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# Advancing Safety in the Oil and Gas Infrastructure via Virtual Reality Technology: A Comprehensive Exploration of Hazard Simulation and Visualisations

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**Abstract**

Virtual reality (VR) technology has transformed various industries and technological paradigms, including oil and gas. With so many subareas and techniques in the field, there is a need for organised knowledge about VR applications, particularly in the oil and gas sector. This paper primarily aims to review previous research on virtual reality methods in various industries, including oil and gas. The objective is to offer researchers and professionals valuable insights and provide a foundation for future advancements in VR applications in this sector. A systematic search for publications on "Application of Virtual Reality," "VR," "Advantages of Virtual Reality," and "Immersive Technology in the Oil and Gas Industry Infrastructure" was conducted to understand the field and provide researchers with insights into the VR system. Trusted databases were meticulously explored to facilitate a systematic review process that illuminated publication trends and the origins of the research. This allows civil engineers to model potential dangers on oil and gas platforms, including gas leaks, fires, broken equipment, and structural instability. They also acquire direct experiential knowledge of potential hazards and obstacles by fully immersing themselves in these virtual environments. Additionally, engineers can better visualise potential hazards like trip hazards, obstructions, electrical hazards, or inadequate safety barriers with VR compared to traditional methods. This improves hazard awareness and allows for proactive risk mitigation strategies. The study finds that VR applications have seen significant growth and diverse applications globally, particularly in risk assessment, safety improvement, and operational efficiency, highlighting the interdisciplinary benefits and increasing adoption of VR technologies in the oil and gas sector.

## 1. Introduction

The adoption of digital devices is growing in various fields of education and training, including risk, hazard, and safety assessment [1]. This trend in adoption is most pronounced between two time periods: first, from 1997 to 2006, when networked computers were extensively utilised for group projects, and second, from 2007 to 2016, when online digital education was at its peak. At the time, researchers were investigating the possibilities of new technology, such as mobile learning platforms, computer-mediated communication, and virtual learning environments [2]-[5]. Although Virtual Reality (VR) is not a novel concept, advancements in immersive technologies, especially in visualization and interactions, are leading researchers to discover an increasing number of applications for it. The most recent virtual reality head-mounted displays (HMDs), including the Oculus Rift and Pico, provide consumers with an even more immersive experience. Within the given framework, "immersion" refers to how an individual becomes engrossed in a virtual setting, frequently resulting in a disconnection from temporal and physical awareness. The end effect is an intense sense of "being" inside the virtual task setting [6].

VR has received significant recognition as a revolutionary educational instrument in the 21st century [7], [37]. Extensive research suggests that VR experiences improve student and industry worker knowledge retention and application [8]. Previous studies emphasised desktop usage for educational purposes and the applications of HMD technology [9], [10]. While Jensen & Konradsen [10] prioritise improving the learning process and results, it is necessary to note that the target audience, such as K–12 education, higher education, vocational training, or job-specific training, is not clarified [38]. Furthermore, the critical analysis of the design components of VR educational applications and the underlying learning theories that control their development is frequently neglected in this research [37].

Virtual Reality (VR) experiences can be classified into two main categories: immersive and non-immersive. By engaging users in virtual surroundings, immersive VR technology transports them to simulated realities and evokes a powerful sense of presence[39]. Specialised gear, like head-mounted displays (HMDs) and sensor gloves, allows users to be fully immersed in a virtual world, blocking out all outside stimuli. In immersive virtual reality, users can achieve spatial immersion by being surrounded by virtual elements such as sights, sounds, and more. This creates the impression that the virtual environment is both authentic and realistic [39]. The Cave Automatic Virtual Environment (CAVE), developed by Waly and Thabet, is a prime representation of a fully immersive virtual reality system. When a user enters an immersive virtual world, the environment changes to fit their location. The user's sense of presence is enhanced as their corresponding location in the virtual world alters in response to their movements [11]-[13]. Opponents of desktop-based VR systems argue that immersive VR's real-time capabilities make it preferable [14]. The Virginia Polytechnic Institute and State University's virtual structural analysis programme (VSAP) is another example of a typical immersive VR system [15]. The system's primary goal is to comprehend buildings' virtual structural behaviour [15].

Since conventional immersive interfaces are expensive and desktop interfaces are cheap but lack quality, VSAP's primary contribution is creating an immersive portal interface. Hence, a modified Virginia Tech CAVE (VT CAVE) of 3 m x 3 m × 2.75 m was created. When it comes to practicality, VT CAVE has shown to be effective. With the right tracking equipment for interactions—like gaming controllers and motion-tracking devices—immersive virtual reality can provide users with a more genuine VR experience. Detecting and demonstrating the subject's movements in the virtual environment is common. Construction site safety instruction was enhanced by deploying a 3D immersive VR power wall [14]. The power-wall setup included three rear-projection screens and an open three-sided CAVE layout utilising 3D stereo projection with active glass. In addition to the eight cameras affixed to the screens, the trainees utilised a head-tracking device with an Xbox controller [16]. Three different programs were employed: Autodesk Revit for modelling the system's building, 3D Studio MAX for modelling other 3D geometry, and AEON Studio v6 for generating virtual reality situations [17], [18]. Virtual reality (VR) training improved student attentiveness and gave participants some control over the environment.

Contrarily, non-immersive VR experiences still provide useful visual and interactive representations without completely immersing users in virtual worlds. These encounters frequently entail using handheld devices, desktop screens, and projection systems to exhibit virtual content [19]. Although non-immersive VR may not offer the same degree of immersion as its immersive counterpart, it enables users to navigate and interact with virtual environments, rendering it appropriate for uses where complete immersion is neither necessary nor practical. Conversely, non-immersive VR is finding use in the classroom by visualising complex ideas and situations to help students better grasp them and stay engaged. Users can interact with virtual objects and datasets in non-immersive VR, which aids in data analysis and decision-making in data visualisation and collaborative environments. Thus, immersive and non-immersive VR experiences present users in various fields with distinct prospects. Non-immersive VR provides beneficial visual and interactive representations, whereas immersive VR delivers an exceptionally realistic and immersive experience [20]-[22].

## 1.1 Gaps in the Systematic Review of Application Virtual Reality

These papers highlight a thorough examination of technological implementations in many industries without focusing on specific methodologies to give researchers insights into recent advancements and achievements. This paper attempts to fill gaps in the current research to provide a theoretical contribution by delving into immersive VR. Through a systematic review of immersive Virtual Reality, Suh & Prophet covered a few components, including healthcare, marketing, and education [23]. As an alternative, exclusively emphasised educational objectives, while focused on significant tasks integrated into immersive VR [9], [24]. Chavez & Bayona took a more holistic view, looking at VR in general engineering rather than immersive VR [24]. Immersive virtual reality was examined by Wang about a range of associated technologies, such as augmented reality and non-immersive VR. Diverse systematic evaluations followed different trajectories concerning VR-based technologies [4]. While some considered industry in a more general context, others dove into more narrow fields like construction engineering or evacuation training [4], [24]. Other reviews did not sufficiently address evaluation techniques, whereas Feng devised methods for quantifying learning outcomes in particular contexts, such as evacuation training [25].

## 2. Research Method

This study investigates current trends in the industrial application of virtual reality, focusing on the oil and gas infrastructure sector and safety risk assessment.A systematic review of relevant literature is utilised to clarify the developments in research regarding the VR trend as part of the selected methodology. The existing literature was analysed following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) method standard [4]. The manual provides an approachable, straightforward theoretical and methodological framework.

The PRISMA framework was employed for this review article due to its ability to streamline the process of conducting a comprehensive review for researchers through systematic dissemination after document screening. In addition, compared to estimates made from individual experiments, PRISMA yields more precise results. This review consists of three separate steps: (i) searching vast databases of academic and scientific literature using keyword and search techniques; (ii) determining which studies to include and which to exclude; and (iii) determining which studies to include based on an eligibility process.

### 2.1 Selection Criteria

A systematically employed mapping approach across digital libraries has been initiated with the aim of augmenting comprehension of the design space about infrastructure and VR-based applications. This research aims to shed light on the connection between design components and implementation materials and the interaction between industrial application domains. Based on the findings, a prospective research agenda and preliminary recommendations for the advancement of VR applications in the industry have been formulated. This method has successfully delivered a thorough understanding of particular research fields. A mapping study, which functions as a specific type of systematic literature review, is also suggested by Kitchenham as a method for comprehending the vast area, including relevant topics and research trends [26]. The standard method of conducting a systematic literature review revolves around a predetermined research issue. The following is a list of the factors that were considered during the selection process for publication:

(a) The paper review exclusively considered literature in the English language to evaluate the research's pertinence.
(b) Various studies encompassing Virtual Reality, its utilization in industry, immersive teaching lessons employing Virtual Reality, and its application in education were reviewed to emphasize the systematic review of the application of Virtual Reality, particularly within the oil and gas industry & infrastructure.
(c) These articles focus on Virtual Reality Technologies within the oil and gas industries.
(d) The article should incorporate practical applications, trends in Virtual Reality Technology, and the benefits of Virtual Reality Technology integration.

### 2.2 Paper Selection Phase

#### 2.2.1 Identification Of Paper

Scopus and similar reputable journal search engines are known for their meticulousness and strict adherence to specific selection criteria. The particular parameters these search engines were fine-tuned to probe were titles, abstracts, keywords, authors, and publication years. The use of specific terms such as "VR," "Application of VR," and "Virtual Reality in the Oil and Gas Sector" were crucial to the search process. The first round of research using Scopus yielded 217 relevant papers. Table 1 shows all specific search parameters and the restricting mechanisms applied to each search engine.

#### 2.2.2 Article Selection

An article selection approach was used to sort the articles based on relevancy. The abstracts were critically examined to determine which articles would advance to the next stage. Articles were only considered for this assessment if they fulfilled the following three requirements: (i) This paper should specifically examine the integration of virtual reality into the infrastructure and operations of the oil and gas industry; (ii) It should concentrate on evaluating practical applications, trends, or analyses of virtual reality as they pertain to the infrastructure and operations of the oil and gas industry; and (iii) It should incorporate publications that are not indexed in Scopus but are cited in the chosen literature.

The initial screening phase was completed by 115 out of 217 academic articles. A "snowball" effect was used to guarantee the inclusion of possibly relevant articles; analysing the references referenced in the evaluated academic papers and then analysing the abstracts revealed an extra 16 publications. On to the second round of screening, when all fifty publications were read in their entirety, trends in research were identified according to publication year, country of origin, and analytical methods used. This led to the identification of 66 papers that fulfilled all requirements.

**Table 1** *Search strategy and limitation parameter search engine*

| Step | Criteria |
|---|---|
| 1 | “Application of Virtual Reality” ”Virtual Reality in Oil and Gas Industry” “Systematic Review of Virtual Reality”. |
| 2 | English Language Only. |
| 3 | Year Publication is limited from 2010 until 2022. |
| 4 | Exclude all subject areas except engineering and industry. |
| 5 | The document type is limited to “article” only. |
| 6 | The document type is limited to “Journal” only. |
| 7 | The publication stage is limited to “Final” only. |

#### 2.2.3 Quality Assessment

The standards set out by Kitchenham and Charters were followed in evaluating primary research quality [26]. This process enabled an assessment of the article's relevance to the research concerns, taking into account potential signs of study bias and the reliability of experimental findings [27]. A quality assessment procedure was applied to five articles that were selected at random to determine their effectiveness:

- Stage 1: The article must be well-commented and focused on Virtual Reality Technology Integration
- Stage 2: The study aims and outcomes background should be contextualized sufficiently, enabling a proper interpretation of the findings.
- Stage 3: The study must contain adequate information to explain how VR was applied to a specific situation.
- Stage 4: The paper must explain the security and privacy concerns.
- Stage 5: Details on how the data was collected, measured, and reported must be provided to assess accuracy.

#### 2.2.4 Data Extraction

Once the articles were deemed to have passed the quality test, data extraction was performed to ensure that the information supplied was accurate and comprehensive. Data extraction was piloted on a smaller research group to ensure it worked before being applied to the full set of studies that made it through quality assessment. The following groups were used to classify the extracted data: contextual data includes information relevant to the study's objective; qualitative data covers elements like author-presented findings and conclusions; and quantitative data consists of information gathered, analysed, and extrapolated from the study's results.

The process of paper selection for our investigation is depicted in Fig. 1. The document describes our database journal platform for finding papers by retrieving relevant literature using Boolean expressions. A total of 66 papers underwent a comprehensive evaluation after implementing advanced filters.

## 3. Content Analysis on Virtual Reality Technologies

### 3.1 Review Virtual Reality Technologies

The oil and gas industry has five main kinds of virtual reality (VR) and related technologies: desktop-based, immersive, 3D game-based, BIM-enabled, and augmented reality (AR). This classification is predicated on visualisation media and display platforms having various uses. The study centres on observing and assessing the implementations of VR technology developments in the oil and gas industry. Although the classification is provided, it does not limit additional investigation into all facets of virtual reality, such as software, hardware, visualisation, and interaction concerns. References like Milgram and Colquhoum [28] and Hale and Stanney [29] provide more thorough taxonomies of virtual reality and virtual environment systems. Fig. 2 displays the total number of primary research articles published on VR technologies between 2010 and 2022. The Most Prominent application of Virtual reality technology is Building Information Modelling (BIM) , which account for 47% of the usage. This is followed by desktop-based virtual Reality application , which represent 26% of the total application.

Augmented Reality (AR) constitutes 15% of the application , highlighting its role in enhancing real-world environment with digital overlays. Immersive Virtual reality and 3D games-based Virtual reality both make up 6% each, with immersive VR primarily used for training and 3D games-based focusing on interactive simulation. This detailed breakdown provides clear understanding of the distribution and significance of various VR application within the industry.

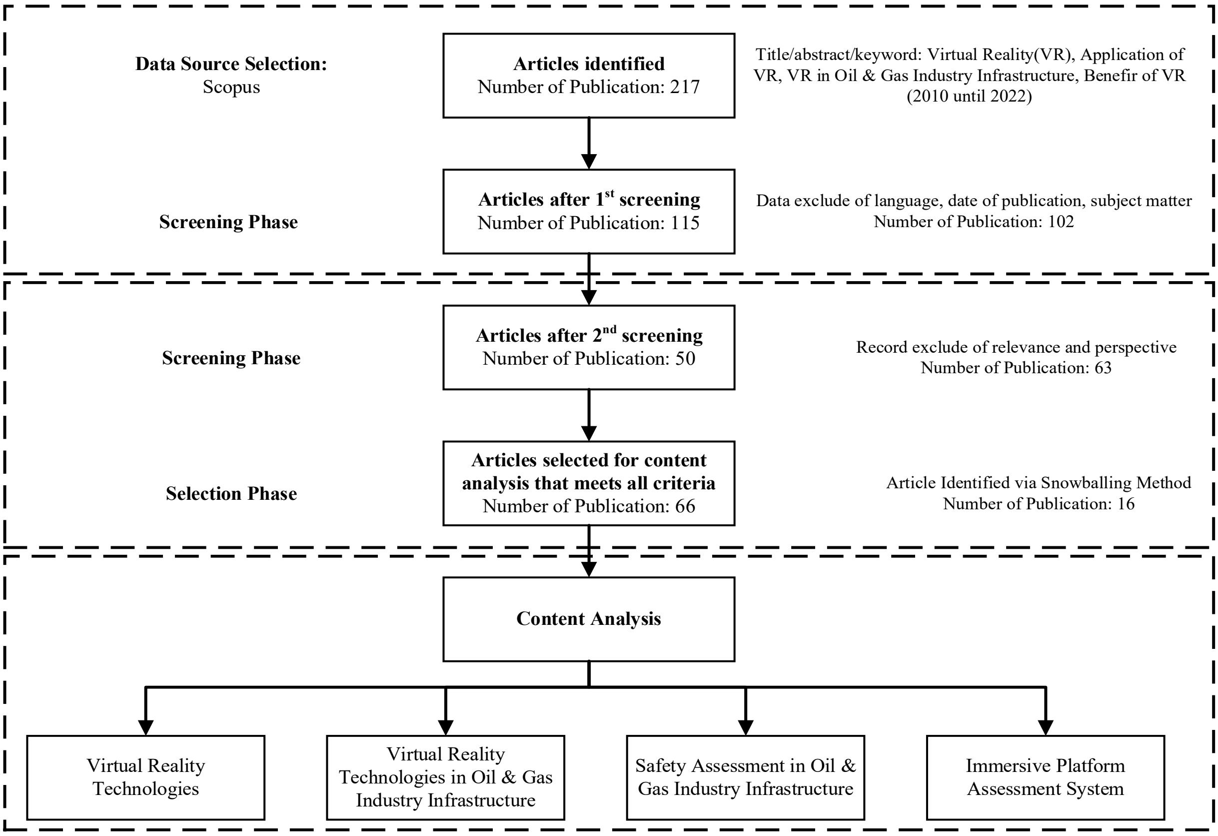
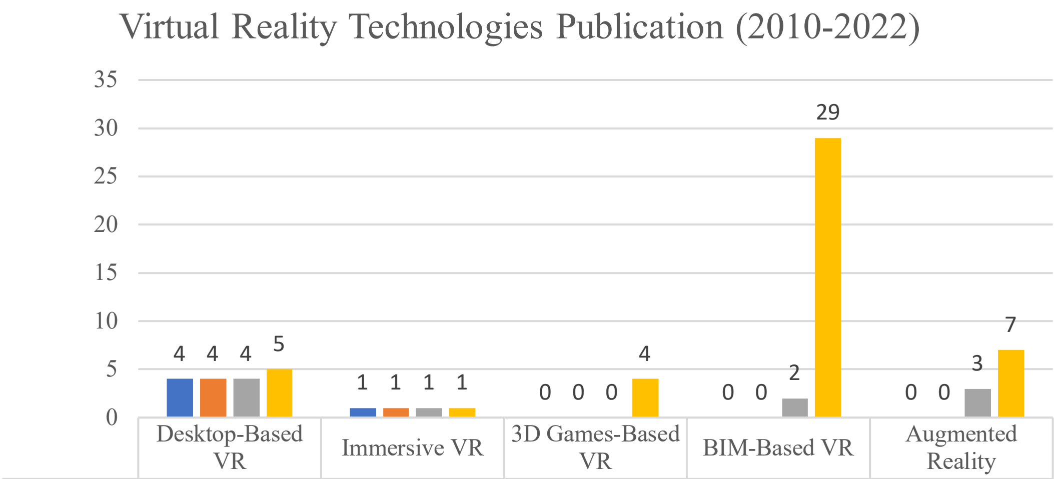



**Fig. 1** *Process of data extraction (paper/journal/articles)*

In its early phases, CEET made extensive use of desktop-based VR. Four of the five research conducted between 2010 and 2012 concern desktop-based VR, as shown in Fig. 2. This technique supposedly allows users to engage in virtual activities on a regular computer screen [30]. Using standard desktop monitors and no additional tracking hardware, it creates a fully immersive 3D virtual environment. The user's spatial and perceptual abilities largely control the virtual world, with most inputs coming from the keyboard and mouse. Desktop VR is more affordable than other VR technologies due to its reliance on common hardware. Both V-REALISM and the Interactive Construction Management Learning System (ICMLS) are essential advancements in desktop-based VR [26], [31], [74]. V-REALISM is a training programme for maintenance engineers that uses CAD to build geometrical models and shows them off through the OpenGL API. The hierarchical nature of V-REALISM makes it easy to navigate and operate models in a virtual setting. Virtual models built with VRML and operations demonstrated through DES and web-based computing are also used by ICMLS to bridge the gap between classroom instruction and real-world construction site operations. A study by Sawhney [32] found that ICMLS is suitable for on-site construction and can be included in CEET. Recent developments in desktop-based VR have concentrated on 3D computer models and virtual laboratories to promote student engagement and comprehension [33], [34], [38].Due to the expensive expense of traditional immersive interfaces and the low quality sacrificed by desktop interfaces, VSAP's primary contribution is the development of an immersive portal interface.

By integrating visual, interactive, network, and multi-user operating technologies, 3D game technology seeks to improve user interactions by creating computer-based training scenes that resemble games. Game-based training can improve student-teacher communication and teamwork by giving them practical, real-world tasks to complete [16]-[18], [40], [73]. Virtual reality in games is less concerned with the immersive impact and more with interactions between in-game objects. For instance, a gaming engine's physics simulation module can provide a detailed description of collision reactions. The detection operations in 3D game-based VR are made simpler using ray tracing and simplified collision boundaries. Then, the in-game object's geometric characteristics and collision boundaries should be distinct. It aids in reducing complexity and can facilitate the computational process of "collision detection" for intricate objects like construction excavators or cranes. One example is the game-based safety training system created by Guo et al. [41]. This system is an online platform where trainees can practise virtual duties like material delivery and equipment operation using input devices, including mouse, keyboard, and game controllers. The system's primary benefit is access to multiple trials at a relatively modest cost. For instance, the game-based technique can test various schedules and methods for operating the equipment. Potential concerns, such as those on health and safety, can be discovered via the testing process. Moreover, Le et al. [43] created a game-based instructional platform to oversee construction defect management.




| | Desktop-Based VR | Immersive VR | 3D Games-Based VR | BIM-Based VR | Augmented Reality |
|---|---|---|---|---|---|
| 2010-2012 | 4 | 1 | 0 | 0 | 0 |
| 2013-2015 | 4 | 1 | 0 | 0 | 0 |
| 2017-2019 | 4 | 1 | 0 | 2 | 3 |
| 2020-2022 | 5 | 1 | 4 | 29 | 7 |

**Fig. 2** *Number of primary studies on virtual reality technologies that have been published from 2010-2022*

Building Information Modelling (BIM) involves making and utilising 3D objects with pertinent property data [39], [44], [45]. Information on significant qualities specifically referred to data needed in a practical building project's life cycle, from design and planning to construction, operation, and maintenance. Hence, unlike other types of VR, BIM-enabled VR uses models to mimic building processes and operations, emphasising data binding and connectivity. Visualisation is among the most essential BIM characteristics [4]. BIM data can be accessed in an immersive visualisation environment, allowing users to analyse cost and material type to produce successful building designs in real-time.

Reviewing the design details, a more in-depth discussion of the building information model's (BIM) architecture, structure, and mechanical, electrical, and plumbing (MEP) components is possible. For instance, using building information modelling (BIM) enabled virtual reality (VR), users may import building designs into a 3D environment complete with all pertinent architectural data, explore the BIM model in VR without squinting at 2D drawings and evaluate the design space in real-time. Automatic systems such as Autodesk Revit Live [46] enable learners to seamlessly transition from traditional 2D drawing design scenarios to those in building information modelling (BIM) interactive virtual environments. This allows them to visualise the integration of design elements and maintain the accuracy of building management data in the virtual environment before the physical construction of the structure. The model's capacity to reflect changes in real time is one of the main advantages of BIM-based VR. Traditional VR models built using VRML may struggle to incorporate real-time data [47]. The compatibility issue could be the root cause of these problems. Numerous decision-making tools have also been developed to aid in the decision-making procedure. The software solution created by Woodward [11] combines 3D models with scheduling information, allowing one to see the construction activity in progress on site while Park designed an interactive building anatomy modelling (IBAM) system [32]. The technology facilitates the student's engagement with the building's components in a virtual reality setting. In addition, an interactive question-and-answer segment may be incorporated to augment the educational journey.

Using various sensory technologies, Augmented Reality (AR) offers a live, direct or indirect picture of a real-world setting while supplementing it with digital data. Visuals, audio, and video can all be delivered by sensory technology. Virtual reality and augmented reality are distinct visualisation technologies. Fonseca found that, in contrast to a VR setting, augmented reality allows users to manipulate things in real-world settings, including changing their size, position, and other attributes [48]. Thus, several research studies suggested that augmented

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reality could open up new avenues of engagement and encourage students to engage actively in the learning process [49]-[51]. Chen built the augmented reality model students used to practise spatial object recognition using ARToolKit [52]. AR can facilitate student learning because it can project various 3D models onto the actual environment [53].

Furthermore, numerous apps have been created to incorporate augmented reality into mobile devices, as these devices are becoming increasingly useful for educational purposes. For example, Williams trained users on context awareness using a mobile augmented reality (MAR) environment [56]. Shirazi created CAM-ART, a mobile context-aware augmented reality tool to benefit undergraduates enrolled in construction engineering programmes [51]. The CAM-ART augmented reality platform defines content using static extensible markup language and object interactions using JavaScript logic. Additionally, Kim created an augmented reality (AR) platform for optimising the construction process via equipment operation adjustments [54]. The benefits of AR in this study involve identifying surrounding restrictions and improving visualisation from the operator's viewpoint.

## 3.2 Review Virtual Reality in Oil and Gas Industry Infrastructure

Virtual reality (VR) has recently grown in popularity to improve technical skills in the infrastructure and oil and gas industries [71], [72]. VR provides a unique training experience that can greatly enhance the abilities and understanding of people working in this challenging and high-risk area through immersive and interactive simulations [9], [21], [55]. This section explores the uses and benefits of VR in improving technical competencies associated with oil and gas infrastructure operations, as it has shown promising results in several domains, including risk assessment safety training [20], [72]. Safety is of the utmost importance in the oil and gas business due to the nature of the work, which includes handling potentially dangerous substances and navigating difficult conditions. Safety training programmes using virtual reality enable employees to practise handling equipment, responding to emergencies, and following protocols safely [19]. Besides, it also helps trainees learn to behave appropriately in high-stakes circumstances by mimicking real-life events like plant crises or hazardous material spills. The oil and gas sector can benefit from VR safety training in several situations, including increased safety awareness, decreased accident rates, and better emergency readiness [20].

Virtual reality remains essential to preparing workers for specialised and complicated jobs in the oil and gas industry. This encompasses tasks like inspecting and fixing equipment [56], [57]. Without costly equipment or genuine operating hazards, trainees can practise these activities in a realistic and controlled setting through virtual reality simulations. Trainees can utilise VR to practise operating complicated machinery, carry out virtual maintenance duties, and spot possible problems, among other uses [21]. Individuals are able to develop problem-solving abilities and technical competencies through these types of training programmes, which ultimately results in enhanced productivity and effectiveness in practical situations.

Moreover, virtual reality provides invaluable opportunities for drilling and well operations training. Well drilling is a delicate procedure that demands careful planning and swift decisions. Trainees can practise realistic drilling scenarios, such as locating the wellbore, evaluating the formation, and selecting the drill bit using VR-based drilling simulators [55]. Trainees may hone their drilling skills, keep tabs on the various drilling factors, and make educated decisions in a simulated setting. Drilling training using virtual reality improves technical competencies and situational awareness via real-time feedback and performance assessment, leading to streamlined operations with less operational risk.

The oil and gas sector can benefit from virtual reality training in technical areas and areas pertaining to collaboration and teamwork. Ensuring staff safety and successfully executing projects depend on effective teamwork. VR team training programmes put participants in realistic oil and gas environments, including maintaining pipelines or operating offshore platforms [22], [24], [58]-[61]. Fostering effective cooperation and decision-making, trainees can practise problem-solving, communication, and coordination in a virtual team setting. The oil and gas sector relies on effective teamwork, which can only be achieved through training that improves both technical competence and the interpersonal skills required for the job. VR exhibits considerable potential for augmenting technical proficiencies within the oil and gas sector. The simulations help individuals in this challenging industry polish their abilities by simulating real-life scenarios. Whether for safety training, specialised duties, or teamwork, virtual reality (VR) provides a flexible and effective platform for boosting technical competencies and performance in oil and gas operations.

## 3.3 Review Immersive Safety & Risk Assessment Protocols in the Oil and Gas Industry

Robust safety protocols are necessary to safeguard workers and avert catastrophes in the oil and gas sector, which is inherently hazardous. Immersive safety assessment and VR emergency response scenarios have become valuable tools for improving safety procedures and reducing hazards in this sector and its infrastructure. This literature review explores virtual reality (VR) in oil and gas industry-specific emergency response and safety assessment simulations. It thoroughly evaluates virtual reality's usefulness, efficacy, and important results in enhancing safety procedures and disaster readiness. The oil and gas industry can significantly benefit from using

VR in safety assessment and emergency response simulations [71]. The development of vital safety skills and decision-making abilities, along with increased engagement and knowledge retention, are all facilitated by this immersive approach. Additionally, the simulations offer a risk-free setting for training employees to operate equipment, identify potential dangers, and implement solutions to reduce such risks [20], [53], [62]. Virtual reality (VR) safety assessment programmes can greatly improve worker competency in the industry's safety culture and reduce accidents [20].

Virtual reality (VR) has shown to be a helpful tool for assessing potential risks to oil and gas infrastructure safety and for simulating emergency responses. In a study on VR-based drilling simulations, discovered that participants exhibited enhanced safety performance, heightened situational awareness, and improved drilling abilities [22], [71]. Researchers found that oil and gas UAV pilots used VR to increase their situational awareness, decision-making, and overall operational performance and use haptic feedback technology in VR to enhance stimulations [21], [71], [72]. It has also enhanced safety practices and decreased incidents in the sector by guiding workers on safety procedures such as confined space entrance, hazard awareness, and fire safety [13], [40], [56], [60], [63], [64]. The simulations enable workers to perform physically demanding safety tasks in a controlled and repetitive environment while facilitating authentic assessment experiences through their interactive and immersive qualities.

Hence, the utilisation of VR for emergency response simulations and immersive safety risk assessment presents significant advantages and empirical evidence of their efficacy in bolstering crisis management as well as safety protocols within the sector. Employees are empowered to cultivate critical safety competencies, enhance their decision-making processes, and heighten their overall safety consciousness by utilising genuine virtual environments and replicating hazardous situations. Integrating virtual reality (VR) technology into safety training programmes can enhance preparedness for emergencies, decrease the occurrence of accidents, and promote a secure working environment [5], [6], [74]. With the rapid progress of VR technology, there is great promise for improving safety risk assessment handling and simulations in the oil and gas industry's infrastructure.

## 4. Trend Analysis According to Country of Origin

Numerous nations, including the US, UK, Norway, Russia, the US, Canada, Brazil, Saudi Arabia, Australia, and the UAE, have joined forces worldwide to study VR in the oil and gas industry, which covers the infrastructure platform. This study covers a wide range of topics relevant to the sector, including environmental management, safety training, production, and exploration. A reflection of their respective positions as global energy powerhouses, each of these nations brings fresh ideas, knowledge, and objectives to the table. This paper explores how VR can improve safety procedures, operational efficiency, resource management, and environmental risk mitigation in the oil and gas production process. Advancements in the oil and gas sector's adoption and usefulness of virtual reality technology are ultimately made possible via the combined efforts of researchers, industry personnel, and lawmakers from all over the globe. Continuous innovation and research are of the utmost importance in determining the trajectory of oil and gas operations in the coming years as technological advancements propel the sector towards greater sustainability, safety, and efficiency. Fig. 3 demonstrates the major contributions that multiple countries have made to experimental and evaluation assessments of virtual reality in the oil and gas sector.

Several countries have actively engaged in pioneering research and development endeavours to enhance operational efficiency and safety standards within the global oil and gas industry. The US has been at the forefront of virtual reality research in the oil and gas industry, contributing 15% to the overall research effort. The United States has investigated several uses, including safety assessment, operational optimisation, and equipment maintenance, by utilising its solid technological sector and large investments in research and development. The sector's dedication to innovation and safety enhancement is evident in notable contributions such as works on real-time monitoring systems, drilling simulations, and safety protocols [7], [20], [22], [36], [59], [65]-[68]. Regarding developing VR applications for the oil and gas industry, China is a key participant, contributing 15% to field research. The rapid growth of China's economy and the country's strong commitment to technical innovation in all sectors are driving this substantial engagement. Research in the field of oil and gas operations in China primarily focuses on methods for simulating drilling operations, assessing performance, and developing thorough protocols for testing equipment. These efforts demonstrate China's unwavering dedication to improving operational efficiency and industry safety. Chinese officials hope to solve pressing problems and encourage long-term expansion in the oil and gas industry by using the technology [21], [30], [32], [70]. Vietnam is recognised for its significant investment in safety training and efficacy in hazardous environments, accounting for 10% of research initiatives in the oil and gas sector. Notable research activities in Vietnam revolve around VR applications tailored to the sector's needs. These efforts comprise a variety of risk mitigation strategies, emergency response preparedness programmes, and safety assessment simulations. By undertaking these initiatives, Vietnam showcases its deep dedication to promoting readiness and safety in all oil and gas operations areas. The

Vietnamese government is taking virtual reality seriously to protect its workers from harm and end serious safety issues in the industry.

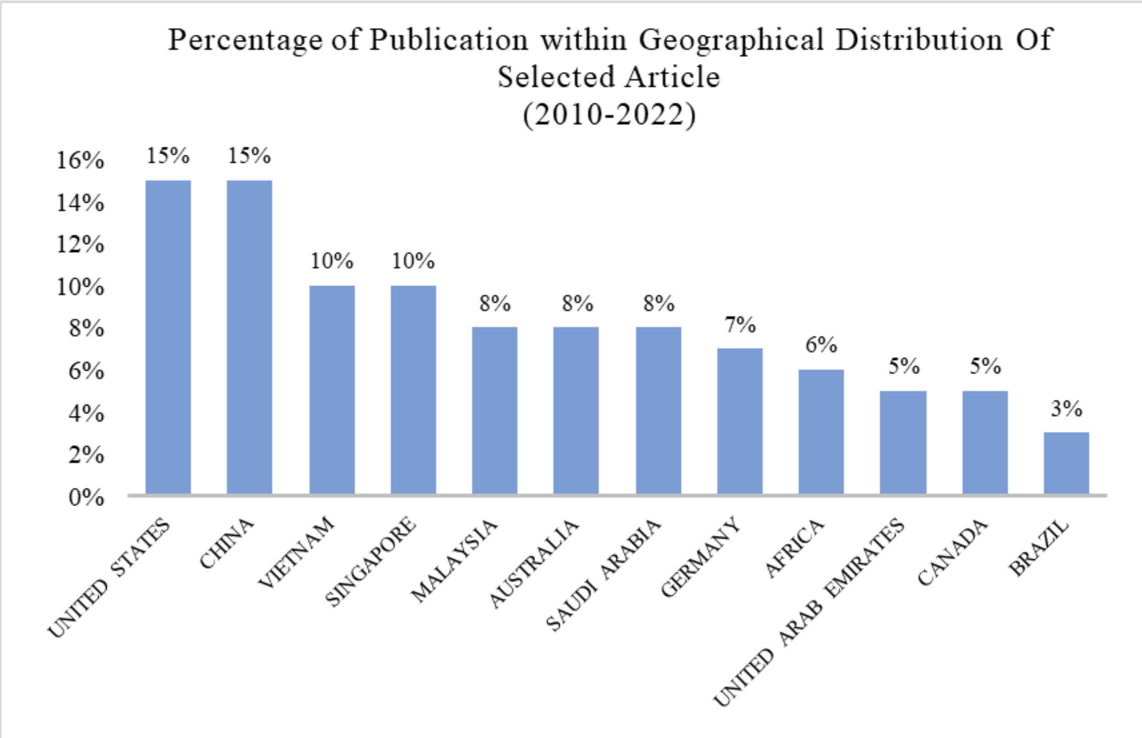


**Fig. 3** *Classification of virtual reality in oil and gas industry paper publication that were published by origin countries in 2010-2022*

Singapore has become a prominent centre for cutting-edge virtual reality applications, accounting for 10% of oil and gas industry research. The nation is concerned with risk management, emergency response training, and safety assessments regarding oil and gas activities. Singapore demonstrates its dedication to advancing industry safety standards and operating processes through initiatives like virtual inspections and VR-based training programmes. These initiatives highlight Singapore's forward-thinking strategy for utilising technology to improve operational efficiency and reduce hazards in the oil and gas industry. Meanwhile, Malaysia's oil and gas industry prioritises safety culture, compliance, and training programmes; the country contributes 8% to global research efforts. Virtual reality safety training simulations, risk management tactics, and operational optimisation methods are all part of the country's research agenda. Malaysia is reiterating its dedication to enhancing operational efficiency and safety measures in the oil and gas industry by investigating these possibilities. Besides, the country intends to improve the efficiency and effectiveness of its oil and gas operations while addressing important safety concerns through virtual reality technology. This commitment shows Malaysia is taking the initiative to promote a safety-first and excellence-oriented culture in the industry. Australia's 8% investment in VR research within the oil and gas industry is instrumental in advancing safety training, risk management, and operational optimisation. The government is researching VR applications extensively to recreate real-world situations that may arise during oil and gas operations. Innovation and efficiency are propelled by these applications, improving situational awareness and enabling collaborative decision-making. Australia is determined to enhance the oil and gas industry's safety standards and operating procedures through virtual reality technology. Like other countries contributing 8% to VR research, Saudi Arabia looks into VR's potential usage in the upstream and downstream processes of the oil and gas industry. The use of virtual reality solutions is crucial to the effort to improve operational efficiency and resource recovery. Reservoir modelling, well optimisation, and refinery process simulation are all focus areas for Saudi Arabian researchers, demonstrating the country's deep dedication to using technology to improve efficiency and longevity in the oil and gas industry. Saudi Arabia aims to enhance operational efficiency, optimise resource allocation, and guarantee the energy and gas sector's sustained viability through VR technology.

With a 7% share of global VR research, Germany is well-known for its cutting-edge VR applications in the logistics of oil and gas supply chain, human-machine interface, and drilling operations. German academics devote much time and energy to studying how VR could boost safety standards, workforce training, and equipment maintenance processes. These projects highlight Germany's resolve to lead the industry in technological innovation and operational excellence, aiming to raise efficiency and safety benchmarks. Furthermore, Africa's extensive engagement in addressing safety regulations, operational efficiency, and environmental management within the infrastructure of the oil and gas industry is reflected in its 6% contribution to VR research. These initiatives highlight Africa's forward-thinking strategy for using virtual reality technology to enhance operational efficiency and reduce hazards in the oil and gas industry. With a 5% share, the UAE studies virtual reality's potential uses in the oil and gas sector, specifically for operational optimisation, environmental monitoring, and safety assessment. The United Arab Emirates is strongly promoting using virtual inspection tools, real-time monitoring systems, and immersive training simulations to improve operational efficiency and safety protocols. These initiatives highlight the UAE's resolve to use innovative technology to boost efficiency and safety in the oil and gas industry, guaranteeing long-term viability and security. Canada uses virtual reality (VR) simulations in the oil and gas industry to prioritise safety assessments, regulatory compliance, and environmental monitoring; the country contributes 5% to VR research. Researchers in Canada are working on several fronts to reduce potential environmental dangers, strengthen safety measures, and foster a safety culture in the workplace. These initiatives ensure responsible resource extraction and operation, which highlight Canada's dedication to sustainability and innovation in the oil and gas industry. Brazil's 3% contribution to VR research addresses challenges unique to the oil and gas industry, including deep-sea exploration, subsea infrastructure maintenance, and offshore platform safety. For the specific difficulties of offshore infrastructure projects, Brazilian researchers are investigating the applications for underwater environment simulation, virtual inspection, and optimisation of drilling operations. The summary of previous research contributions by various countries is presented in Table 2.

Ultimately, nationwide investments in virtual reality (VR) studies of the oil and gas sector demonstrate a concerted effort to improve sustainability, operational efficiency, and safety. These nations are trying to enhance oil and gas operations, promote a safety culture, and tackle industry-specific issues by using VR in novel ways. Their endeavours serve to emphasise the significance of responsible practices, collaboration, and innovation in influencing the trajectory of the oil and gas sector.

**Table 2** *Literature review table for virtual reality in oil and gas industry paper publication*

| Country | Contribution to Global VR Research (%) | Focus Area (VR Applications) | Research Activities |
|---|---|---|---|
| United States | 15% | Safety assessment, operational optimization, equipment maintenance | Real-time monitoring systems, drilling simulations, safety protocols |
| China | 15% | Drilling operations simulation, performance assessment, equipment testing protocols | Simulation of drilling operations, development of testing protocols to enhance operational efficiency and safety |
| Vietnam | 10% | Safety training, risk mitigation, emergency response | VR applications for risk mitigation strategies, emergency response preparedness, safety assessment simulations |
| Singapore | 10% | Risk management, emergency response training, safety assessments | Virtual inspections, VR-based training programs for safety and operational efficiency |
| Malaysia | 8% | Safety culture, compliance, training programs | VR safety training simulations, risk management strategies, operational optimization methods |
| Australia | 8% | Safety training, risk management, operational optimization | VR applications for recreating real-world scenarios in oil and gas operations, situational awareness, collaborative decision-making |

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| | | | |
|---|---|---|---|
| Saudi Arabia | 8% | Upstream and downstream processes, operational efficiency, resource recovery | Reservoir modeling, well optimization, refinery process simulation |
| Germany | 7% | Supply chain logistics, human-machine interface, drilling operations | VR applications to enhance safety standards, workforce training, equipment maintenance |
| Africa | 6% | Safety regulations, operational efficiency, environmental management | VR technology for operational efficiency, hazard reduction in oil and gas infrastructure |
| UAE | 5% | Operational optimization, environmental monitoring, safety assessment | Virtual inspection tools, real-time monitoring systems, immersive training simulations |
| Canada | 5% | Safety assessments, regulatory compliance, environmental monitoring | VR simulations for safety assessments, regulatory compliance, environmental hazard mitigation |
| Brazil | 3% | Deep-sea exploration, subsea infrastructure maintenance, offshore platform safety | Applications for underwater environment simulation, virtual inspection, optimization of drilling operations for offshore infrastructure challenges |

## 5. Future Recommendations

Future recommendations include exploring the integration of VR with emerging technologies such as artificial intelligence and machine learning to enhance predictive maintenance and operational decision-making. Further research could focus on the development of standardized metrics and frameworks for assessing the impact of VR on operational efficiency and safety in the oil and gas sector. Additionally, expanding VR applications to support remote operations, emergency response training, and environmental monitoring could provide significant benefits. There is also a need for longitudinal studies to evaluate the long-term effectiveness of VR training programs and to explore cost-benefit analyses to justify broader adoption of VR technologies in the industry.

## 6. Conclusion

This research paper provides a comprehensive analysis of virtual reality (VR) applications in the oil and gas sector. Through the meticulous analysis of data from 217 citations using PRISMA techniques, the study conducted an exhaustive review of 66 studies of the applications of VR in this industry. Publications about VR infrastructure in the oil and gas sector have been steadily increasing since 2010, reaching a peak in 2022. There appears to be an increasing awareness of the possibilities of virtual reality technology to solve problems in the industry, particularly in the areas of risk, hazard, and safety assessment, as indicated by this upward trend. This distribution contributed from various countries highlights the considerable interest and participation on a global scale in investigating VR solutions for the oil and gas industry's infrastructure.

The article also highlights the value of virtual reality as a tool for tracking national infrastructures, and it does so using input from twelve different nations. Given that 47% of all VR apps are BIM-enabled, it's safe to assume that this technology is well-received and widely used in the industry. Additionally, the paper highlights the interdisciplinary character of virtual reality (VR) investigation in the oil and gas sector. Numerous authors integrate VR with additional analytical techniques to augment comprehension and insights across various domains within the industry infrastructure platform. The multiple advantages of VR technology in the oil and gas industry are highlighted by this interdisciplinary approach, which facilitates the resolution of complex issues and the optimisation of operations. Potential areas for future investigation include exploring the integration of VR with artificial intelligence for predictive maintenance, expanding VR applications for remote operations and crisis management, and developing standardized metrics for assessing VR's impact on operational efficiency and safety outcomes in the oil and gas sector.

However, this study has several limitations that need to be acknowledged. One major limitation is the reliance on published literature, which may not fully capture the most recent industry practices or proprietary innovations in VR technology that companies may be using internally. Additionally, the review is constrained by the quality and scope of the available studies, which may vary in terms of methodology and depth of analysis. Another limitation is the lack of longitudinal data that could provide insights into the long-term impacts of VR implementation on operational efficiency and safety outcomes in the oil and gas sector. To address these limitations, future research should focus on conducting longitudinal studies that track the adoption and outcomes of VR applications over time. It would also be beneficial to expand the scope of research to include case studies from companies that are early adopters of VR technology, providing real-world insights and lessons learned. Further exploration into the integration of VR with emerging technologies such as artificial intelligence and machine learning could also open new avenues for predictive maintenance and enhanced operational efficiencies. Additionally, developing standardized metrics and frameworks for evaluating the impact of VR on operational efficiency and safety would provide a more structured approach for future investigations and help in comparing the effectiveness of different VR applications across the industry.

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## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***study conception and design:*** *Ahmad Syazani Muda, Mohamad Farid Misnan;* ***data collection:*** *Ahmad Syazani Muda, Mohamad Farid Misnan;* ***analysis and interpretation of results:*** *Ahmad Syazani Muda, Mohamad Farid Misnan, Rosidah Sam, Mohd Azri Abdul Aziz;* ***draft manuscript preparation:*** *Ahmad Syazani Muda, Mohamad Farid Misnan. All authors reviewed the results and approved the final version of the manuscript.*

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