunities, previous research has also identified several challenges. Technological immaturity, platform-specific content creation challenges, hardware limitations, and user discomfort are among the reported issues (e.g., [Abro et al., 2025](#); [Boopathy et al., 2024](#); [Mula et al., 2024](#); [Yang et al., 2023](#)). For example, the technology may not always function properly and can occasionally produce errors. Content creation can also be challenging, as virtual materials (e.g., VR content) must be closely aligned with real-world environments. Moreover, the use of tools such as VR headsets may become uncomfortable for some individuals after prolonged use (e.g., [Abro et al., 2025](#); [Yang et al., 2023](#)). In addition, concerns related to privacy, autonomy, and ethical use when employing these platforms have been reported. For instance, some individuals may perceive their privacy as being compromised due to continuous monitoring and evaluation, and may also experience an increased sense of dependency on these systems (e.g., [Mula et al., 2024](#)).

Existing review studies have provided valuable insights; nonetheless, several aspects still warrant further attention (see [Table 1](#)). Most of these studies have primarily focused on XR ([Abro et al., 2025](#); [Ahmad et al., 2015](#); [Boopathy et al., 2024](#); [Devagiri et al., 2022](#); [Hoedt et al., 2016](#); [Javaid et al., 2021](#); [Lagorio et al., 2022](#); [Leder et al., 2022](#); [Mula et al., 2024](#); [Yang et al., 2023](#)). Limited attention has been given to games in these studies ([Andari et al., 2022](#)). Review investigations covering empirical studies that have employed games for training in advanced manufacturing contexts remain scarce. Furthermore, many of these works have concentrated on a single category of XR, such as VR ([Ahmad et al., 2015](#); [Hoedt et al., 2016](#); [Yang et al., 2023](#)), with relatively few studies examining XR technologies collectively. In addition, some articles have focused on specific occupational groups within industry (e.g., logistics workers; [Lagorio et al., 2022](#)). A review study encompassing all industrial groups could yield broader insights. Moreover, several studies have been limited to particular sectors, including clothing, aerospace, and

dentistry ([Ahmad et al., 2015](#); [Andari et al., 2022](#); [Javaid et al., 2021](#)). Adopting an inclusive framework that captures research across diverse industrial environments could be informative. Overall, review studies in this domain remain limited, and more comprehensive syntheses are needed to provide an inclusive and coherent synthesis of existing findings and conclusions.

Given the growing interest in the application of immersive technologies in advanced manufacturing settings (see [Andari et al., 2022](#); [Devagiri et al., 2022](#); [Mula et al., 2024](#)), and considering that inclusive review studies that examine XR collectively while incorporating investigations on serious games could provide a more comprehensive synthesis of the existing literature, this study aims to conduct a systematic review of the empirical research on the application of immersive technologies for workforce training in advanced manufacturing.

Although previous reviews have provided valuable insights into the applications and outcomes of specific immersive technologies (e.g., VR) and contexts ([Tusher et al., 2024](#); [Radhakrishnan et al., 2021](#)), an integrated understanding of immersive technology-enabled training and education within advanced manufacturing context remains limited. Therefore, the important questions remain around which immersive technologies are most commonly used, where they are applied, what outcomes they generate and what are the key success factors in implementation of such technologies with a focus on ‘immersive technology’ as the unit of analysis as opposed to a certain technology. Therefore, to address these gaps, this review is guided by the following research questions.

- RQ1: Which immersive technologies are being used more frequently for education and training in advanced manufacturing?
- RQ2: What are the main sectors and operational domains in which these technologies are applied?

- RQ3: What outcomes (educational, operational, or organizational) have been reported?
- RQ4: What are the key factors for successful implementation of immersive technologies for training and education in advanced manufacturing?

As such, this review intends to provide a comprehensive overview of current trends, outcomes, and conclusions, thereby informing both researchers and practitioners about the potential and limitations of immersive and gamified approaches to workforce training specifically situated within the advanced manufacturing context.

Methods

This review was conducted using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) approach (Moher et al., 2009). Among the three main types of systematic reviews, this study adopted a domain-based review to examine the use of immersive technologies in advanced manufacturing training and education. The review procedures, scope, databases, search terms, eligibility criteria and screening and data extraction process were agreed upon by the research team before screening commenced. However, the review was not prospectively registered in a public repository which is acknowledged as a methodological limitation.

The search was conducted in ACM, IEEE, Science Direct, Scopus, and Web of Science (WOS). To define the search term, the authors focused on three research components: advanced manufacturing, immersive technologies, and training and education. After reviewing prior review papers, sampling related papers, and collaborating iteratively within a multidisciplinary team, the final search term was determined as follows:

“advanced manufacturing”) AND (“gamification” OR “serious game” OR “Augmented reality” OR “virtual reality” OR “extended reality” OR “mixed reality”) AND (“training” OR “education”)

A total of 1,421 search results were imported into the Covidence platform for duplicate removal, further analysis, screening, and data extraction (see Figure 1). The screening process involved both abstract screening and full-text review stages. Three authors participated in the screening process. During the screening process one reviewer author independently assessed all records (both in abstract stage and full text stage), while a second reviewer (one of the remaining two reviewer authors) independently reviewed each record. A study was required to receive two “pass/include” decisions to proceed. In cases where screening decisions differed between reviewers, the study was discussed among the research team to make a decision. Studies that passed abstract screening then proceeded to undergo full-text assessment. Full-text inclusion decisions were resolved in a similar manner as explained above through discussion and consensus where required.

Furthermore, eligibility criteria were established following PICOS framework. Regarding the Population, studies were required to focus on advanced manufacturing context, industries, workers, trainees, students, and professionals undertaking manufacturing related training. Regarding the Intervention, studies were required to examine at least one

immersive technology (AR/VR/Serious games). Regarding the Comparators, both comparative and non-comparative studies were eligible. Regarding Outcomes, studies required to report educational, training, performance, learning, behavioral or implementation-related outcomes. Regarding Study design, only peer reviewed empirical studies were included (journal articles and conference papers). The studies also required to be published in English, and dated between 2015 and 2025. Reviews, and conceptual papers were not considered. To be included, studies were also required to address all three review pillars: (1) advanced manufacturing, (2) immersive technologies, and (3) training or educational applications.

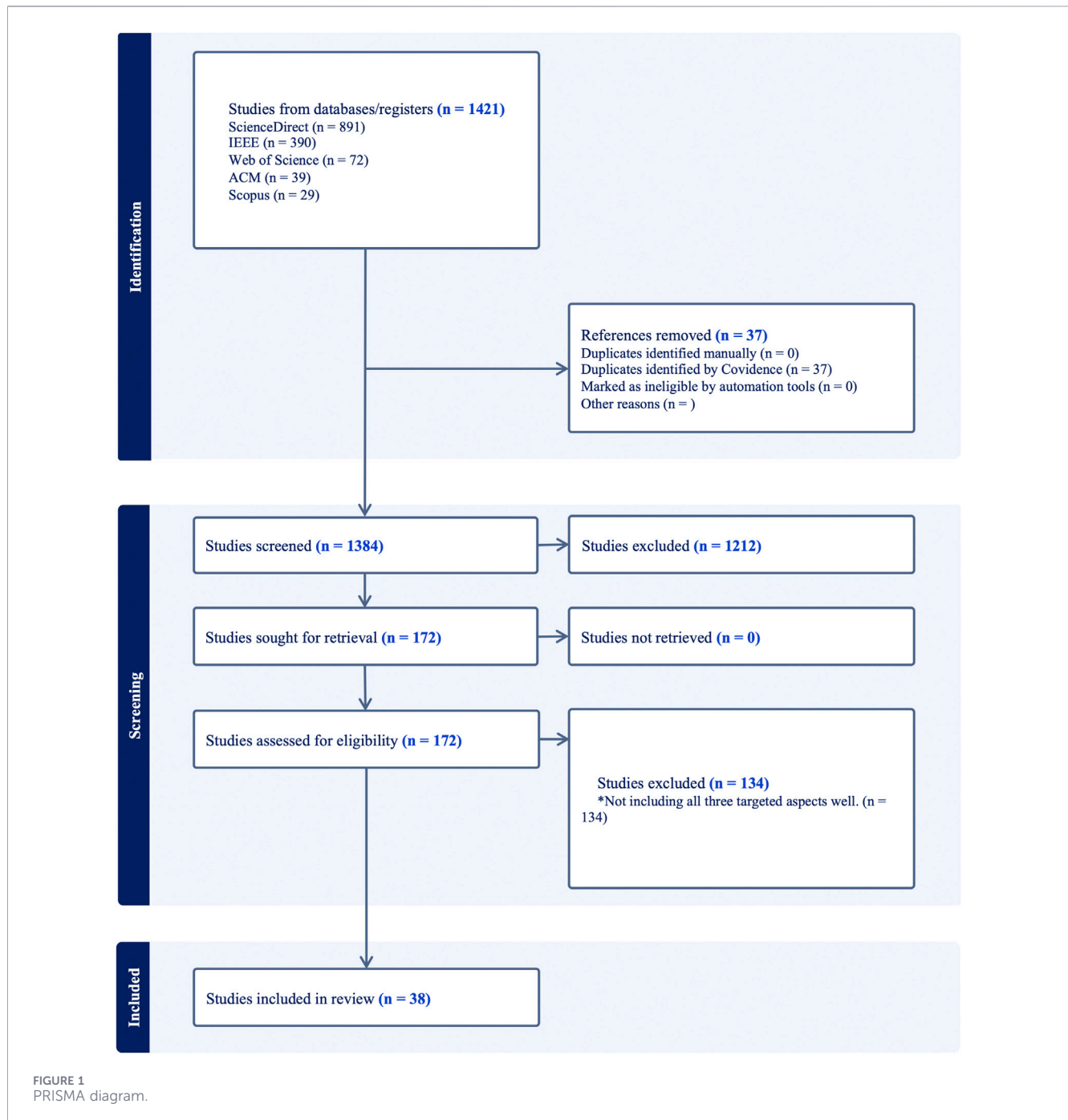
Data extraction was undertaken by one author and independently verified by a second author. Across the screening and extraction stages, all three authors were involved in quality assurance and the resolution of disagreements. Data were extracted using a structured extraction template within Covidence platform and included bibliographic information, publication year, region where the study conducted, main findings, objectives, context of the study, immersive tech-related findings, evidence of any academia-industry collaboration, outcomes measured, type of technology used, training and education context and outcomes, size of the company where technology implemented where applicable, and effectiveness outcomes.

Methodological quality assessment

In order to assess the methodological quality of the studies included in this review, the Mixed Methods Appraisal Tool (MMAT) version 2018 (Hong et al., 2018) was used. Among different appraisal tools MMAT was selected due to the studies included in this review having used different methods (quantitative, qualitative, mixed-method) and different study designs. Following MMAT guidelines, each study was first screened using the two general screening questions and once passed, it was subsequently appraised based on the questions associated with the specific study method. During this process one author conducted the initial assessment and then a second author independently reviewed the ratings. A few studies also did not pass the two general screening questions as their type could not be matched to a MMAT category, however they were retained upon consensus by authors as they provided information that was of value to the current review. A summary of the appraisal results can be found in Table 2.

Results

Table 3 summarizes the studies reviewed. The majority of reviewed studies focused on immersive technologies, particularly AR (e.g., Apostolopoulos et al., 2022; Bun et al., 2020; Fan et al., 2024; Gors et al., 2021; Laviola et al., 2022; Maio et al., 2023; Moghaddam et al., 2021; Neb and Strieg, 2018; Pilati et al., 2020; Rakesh et al., 2024; Tobiskova et al., 2024; Zhang et al., 2024) and VR (e.g., Abidi et al., 2019; Nasri et al., 2024; Obermair et al., 2024; Söderlund et al., 2024; Tangitsitharoen and Lawankowit, 2024). Relatively few studies have studied serious games (Jaiswal et al., 2024; Mustafee et al., 2015; Perini et al., 2017). In addition, among emerging and innovative training approaches, the use of machine



learning is reported to be an underexplored area (Patel and Manickam, 2024). While the majority of these technologies in the reviewed studies were expert-designed (i.e., developed primarily by researchers and without direct contributions from industry professionals and users; e.g., Abidi et al., 2019; Moghaddam et al., 2021; Rakesh et al., 2024; Tangjitsicharoen and Lawankowit, 2024; Tobiskova et al., 2024), a few studies involved co-designed technologies (i.e., developed through collaboration with industry professionals and users; e.g., Jaiswal et al., 2024; Maio et al., 2023; Verdu et al., 2024).

The included studies also covered a wide range of methodological orientations. Some studies used experimental

comparative designs mainly to assess effects on performance, task completion, accuracy, and other task centric factors. Others focused on implementation of the technology within jobs and the user/workers experience, and technical feasibility. Table 4 presents a summary of the variations in methodological orientations in included studies.

As shown in Table 4, the reviewed studies collectively suggest that immersive technologies in advanced manufacturing can be understood through three complementary perspectives. First, several studies focused on the *worker*, that is how workers interact with immersive technologies through factors such as usability, cognitive workload, user experience, acceptance, and

TABLE 2 Summary of MMAT.

Study	MMAT category	S1	S2	Q1	Q2	Q3	Q4	Q5
Abidi et al. (2019)	Quantitative randomized controlled trial	Yes	Yes	Yes	Yes	Yes	No	Yes
Al-Ahmari et al. (2018)	Quantitative randomized controlled trial	Yes	Yes	Yes	Cannot tell	Yes	No	Yes
Apostolopoulos et al. (2022)	Quantitative descriptive	Yes	Yes	No1	Yes	Cannot tell	No	Cannot tell
Arana-Landin et al. (2023)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Bale et al. (2024)	Not appraisable with MMAT due to the type of study	Yes	No	N/A	N/A	N/A	N/A	N/A
Bertagna et al. (2025)	Quantitative descriptive	Yes	Yes	Cannot tell	Yes	Cannot tell	Cannot tell	Cannot tell
Bun et al. (2020)	Quantitative descriptive	Yes	Yes	No	Cannot tell	No	Yes	Yes
Cirillo et al. (2024)	Quantitative non-randomized	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Delgado et al. (2020)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Di Pierro et al. (2020)	Mixed methods	Yes	Yes	Cannot tell	Yes	Yes	Yes	Yes
Fan et al. (2024)	Quantitative descriptive	Yes	Yes	No	Cannot tell	Yes	Cannot tell	Yes
Gors et al. (2021)	Quantitative descriptive	Yes	Yes	No	Cannot tell	Yes	Cannot tell	Yes
Gualtieri et al. (2018)	Not appraisable with MMAT due to the type of study	Yes	No	N/A	N/A	N/A	N/A	N/A
Gualtieri et al. (2023)	Qualitative	Yes	Yes	Cannot tell	Yes	Yes	Cannot tell	Yes
Gupta et al. (2019)	Quantitative non-randomized	Yes	Yes	Cannot tell	Yes	Yes	No	Yes
Jaiswal et al. (2024)	Quantitative descriptive	Yes	Yes	No	Cannot tell	Cannot tell	Cannot tell	Cannot tell
Jalilvand et al. (2024)	Quantitative non-randomised	Yes	Yes	No	Yes	Yes	Yes	Yes
Kuhn and Lucke (2021)	Mixed methods	Yes	Yes	Cannot tell	Yes	Yes	Yes	Cannot tell
Laviola et al. (2022)	Quantitative non-randomised	Yes	Yes	No	Yes	Yes	Yes	Yes
Maio et al. (2023)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Moghaddam et al. (2021)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mustafee et al. (2015)	Not appraisable with MMAT due to the type of study	Yes	No	N/A	N/A	N/A	N/A	N/A
Nasri et al. (2024)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Neb and Strieg (2018)	Qualitative	Yes	Yes	Yes	Yes	Yes	Cannot tell	Cannot tell
Obermair et al. (2024)	Quantitative non-randomised	Yes	Yes	Yes	Yes	Yes	Cannot tell	Yes
Patel and Manickam (2024)	Quantitative descriptive	Yes	Yes	YES	NA	Yes	Yes	Yes

(Continued)

TABLE 2 Continued

Study	MMAT category	S1	S2	Q1	Q2	Q3	Q4	Q5
Pathak et al. (2024)	Mixed methods	Yes	Yes	Yes	YES	Yes	Yes	YES
Perini et al. (2017)	Mixed methods	Yes	Yes	Yes	Yes	Cannot tell	Yes	Cannot tell
Pilati et al. (2020)	Quantitative non-randomised	Yes	Yes	Cannot tell	Yes	Yes	No	Yes
Rakesh et al. (2024)	Quantitative non-randomised	Yes	Yes	Cannot tell	Cannot tell	Cannot tell	No	Cannot tell
Saggiomo et al. (2016)	Quantitative descriptive	Yes	Yes	YES	YES	Yes	Cannot tell	Yes
Shankhwar et al. (2022)	Quantitative randomised controlled trial	Yes	Yes	Yes	Yes	Yes	Cannot tell	Yes
Söderlund et al. (2024)	Qualitative	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tangjitsitharoen and Lawankowit (2024)	Not appraisable with MMAT due to the type of study	Yes	Yes	N/A	N/A	N/A	N/A	N/A
Tender et al. (2024)	Qualitative	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tobiskova et al. (2024)	Mixed methods	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Verdu et al., 2024	Not appraisable with MMAT due to the type of study	Yes	Yes	N/A	N/A	N/A	N/A	N/A
Zhang et al. (2024)	Quantitative descriptive	Yes	Yes	No	Cannot tell	Yes	Cannot tell	Cannot tell

learning preferences. Second, a substantial body of research focused on *the work* itself, investigating how immersive technologies influence task execution, training effectiveness, performance, accuracy, efficiency, knowledge acquisition, and error reduction. Third, some studies focused on the broader *context in which training occurs*, exploring issues related to organizational readiness, technology adoption, implementation feasibility, *etc.* Together, these perspectives demonstrate that the effectiveness of immersive technologies depends not only on technical functionality, but also on human factors and the organizational environments within which these technologies are deployed.

Immersive technologies were implemented across various industries, including the foundry and heat treatment (Tangjitsitharoen and Lawankowit, 2024), thermoforming manufacturing (Jalilvand et al., 2024), welding (Rakesh et al., 2024; Shankhwar et al., 2022), cold spray (Nasri et al., 2024), additive manufacturing (Fan et al., 2024; Zhang et al., 2024), construction (Delgado et al., 2020; Tender et al., 2024), textile (Saggiomo et al., 2016), medical and surgery (Gupta et al., 2019), electric motor manufacturing (Patel and Manickam, 2024; Obermair et al., 2024), automotive (Apostolopoulos et al., 2022; Söderlund et al., 2024), agricultural machinery (Verdu et al., 2024), marine (e.g., ship repair and maintenance; Bertagna et al., 2025; Moghaddam et al., 2021), wind energy (Mustafee et al., 2015), and mining (Jaiswal et al., 2024). A substantial portion of studies applied these platforms within general industrial context. Among the specific industry domains,

additive manufacturing and automotive sectors were the most frequently represented. These technologies were applied to diverse operational domains, including assembly (e.g., Laviola et al., 2022; Maio et al., 2023; Obermair et al., 2024), safety (e.g., Tender et al., 2024), logistics (e.g., Maio et al., 2023), tool use (e.g., Rakesh et al., 2024; Saggiomo et al., 2016), maintenance (e.g., Mustafee et al., 2015; Patel and Manickam, 2024; Tobiskova et al., 2024). Several studies also reported applications across multiple operational domains (e.g., Apostolopoulos et al., 2022). Among the operational domains, assembly was the most frequently targeted application area (see Table 5).

The reviewed studies reported potentially beneficial outcomes relating to knowledge acquisition, task performance, and task-completion time (Abidi et al., 2019; Al-Ahmari et al., 2018; Apostolopoulos et al., 2022; Arana-Landín et al., 2023; Bale et al., 2024; Bertagna et al., 2025; Cirillo et al., 2024; Delgado et al., 2020; Fan et al., 2024; Gors et al., 2021; Gualtieri et al., 2018; Gualtieri et al., 2023; Gupta et al., 2019; Jaiswal et al., 2024; Kuhn and Lucke, 2021; Laviola et al., 2022; Maio et al., 2023; Mustafee et al., 2015; Nasri et al., 2024; Neb and Strieg, 2018; Obermair et al., 2024; Pathak et al., 2024; Pilati et al., 2020; Rakesh et al., 2024; Shankhwar et al., 2022; Söderlund et al., 2024; Tender et al., 2024; Tobiskova et al., 2024; Verdu et al., 2024; Zhang et al., 2024). The reviewed studies also reported associations between the use of immersive technologies and greater accuracy (Bale et al.,

TABLE 3 The empirical studies.

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Laviola et al. (2022)	Validating a 'minimal AR' authoring approach to convey manufacturing work instructions	AR	Expert-designed	General/Not specified	Assembly	The results showed that providing more information than the minimal necessary does not improve task performance	+
Maio et al. (2023)	Evaluate a pervasive markerless AR tool, to support and train of logistics operators	AR	Co-designed	Industrial shop floor	Assembly and logistics	Head-mounted display-based AR solution was significantly faster, less mentally and physically demanding, and more satisfying than paper manuals and handheld AR.	+
Bun et al. (2020)	Assessed the readiness of polish industrial companies to adopt AR solutions in practice	AR	Expert-designed	General/Not specified	Industry	Most surveyed companies were not prepared to implement AR. Contributing factors included low digitization and robotization levels, limited use of mobile devices, absence of AR/VR equipment, and insufficient funding	Mixed
Tobiskova et al. (2024)	Assessed an AR prototype developed to support user guidance in industrial procedures, focusing on tool change tasks	AR	Expert-designed	General/Not specified	Industrial production	The AR prototype aided tool changes, was associated with moderate cognitive workload and favorable usability ratings. It also showed potential for troubleshooting and was favored for integration with apprenticeship training	+
Abidi et al. (2019)	Evaluated the effectiveness of a virtual manufacturing assembly simulation system for training	VR	Expert-designed	General/Not specified	Assembly	Participants trained with VR committed fewer errors and completed assembly tasks faster than those trained with traditional methods	+
Tangjitsitharoen and Lawankowit (2024)	Evaluating a VR application for training in foundry and heat treatment operations	VR	Expert-designed	Manufacturing	Foundry and heat treatment	The VR system delivered 90% simulation accuracy and was designed to provide immersive, standardized and accessible procedural training. It also supports future upgrades like accuracy tracking and performance scoring	+

(Continued)

TABLE 3 Continued

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Shankhwar et al. (2022)	Evaluating a visuo-haptic XR training system to provide safe and effective welding training	XR	Expert-designed	Metal manufacturing	Arc welding	The visuo-haptic XR system led to better welding performance than traditional video training, producing smoother, higher-quality welds and reducing errors and dependence on guidance	+
Rakesh et al. (2024)	Evaluating an immersive AR application to support training in robotic welding	AR	Expert-designed	Welding	Robotic welding	Users of the AR system learned robotic welding 34% faster than those with traditional training, and 85% reported better retention and understanding of concepts	+
Patel and Manickam (2024)	Evaluating a metaverse-based maintenance training system to enhance learning effectiveness, engagement, and personalization	VR	Expert-designed	Electric motor industry	Electric motor maintenance	The platform demonstrated technical feasibility for VR-based maintenance learning by boosting user understanding, shortening training time, and providing adaptive, data-driven feedback <i>versus</i> traditional methods	+
Jaiswal et al. (2024)	Developing a VR-based serious game to train mining workers in safety procedures and hazard recognition	VR-based game	Co-designed	Coal mining industry	Operations and hazard awareness	The VR-based training game received positive preliminary feedback regarding user engagement, understanding of safety practices, and perceived training effectiveness	Mixed
Fan et al. (2024)	Introducing a training system for a metal printer using AR.	AR	Expert-designed	Metal additive industry	Metal additive manufacturing	The results demonstrated strong technical recognition performance for accuracy, human-machine interaction, and operational understanding and received generally positive user feedback	+
Perini et al. (2017)	Identifying learning requirements for advanced manufacturing skills and to design a digital game-based learning solution to support education and training for sustainable manufacturing	Serious game	Expert-designed	Sustainable manufacturing	Sustainability management	The game effectively addressed key learning requirements for manufacturing education and was suitable for both university and industrial training	+

(Continued)

TABLE 3 Continued

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Moghaddam et al. (2021)	Examining the role of AR as a workplace-based learning and training technology to support manual and semi-automated manufacturing tasks	AR	Expert-designed	Marine industry	Electro-mechanical assembly of a fuel cell module for marine engines	While AR and traditional training yielded similar completion times, learning gains, and independence, AR training notably decreased errors even after support was withdrawn	Mixed
Jalilvand et al. (2024)	Comparing MR and VR environments for training operators in monitoring and controlling thermoforming processes	MR; VR	Expert-designed	Thermoforming manufacturing	Manufacturing	MR was preferred over VR and video-based training. MR provided a stronger sense of presence, higher user satisfaction, reliability, and user-friendliness	+
Al-Ahmari et al. (2018)	Evaluating the effectiveness of 3D-printed models as a manual assembly training method compared with conventional drawings and VR.	VR	Expert-designed	Industry	Assembly	3D-printed model-based training led to significantly faster assembly, fewer errors and frustration points, and lower workload than conventional and VR methods	-
Apostolopoulos et al. (2022)	Leveraging AR to introduce users to hybrid systems, IoT, and new assembly processes	AR	Expert-designed	Automotive industry	Manufacturing	The AR-based framework received favorable usability feedback, with users finding the training modes intuitive, user-friendly, and helpful for learning in complex hybrid manufacturing settings	+
Söderlund et al. (2024)	Evaluating the feasibility of multi-user VR training as an alternative or complement to traditional, supervisor-led operator training in the automotive industry	VR	Co-designed	Automotive industry	Assembly	Multi-user VR may not entirely replace supervised training, but it has real promise to improve or supplement current methods	Mixed
Verdu et al. (2024)	Presenting a MR environment for assembly training, supported by virtual sensors	MR	Co-designed	Agriculture machine industry	Manual assembly (i.e., process understanding, functionality, and disturbances)	The system allowed operator training without interrupting production, using only virtual assets. This approach was designed to support flexible training without interrupting production for diverse products with short life cycles and frequent variations	+
Bertagna et al. (2025)	Explored how VR/AR, integrated with industry 4.0 technologies can enhance ship maintenance and crew training	VR; AR	Expert-designed	Shipbuilding industry	Shipbuilding and maintenance	Reduced human error and execution time while simplifying operational tasks was observed	+

(Continued)

TABLE 3 Continued

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Pilati et al. (2020)	Examining how industry 4.0 technologies can support operator training in manual assembly	AR	Expert-designed	Industry	Manual assembly (i.e., learning rate and process efficiency)	The results showed a 22% improvement in learning rate and up to a 51% reduction in process duration during the initial assembly cycles	+
Zhang et al. (2024)	Examining the use of AR for professional training for laser powder bed fusion in metal additive manufacturing	AR	Expert-designed	Metal additive industry	Laser powder bed fusion	The AR system achieved high recognition accuracy and responsiveness, enabling participants to efficiently learn procedural steps and improving the overall training process	+
Delgado et al. (2020)	Examined the application of AR and VR in the architecture, engineering, and construction sectors	AR; VR	Co-designed	Architecture and construction	Design support, construction support, operations and management support, and training	AR/VR participants and reviewed cases identified potential benefits relating to engagement, communication, efficiency, safety, and learning outcomes	+
Tender et al. (2024)	Information modelling and VR for occupational safety and health training	VR	Co-designed	Construction industry (tunnelling sector)	Occupational safety and health	Improved safety-by-design, better hazard perception, a projected 20% cut in training time, and a 10% drop in accidents. Challenges included cost efficiency, portability, and accessibility	Mixed
Obermair et al. (2024)	Evaluating the effectiveness of VR training compared to conventional approaches for assembly	VR	Expert-designed	Electric motor industry	Assembly (i.e., efficiency and precision)	VR enhanced task completion by 10% and improved accuracy, efficiency and precision in assembly training	+
Gualtieri et al. (2023)	Proposing a human-centered AR-based model to enhance training and reduce occupational risks	AR	Expert-designed	General/Not specified	Safety training and real-time risk management	Participants identified potential applications for hazard perception and safety training, but current hardware and software are not yet ready for widespread industrial use	Mixed
Kuhn and Lucke (2021)	Introducing a low-threshold training concept designed to integrate IoT technologies into higher education and employee training	Various immersive tech	Expert-designed	General/Not specified	Production management/higher education	The model supported microlearning, enabling quick implementation, flexible adaptation, and scalability. It reduced preparation and improved engagement while linking training to real-world manufacturing applications	+

(Continued)

TABLE 3 Continued

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Gors et al. (2021)	Generating AR assembly instructions	AR	Expert-designed	General/Not specified	Assembly	The framework was successfully validated in an industrial case, enabling clear AR guidance, automatic state tracking, and low-error task completion by inexperienced operators	+
Arana-Landín et al. (2023)	Investigating how industry 4.0 technologies influence occupational health and safety	Various	Expert-designed	General/Not specified	Occupational health and safety and risk management	Most technologies lower physical and ergonomic risks but add new psychosocial ones	Mixed
Cirillo et al. (2024)	Examined the impact of digital technology adoption on labor flows and training	Various	Expert-designed	General/Not specified	Manufacturing	Technologies improved employability, particularly for young workers, increased training participation rate and reduced training costs	+
Neb and Strieg (2018)	Using AR for assembly planning	AR	Expert-designed	General/Not specified	Assembly (i.e., feasibility and efficiency)	The AR-based approach allowed intuitive creation and execution of assembly instructions and was effective for training and planning, though limited by current HoloLens hardware constraints	Mixed
Nasri et al. (2024)	VR training apprenticeship designed to teach entry-level workers the step-by-step process of cold spray advanced manufacturing	VR	Expert-designed	Cold spray industry	Cold spray task (i.e., errors, performance, cognitive load, user experiences)	VR training was perceived helpful, accessible, informative and reduced task errors. It improved learning outcomes and supported workers training	+
Pathak et al. (2024)	Investigating the transformative potential of integrating the internet of things (IoT) and AI to develop intelligent educational ecosystems for industry 5.0 workforce	AR	Expert-designed	General/Not specified	Manufacturing	Improved organizational flexibility, employee engagement, higher knowledge retention, faster skill development, and reduced training costs	+
Bale et al. (2024)	Assessed how organizations use AR and VR to digitize knowledge and improve training in different industries	AR; VR	Expert-designed	General/Not specified	Knowledge (i.e., safety, repair, treatment) and soft skills	Demonstrated AR/VR's positive impact on knowledge management and workforce development	+
Di Piero et al. (2020)	Exploring how industry 4.0 technologies are reshaping work tasks and driving demand for new professional skills	Various	Expert-designed	General/Not specified	Manufacturing	Noted efficiency gains but stressed the need to clearly define skills required for rapid tech adoption in manufacturing	Mixed

(Continued)

TABLE 3 Continued

Author(s)	Objective(s)	Technology (ies)	Design	Industry	Domain	Nature of impact	Impact
Saggiomo et al. (2016)	Developing AR-based assistance systems for weaving machines to support skill development	AR	Expert-designed	Textile industry	Using weaving machines and handling weaving machine issues	The AR-based mobile application could assist operators in addressing issues such as weft yarn breakages by detecting fault locations and providing tailored, case-specific guidance	+
Gualtieri et al. (2018)	Discussed the role of training and education in supporting SMEs during the industry 4.0 transition	Various	Expert-designed	Advance automation industry	Manufacturing	Highlighted to role of the “knowledge triangle” (research, teaching, industry), fostering cooperation and providing tailored training for SMEs in advanced automation and industry 4.0	+
Gupta et al. (2019)	Evaluating a framework integrating haptic and immersive VR platforms to create an interactive and repeatable training environment	VR	Expert-designed	Orthopedic surgery	Orthopedic surgery education	The results showed significant improvement in participants’ understanding of the surgical process after using the simulator	+
Mustafee et al. (2015)	Exploring the use of digital education games for teaching maintenance, repair, and operations concepts in offshore wind energy	Digital serious game	Expert-designed	Energy industry	Knowledge on maintenance, repair, and operations	The game was found effective in improving players’ understanding of maintenance, repair, and operations concepts relevant to offshore wind farms	+

2024; Fan et al., 2024; Tangiitsitcharoen and Lawankowit, 2024; Zhang et al., 2024), lower mental workload (Al-Ahmari et al., 2018; Arana-Landín et al., 2023; Bale et al., 2024; Kuhn and Lucke, 2021; Laviola et al., 2022; Nasri et al., 2024; Tobiskova et al., 2024), and fewer errors (Al-Ahmari et al., 2018; Abidi et al., 2019; Bale et al., 2024; Bertagna et al., 2025; Gors et al., 2021; Gualtieri et al., 2023; Laviola et al., 2022; Moghaddam et al., 2021; Nasri et al., 2024; Obermair et al., 2024; Tender et al., 2024). Additionally, immersive technologies were reported to support troubleshooting and fault detection (Patel and Manickam, 2024; Saggiomo et al., 2016; Tobiskova et al., 2024), contribute to greater awareness of potential hazards (Arana-Landín et al., 2023; Bale et al., 2024; Delgado et al., 2020; Jaiswal et al., 2024; Tender et al., 2024), reduce reliance on external guidance or hints (Bale et al., 2024; Gors et al., 2021; Jalilvand et al., 2024; Shankhwar et al., 2022; Verdu et al., 2024), and support management and decision making capabilities (Arana-Landín et al., 2023; Bale et al., 2024; Delgado et al., 2020; Mustafee et al., 2015; Perini et al., 2017). It should also be noted that since the reviewed studies used different methodological designs, the aforementioned findings represent outcomes and associations rather than demonstrated causal effects.

In addition to the benefits of immersive technologies, several studies also discussed challenges. The reviewed literature highlighted issues such as the workforce’s lack of preparedness for adopting these technologies (Bun et al., 2020), the need to acquire new skills to use them effectively (Di Pierro et al., 2020), limited availability of technological devices and difficulties in ensuring large-scale access (Bun et al., 2020; Tender et al., 2024), high implementation costs and insufficient funding (Bun et al., 2020; Tender et al., 2024), and the immaturity of software and hardware (e.g., limited battery capacity; Gualtieri et al., 2023; Neb and Strieg, 2018). Other reported concerns included privacy issues (e.g., continuous surveillance; Arana-Landín et al., 2023), potential dependency on these technologies and reduced job security (Arana-Landín et al., 2023), as well as physical discomfort associated with prolonged use (Arana-Landín et al., 2023; Neb and Strieg, 2018). Overall, while the reviewed studies predominantly reported positive outcomes or perceived benefits, some presented mixed conclusions (e.g., Arana-Landín et al., 2023; Bun et al., 2020; Jaiswal et al., 2024; Söderlund et al., 2024; Tender et al., 2024), as the associated challenges may hinder the realization of these technologies’

potential benefits in industrial contexts. Moreover, this review did not suggest a general conclusion that immersive technologies or serious games are either consistently effective or ineffective across training contexts. Instead, several studies indicated that implementation-related challenges may constrain their potential or perceived benefits.

Methodological quality of the included studies

As indicated in the Methods section, methodological quality assessment of the included studies was done using MMAT (see Table 2). Most studies clearly included research objectives and collected appropriate data to address the research objectives. Several studies also demonstrated strong methodological characteristics. However, some common limitations included small sample sizes, convenience sampling strategies, insufficient reporting of the sampling and recruitment procedures, and limited discussion of non-response bias and lack of assessor blinding in experimental studies. A few studies also were classified as “not appraisable using MMAT” as the type of study could not be matched to a MMAT category. Therefore, although the evidence from the included studies provides valuable insight into addressing the research questions, due to methodological variability across the included studies, the findings should be interpreted taking into account the aforementioned variability.

Discussion

This study aimed to systematically review the scientific literature on the application of immersive technologies for educational and training purposes in advanced manufacturing settings. The reviewed studies suggest that these platforms, particularly immersive technologies (e.g., Abidi et al., 2019; Apostolopoulos et al., 2022; Bun et al., 2020), have gained attention in advanced manufacturing contexts across various sectors, such as the automotive and marine industries (e.g., Apostolopoulos et al., 2022; Moghaddam et al., 2021). The reviewed studies predominantly reported positive findings or perceived benefits for workers and industry (e.g., Apostolopoulos et al., 2022; Bale et al., 2024; Cirillo et al., 2024; Delgado et al., 2020; Fan et al., 2024; Gors et al., 2021). Some comparative studies, for example, reported better assembly-task performance among participants trained using immersive technologies (e.g., Abidi et al., 2019). However, the strength of this evidence varied according to study design and methodological quality. For instance, there may be a risk of reduced worker autonomy and job insecurity among the workforce due to overreliance on these platforms (e.g., Arana-Landín et al., 2023). Our findings are consistent with some conceptual, commentary, and review articles that have similarly underscored both the potential opportunities and the challenges associated with integrating immersive technologies in advanced manufacturing settings (e.g., Abro et al., 2025; Lagorio et al., 2022; Yang et al., 2023). However, these predominantly positive findings should be interpreted cautiously in light of the methodological limitations and variability identified through the MMAT assessment.

According to the reviewed studies, AR and VR were the technologies that were most frequently used in advanced manufacturing environments (e.g., Bun et al., 2020; Fan et al., 2024; Gors et al., 2021; Moghaddam et al., 2021; Nasri et al., 2024; Neb and Strieg, 2018; Pilati et al., 2020; Tangjitsitcharoen and Lawankowit, 2024; Tobiskova et al., 2024). In contrast, serious games and other immersive technologies were less frequently employed and studied (e.g., Jaiswal et al., 2024; Patel and Manickam, 2024). However, these approaches should not necessarily be viewed as competing alternatives. Instead, game mechanics and XR environments may be combined within hybrid systems, such as gamified VR training systems, to integrate spatial, cognitive, and motivational forms of immersion. This may be important, as different technologies could create distinct user experiences with different outcomes (Verhulst et al., 2021) and hybrid approaches may provide complementary benefits, although further empirical comparative research is needed to determine whether they produce synergistic effects and to what extent. The performance and effectiveness of various technologies (e.g., XR) could differ across contexts, applications, and target populations. For example, some individuals may experience challenges, such as heightened cybersickness, when trained in non-gamified environments compared to gamified environments (e.g., Zorzi et al., 2023). Therefore, broadening the research and application focus could support a more comprehensive understanding of technologies for workforce education and training in advanced manufacturing contexts and provide wider implementation options (e.g., integrating multiple platforms). This could also help identify the most suitable solutions for specific contexts, populations, and purposes.

In addition, it is also worth emphasizing that the findings of this review should not be interpreted as suggesting that immersive technologies are equally suitable across different training contexts. Considerable variations were observed in the reviewed studies' technological characteristics, user requirements, and objectives. As suggested by previous research, the suitability of immersive technologies heavily depends on factors such as task complexity, industry context, logistical constraints, and objectives (Alam and Ryu, 2025). Therefore, the emphasis of this review is to provide a broad synthesis of immersive technology approaches to training in advanced manufacturing and highlighting areas where more investigation is required rather than identifying a universally superior technology.

The findings of this review also suggest that the effectiveness of immersive technologies in training in advanced manufacturing settings is highly dependent on alignment between the worker, the work, and the context in which training occurs. Studies focusing on workers highlighted the importance of factors such as usability, cognitive load, use experience and acceptance. Studies focusing on work highlighted that using immersive technologies is most beneficial and valuable when training involves complex tasks and procedures, requires spatial understanding and involve safety concerns. And lastly, studies focusing on the context within which training occurs highlighted the importance of issues such as organizational readiness and adoption, stakeholder involvement, implementation support and resources. Therefore, it can be inferred that rather than being considered as universally effective solutions,

TABLE 4 Classification of included studies' methodological orientations.

Evidence category	Included studies	Main purpose	Common evidence generated
Experimental and comparative effectiveness studies	Abidi et al. (2019); Al-Ahmari et al. (2018); Gupta et al. (2019); Jalilvand et al. (2024); Laviola et al. (2022); Obermair et al. (2024); Pilati et al. (2020); Rakesh et al. (2024); Shankhwar et al. (2022)	Compare immersive training with other forms of training, or to assess changes in learner performance following an intervention	Task-completion time, errors, accuracy, learning rate, knowledge acquisition, workload and performance in simulated or real tasks
Observational, organizational and field-based studies	Arana-Landín et al. (2023); Cirillo et al. (2024); Delgado et al. (2020); Di Pierro et al. (2020); Saggiomo et al. (2016); Tender et al. (2024)	Examine workplace needs, technology adoption, organizational effects, implementation conditions in real or industry-related settings	Organizational outcomes, workforce requirements, barriers, adoption factors, safety implications
Usability and user experience	Apostolopoulos et al. (2022); Gualtieri et al. (2023); Jaiswal et al. (2024); Kuhn and Lucke (2021); Nasri et al. (2024); Neb and Strieg (2018); Söderlund et al. (2024); Tobiskova et al. (2024); Zhang et al. (2024)	Assess if immersive technologies are usable, acceptable, engaging and appropriate for users and training contexts	Usability, cognitive workload, presence, satisfaction, acceptability, perceived usefulness, participant feedback and design recommendations
Integrated design and efficacy	Maio et al. (2023); Moghaddam et al. (2021); Perini et al. (2017)	Combine system development or co-design with user evaluation, comparative testing or iterative refinement	Performance outcomes, usability findings, stakeholder feedback, design requirements and evidence from multiple methodological components
Prototype and technical validation	Bertagna et al. (2025); Bun et al. (2020); Fan et al. (2024); Gors et al. (2021); Patel and Manickam (2024); Pathak et al. (2024); Tangjitsitcharoen and Lawankowit (2024); Verdu et al., (2024)	Develop, demonstrate or technically validate an immersive training system, or technology	Technical accuracy, system functionality, proof-of-concept outcomes, expert validation and preliminary implementation findings
Developmental studies	Bale et al. (2024); Gualtieri et al. (2018); Mustafee et al. (2015)	Developmental and implementation process and analyzing cases	Implementation examples and proposed application factors

immersive technologies' value depends on the worker, work, context alignment and dynamic.

In the majority of the reviewed studies, immersive technologies were expert-designed as opposed to co-designed with users and stakeholders (e.g., Abidi et al., 2019; Moghaddam et al., 2021; Rakesh et al., 2024; Tangjitsitcharoen and Lawankowit, 2024), whereas only a limited number involved co-design approaches (e.g., Maio et al., 2023; Verdu et al., 2024). Co-design processes may enhance the authenticity and contextual relevance of immersive technologies by incorporating the perspectives and experiences of potential end users and key stakeholders within industry settings (e.g., see Cedstrand et al., 2021; Pors et al., 2022). For instance, important practical considerations may be overlooked during the development phase without sufficient engagement with stakeholders, particularly end-users. Several studies suggest that adopting co-design approaches can make the developed immersive experiences more applicable and contextually appropriate (e.g., see Cedstrand et al., 2021; Pors et al., 2022).

It was also shown that, immersive technologies have been applied across a wide variety of industries, such as welding, construction, and marine (e.g., Delgado et al., 2020; Moghaddam et al., 2021; Rakesh et al., 2024). Additive manufacturing (7.5%; e.g., Fan et al., 2024) and automotive (7.5%; Söderlund et al., 2024) were the most frequently studied/applied contexts, whereas industries

such as textile (2.5%; Saggiomo et al., 2016) and agriculture (2.5%; Verdu et al., 2024) were less frequently seen. These findings suggest that, while these technologies have been studied and applied across several industries, research has been concentrated on certain sectors, and evidence remains scant in other sub-sectors of advanced manufacturing such as food and beverages. This might be partly due to the fact that since in most cases assembly procedures are selected for such technology integration, industrial settings that have less assembly activities have lower presence. It is important to note that generalizability of the results require a wider application of immersive technologies in different type of advanced manufacturing settings as different contexts may involve distinct environments, tasks, responsibilities, challenges, hazards, and goals. For example, mining work could involve harsh conditions, high risk, and a fast-paced routine (e.g., requiring intense focus for short periods) compared with many other industries. Consistent with this, research suggests that individuals in different occupations may experience varying long-term outcomes (e.g., greater health decline among blue-collar workers with age; Kajitani, 2015) and report certain challenges more frequently (e.g., feeling sleepy more often among blue-collar workers; Schreuder et al., 2008). Therefore, considering a broader range of industries when conducting research and applying immersive technologies appears both necessary and relevant. Such an approach could facilitate more industry-specific

TABLE 5 Industry and operational domains of the studies.

Industry	Operational domain												General context															
	Foundry and heat treatment		Thermoforming manufacturing		Welding		Cold spray		Additive manufacturing		Construction			Textile		Medical and surgery		Electric motor manufacturing		Automotive		Agricultural machinery		Marine		Wind energy		Mining
% Studies	2.5%	2.5%	2.5%	2.5%	5%	2.5%	2.5%	2.5%	7.5%	5%	5%	2.5%	2.5%	2.5%	2.5%	2.5%	2.5%	5%	5%	7.5%	2.5%	2.5%	5%	2.5%	2.5%	2.5%	2.5%	45%
Operational domain	Assembly						Safety						Logistics				Tool use				Maintenance				Multiple			
% Studies	30%						10%						2.5%				22.5%				10%				25%			

conclusions regarding the applications and functioning of these platforms.

Based on the reviewed studies, immersive technologies were applied across different operational domains. The assembly domain (30%; e.g., [Abidi et al., 2019](#)) was the most frequently studied/employed. An example of such domain of use is where in a VR environment, a product to be assembled is displayed, with each component shown, described, and accompanied by instructions for the correct assembly order (e.g., [Abidi et al., 2019](#)). In contrast, the logistics domain (2.5%; [Maio et al., 2023](#)) was less frequently studied/employed. Considering that each category of industrial tasks may have distinct requirements, conditions, and levels of complexity (e.g., see [Scallan, 2003](#)), it is important to account for the operational domain when studying and applying immersive technologies. While certain domains, such as assembly, have been relatively well investigated, other operational domains appear to require further attention.

The reviewed studies reported several potential benefits associated with immersive technologies in advanced manufacturing, including greater performance accuracy and efficiency, improved hazard awareness, and support for decision-making. For example, in one comparative study, VR-based learning about a product, its components, and the correct assembly sequence was associated with greater product knowledge, better assembly-task performance, and fewer errors than traditional training (e.g., [Abidi et al., 2019](#)). Similarly, using AR for welding was associated with lower perceived task complexity and cognitive load, allowing individuals to understand and experience procedures in a virtual welding environment more effectively (e.g., [Laviola et al., 2022](#); [Tobiskova et al., 2024](#)). A developmental study of a virtual foundry and heat-treatment environment suggested that the system could support users' understanding of relevant procedures; however, the evidence primarily concerned technical and instructional feasibility rather than comparative training effectiveness (e.g., [Tangjitsitharoen and Lawankowit, 2024](#)). Likewise, a preliminary evaluation of gamified VR training for mining operations reported positive user perceptions regarding engagement, understanding, and safety-related learning; however, the evidence did not establish causal improvements in task performance or safety compliance (e.g., [Jaiswal et al., 2024](#)). These findings suggest that immersive technologies have the potential to support both educational objectives (e.g., learning about tasks and relevant challenges) and hands-on experience (e.g., practicing tasks in a safe, controlled environment). While most studies reported the positive impacts of these platforms, some also highlighted potential challenges. These challenges were not related to inherent negative effects of the technologies but rather to practical issues that may arise during their application.

It is also worth noting that beyond the applications, technologies and challenges identified in the reviewed studies around the use of immersive technologies in training in advanced manufacturing, the broader literature in other contexts includes several important factors that seems to be underexplored although proven to be important contributors to success in implementation of such technologies. For instance, personalization of training experiences, adaptive learning pathways, competence estimation,

TABLE 6 Taxonomy of reviewed studies.

Types of industrial training	Focus of training	Technologies	Studies
Introduction, familiarization, and education	Learning the systems, environments and workflows	VR, serious games	Tangjitsitcharoen and Lawankowit (2024); Jaiswal et al. (2024); Kuhn and Lucke (2021); Perini et al. (2017)
Process and operational	Assembly, maintenance, inspection	AR, VR, MR	Abidi et al. (2019); Al-Ahmari et al. (2018); Maio et al. (2023); Moghaddam et al. (2021); Obermair et al. (2024); Pilati et al. (2020); Bertagna et al. (2025); Rakesh et al. (2024); Shankhwar et al. (2022); Nasri et al. (2024)
Hazard awareness and safety	Risk and safety procedures	AR, VR	Jaiswal et al. (2024); Tender et al. (2024); Gualtieri et al. (2023); Arana-Landín et al. (2023)
Cognitive and problem-solving	Sustainability, process, and monitoring	VR, MR, serious games	Perini et al. (2017); Jalilvand et al. (2024); Di Pierro et al. (2020); Mustafee et al. (2015)
Performance and on-the-job task training (hard skills)	Real-time tasks guidance	AR, MR	Laviola et al. (2022); Apostolopoulos et al. (2022); Tobiskova et al. (2024); Gors et al. (2021); Verdu et al. (2024); Saggiomo et al. (2016); Neb and Strieg (2018)
Adoption and implementation	Organizational capability	Mixed	Bun et al. (2020); Cirillo et al. (2024); Delgado et al. (2020); Di Pierro et al. (2020); Gualtieri et al. (2018); Tender et al. (2024); Arana-Landín et al. (2023)
Soft skills, knowledge and development	Individual capability	AR, VR, serious games	Bale et al. (2024); Mustafee et al. (2015); Perini et al. (2017); Kuhn and Lucke (2021); Di Pierro et al. (2020); Gualtieri et al. (2018); Cirillo et al. (2024)

categories are not mutually exclusive.

and systematic assessment of learner progress (Carvalho et al., 2025; Liu and Li, 2026; Zahabi et al., 2020). While some of the reviewed studies included data-driven elements to support training, the majority focused on demonstrating feasibility and task effectiveness rather than optimizing learning experience. In addition, in terms of implementation, although issues such as adoption and workforce readiness are discussed in some of the studies included in this review, there seems to be a lack of evidence in explaining mechanisms that enable or facilitate workforce readiness and adoption such as competence, learning preferences, and organizational cultures (Akinradewo et al., 2025; McPhee et al., 2026). These issues can open doors to further investigations in this area and significantly contribute to long-term success of using immersive technologies in training.

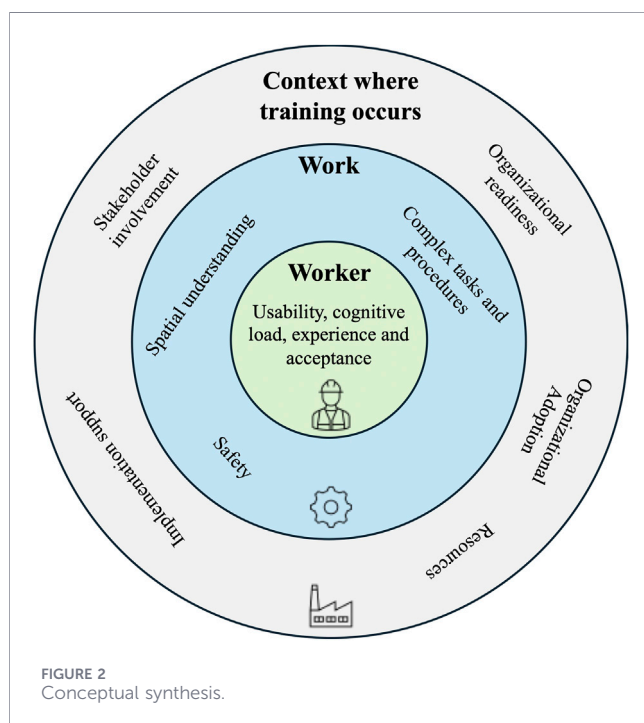
Some studies noted that the workforce may be unfamiliar with these technologies and may need to acquire new skills to use immersive technologies on smart devices (Bun et al., 2020; Di Pierro et al., 2020). Other studies highlighted that the cost of providing these technologies at a large scale, as well as creating content for them (e.g., developing a VR environment or designing a game), could be a challenge, particularly for small industries (Bun et al., 2020; Tender et al., 2024). Additionally, these platforms may not always function optimally at the software or hardware level. For instance, AR applications may not consistently align precisely with the real world, and VR headsets may have limited battery capacity, reducing applicability for longer sessions (Gualtieri et al., 2023; Neb and Strieg, 2018). Furthermore, some users may have privacy concerns, as they could be subject to surveillance while using

these platforms (Arana-Landín et al., 2023). Research also suggested that advanced functionalities and increased dependency on these platforms may contribute to feelings of job insecurity among some workers (Arana-Landín et al., 2023). Physical discomforts, such as prolonged use of VR headsets, were also reported as a challenge (Arana-Landín et al., 2023; Neb and Strieg, 2018). In this context, these studies discussed that there is still considerable room for technical refinement and strategic planning to ensure sustainable use of these platforms. This could include reducing costs, increasing worker acceptance, and mitigating psychological and physical discomforts (e.g., by implementing strict privacy principles or designing VR headsets that are lighter and more ergonomic).

Furthermore, the findings of this review indicate that immersive technologies such as VR and AR are primarily utilized for task-specific job training, whereas serious games are predominantly employed for broader training related to job concepts or organizational development. Drawing upon this distinction, the reviewed studies can be categorized based on the type of industrial training they involved as well as training focus and technologies used. In terms of the different types of industrial training, some common themes such as introductory, familiarization and educational; process and operational; hazard awareness and safety; cognitive and problem-solving; performance and on-the-job task training; adoption and implementation; and soft-skills, knowledge and development could be seen. Table 6 provides a taxonomy based on the aforementioned categories and maps the reviewed studies against each category. The taxonomy provided in Table 6

TABLE 7 Summary of key findings and recommendations.

Area	Key findings	Key challenges	Future directions
Technology	VR and AR are the most dominant forms of technologies used	Over-reliance of specific and limited number of platforms	Exploring wider range of technologies and hybrid approaches (e.g., gamified VR experiences)
Design	Most systems are expert-designed	Limited co-design with potential end users	Increase stakeholder involvement and use collaborative user centric design approaches such as co-design
Context	A wide range of industries seemed to be represented	Concentration seems to be on additive manufacturing and automotive	Expand to underrepresented sectors
Outcomes	Improved knowledge, performance, safety, accuracy	Evidence examined mainly short-term	More longitudinal studies to be conducted
Adoption	Limited use of intelligence and adaptive systems	Limited personalization and competence assessment	Explore adaptive and personalized learning models drawing from other contexts



suggests that beyond differences in use cases of each technology (e.g., AR more on-the-job, VR more safety, process and familiarization, and games more around problem solving, and knowledge development), there seems to be a heavier focus on using technologies for process related, technical, and safety cases and less on cognitive development, learning, and soft-skills which may be an avenue for further investigations for future research.

An important finding from the review was the absence of clear evidence demonstrating active collaboration between higher education institutions and advanced manufacturing industries in the development and delivery of training and educational programs. Given the rapid evolution of the industry and the ongoing need for workforce upskilling, a more robust collaborative framework between educational providers and industry partners is necessary. Such a model would better address the challenges of implementing

immersive technologies in training and education on a large scale, while also ensuring cost-effectiveness for small and medium-sized enterprises. Table 7 provides a summary of the key findings, challenges and future directions.

Theoretical and practical implications

From a theoretical perspective, this review contributes to the growing body of research on immersive technologies in workforce training by synthesizing evidence from fragmented streams of literature that have traditionally focused on specific technologies, industries, or applications. Instead of treating immersive technologies as solely technical systems, our findings suggest that their effectiveness is created through alignment and interaction between the worker, the work, and the organizational context in which training occurs. Drawing upon this observation, this review proposes a conceptual synthesis framework (Figure 2), that organizes literature around the three layers discussed. As such we propose that when it comes to measuring outcomes and success of deploying immersive technologies in advanced manufacturing setting, they should be evaluated through a range of factors from each layer. As such, this review extends existing discussions related to experiential learning, human-centered design, technology adoption and industry 4.0 workforce development by providing a holistic perspective on the conditions and dynamics that enable successful implementation of immersive technologies in training advance manufacturing workforce.

According to the reviewed studies, the use and study of immersive technologies in advanced manufacturing is growing, and valuable findings and insights have been reported. However, there still appears to be considerable scope for serious games to be further explored in both research and industry. Furthermore, although immersive technologies have been studied and implemented across a variety of industries and operational domains, there still appear to be areas that require additional attention. Further investigation and application of these platforms across industries (e.g., pharmaceutical) and operational domains (e.g., logistics departments) could be informative. Moreover, the reviewed studies reported several potential benefits, including associations with better performance, lower

cognitive workload, and fewer errors. At the same time, challenges associated with these platforms (e.g., costs, psychological and physical discomfort) have also been noted. Greater attention to these challenges could support a more balanced understanding of immersive technologies and inform their implementation in manufacturing settings. In summary, immersive technologies appear to offer potentially valuable opportunities across advanced manufacturing domains, but further research and industry engagement seems needed. There still appears to be room for improvement at both theoretical and practical levels (e.g., through technical refinement, the adoption of more user-centered design approaches, and sustainable long-term planning).

Moreover, with regards to practical recommendations to the practitioners and organizations in the field, the authors propose several recommendations based upon the results of this study. First, we recommend that the organizations considering using immersive technologies in their training should first align technology selection with the unique characteristics of their tasks and workforce rather than adopting a technology driven approach. Second, we recommend to organizations to invest in workforce readiness, provide support and incorporate user feedback in the design and implementation of immersive technologies in training and evaluate implementation success not only based on the enhancements in task-related outcomes but also in terms of user acceptance, accessibility and long-term sustainability. Lastly, use of co-design and implementation approaches in partnership with workers, technology developers, educational institutions and industry stakeholders is highly encouraged to facilitate successful implementation and reduce barriers.

Furthermore, since different immersive technologies are better suited to different training objectives, we recommend practitioners to consider where and under which conditions those technologies can bring about the most benefits. For instance, AR appears to be particularly useful when training is embedded within real workplaces and workstations, and contextual guidance is required during the task. In contrast, VR seems specifically valuable for training that involves hazardous, expensive, difficult to access, and safety-critical environments. Serious games and gamification can be particularly useful when complementing AR and VR as well as in situations where motivation, engagement, problem solving behavioral learning and decision making is of focus. In addition, in light of our findings regarding co-design and collaborative methods in designing immersive training systems, we recommend practitioners to consider design approaches that involve workers, educators, technology developers, and other industry stakeholders to enhance contextual alignment, acceptance, and sustainability of such training systems.

Limitations and future research

This review has several limitations. First, this review does not include dissertations and grey literature. However, given the substantial number of articles that were screened, included, and discussed, it is reasonable to expect that much of the relevant content from dissertations and grey literature overlaps with the sources

already reviewed in this study. In addition, although multiple databases were searched, it is possible that some relevant studies in other databases were not captured.

Second, this study only includes English-language literature. As a result, the findings and conclusions of several relevant studies published in other languages are not represented. Future research can address this limitation by including non-English literature, which may broaden the scope of evidence in this area.

Third, the review covers studies published between January 2015 and May 2025. Consequently, studies published after the search period were not included. Given the rapid development of immersive technologies, future reviews may wish to incorporate more recent research to capture emerging developments in the field. Reviews adopting a broader publication window may provide additional historical context and capture the timeframe of developments.

Fourth, since Advanced Manufacturing is a developing concept, some studies may use the term “manufacturing” even when they focus on advanced manufacturing. The search strategy used for this review employed the terms “advanced manufacturing” deliberately to maintain alignment with the pre-defined review domain, however, we acknowledge that this may have resulted in exclusion of some studies framed using similar terminologies such as smart manufacturing or simply using manufacturing in exchange for advanced manufacturing in contexts that would otherwise align with the scope of this review.

Fifth, although the methodological quality of the included studies was assessed using MMAT, the reviewed studies seemed to be heterogeneous in terms of design, technologies, participants, training goals, and outcomes that were measured. As such, while this diversity provides a broad and holistic overview, it limits direct comparison across studies and reduces the ability to draw generalizable conclusions.

Finally, the review was not prospectively registered in a public repository prior to commencing the process. Although the review procedures were agreed upon by a transdisciplinary research team before screening commenced, prospective registration would have provided additional benefits such as a better record of the planned methodology and subsequent modifications.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AT: Conceptualization, Funding acquisition, Methodology, Supervision, Writing – review and editing. AB: Conceptualization, Funding acquisition, Writing – review and editing. MS: Conceptualization, Funding acquisition, Writing – review and editing. AS: Conceptualization, Funding acquisition, Writing – review and editing. RS: Data curation, Formal Analysis, Writing – original draft.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/frvir.2026.1949492/full#supplementary-material>

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