

Barriers to the Application of Digital Technologies in Construction Health and Safety: A Systematic Review

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Abstract: Construction is one of the most dangerous industries, with workers frequently exposed to hazardous environments, resulting in numerous occupational injuries and illnesses globally. While digital technology (DT) can improve construction health and safety management, there are barriers to its global adoption. This research examines these barriers in both developed and developing countries. A systematic review of 88 articles identified critical barriers, including technical issues, training and knowledge gaps, implementation challenges, data analysis limitations, and system efficiency problems. Standardising the use of new technology is challenging due to the constantly changing nature of construction projects. There is a lack of knowledge on increasing the use of DT in construction. Future research should focus on targeted strategies, pilot studies, and prioritising workers' health to overcome context-specific barriers and maximise the benefits of these innovative tools to prevent injuries and improve health and safety management.

Keywords: artificial intelligence; construction; digital technologies; health and safety; systematic review



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1. Introduction

Construction work is notorious for its hazardous, chaotic, and uncomfortable conditions. The International Labour Organisation (ILO) has recorded that construction workers are constantly exposed to risky substances, unsafe environments, radiation, noise, and vibrations [1,2]. Shockingly, in 2020, the overall cost of injuries in the construction industry increased by 34% compared to 2018, and the fatal injury rate in this industry is four times higher than in other sectors [3]. These alarming statistics highlight the pressing need for improved construction health and safety (H&S) protocols, which remain a global concern. Researchers have challenged the traditional approach to construction H&S management, deeming it insufficient to ensure construction workers' well-being [4,5]. They have proposed more sophisticated techniques, such as digital innovations, including wearables, artificial intelligence (AI), augmented reality/virtual reality (AR/VR), and building information modelling (BIM), to enhance construction H&S practices [6].

The potential of digital technologies in advancing H&S procedures is significant and has been demonstrated in recent years [7]. For example, smart wearables can monitor an employee's heart rate, physical position, and fatigue levels, and issue alarms when necessary [8]. Machine learning algorithms can proactively identify and minimise hazards by analysing patterns in historical incident data [9]. Digital twins and immersive simulations can provide workers with realistic training environments without exposing them to actual risks [10]. Despite these clear benefits, the adoption of digital technologies in the construction industry has not been widespread. The Smart Market Report reveals that only

47–71% of businesses in wealthy nations, including the United States (US), United Kingdom (UK), Germany, and Singapore, have implemented digital solutions, while a mere 4–13% of businesses in emerging economies have carried out the same [11]. This low adoption rate can be attributed to various barriers, such as a lack of leadership support, inadequate IT infrastructure, cybersecurity hazards, low awareness of the benefits, technical skills gap, and costly software and hardware [12,13].

Various studies have explored the barriers to the application of digital technology (DT) in managing construction H&S [14–16], with some focusing on technical concerns or training deficiencies in developed countries [17–20], and others highlighting financial and infrastructure limitations in developing nations [12,21,22]. However, none have attempted to compare these barriers in developed and developing countries, leaving a knowledge gap in understanding the universal and context-specific obstacles. This review aims to fill this gap by consolidating research findings from both perspectives, revealing critical differences and common challenges. Therefore, the current study employs a systematic literature review (SLR) to present the state-of-the-art barriers to DT implementation in construction H&S. To guide this review, four research questions were formulated:

RQ1: What is the growth of DT health and safety management studies in developed and developing countries?

RQ2: What is the research focus on the use of DT in health and safety?

RQ3: What are the current barriers to using DT to manage health and safety in the construction sector of developed and developing countries?

RQ4: What differences exist between the barriers to applying DT in managing health and safety in the construction sector of developed and developing countries?

This study contributes to both practice and academia by providing a foundation for future quantitative research to identify critical barriers to DT applications in specific contexts. It offers insights into the differences in barriers between developed and developing countries, enabling targeted strategies for promoting adoption worldwide. This study highlights the need for contextualised approaches to overcome obstacles in different settings. Also, some key findings include the following: The barriers to adopting DT in H&S management were categorised into five main areas: technical issues, training and knowledge, data analysis and system limitations, implementation challenges, and efficiency challenges. Developed countries face issues such as technical compatibility problems, high implementation costs, and lack of client demand for newer digital interfaces. Developing countries encounter more significant challenges due to financial constraints, lower digital literacy levels among construction professionals, inadequate infrastructure, and equipment standardisation issues.

Both developed and developing countries face knowledge gaps that require worker-training programs, but the extent and nature of these gaps differ.

2. A Review of Construction Health and Safety Research

2.1. Global Perspectives on Construction Health and Safety

The issue of health and safety in the construction industry has drawn global attention due to its high rates of occupational injuries and fatalities. According to Bagir et al. [1], the construction sector surpasses other industries in risk factors such as incorrect posture, heavy machinery, falls from heights, heavy lifting and carrying, and poor weather and wind conditions. Furthermore, Nnaji and Karakhan [19] emphasised the importance of prioritising the well-being of the construction workforce, as they play a vital role in producing high-performance buildings and civil works. This concern is reflected in the latest statistics by the U.S. Bureau of Labour Statistics (BLS), which reported 5333 fatal occupational accidents in 2019, with 1061 occurring in the construction industry [23]. Similarly, Eurostat data from 2018 highlight the severity of the issue, with 3332 fatal incidents recorded in Europe, where one-fifth of those were in the construction industry [24]. These alarming figures demonstrate the urgent need for global strategies to ensure the health and safety of construction workers.

2.2. Barriers to the Application of DT in Construction Health and Safety Management

The construction industry has lagged behind other industries when implementing new technologies like digital platforms to enhance health and safety management [19]. This gap offers a tremendous opportunity because implementing this cutting-edge technology can significantly improve construction site compliance monitoring, risk minimisation, and accident prevention [25]. Wider adoption is, however, hampered by many essential obstacles. According to Asadzadeh et al. [26], the lack of technical training on various DTs for workers and their supervisors is one of the biggest problems. Compared to other industries, the workforce in this industry is typically older and has lower levels of education and computer literacy [27].

Workers also lack interest due to data privacy issues. According to Häikiö et al. [28], construction workers hesitate to adopt digital technologies due to identity disclosure and related data privacy issues. Most lack experience with digital devices, analytics software, and other emerging technologies essential for the digital transformation of safety procedures [29]. Researchers like Zhou and Ding [30] believe some challenges arise from physical interaction with technologies. They stated that wearable technology and its high-tech solutions make it difficult for workers to interact physically.

Furthermore, problems of poor or inadequate policies have been stated as a hindrance. Huang et al. [31] stated that despite the government's numerous efforts and investments in research and development (R&D) to enhance technology, policies and incentive initiatives remain unclear. Given these barriers, researchers like Eigege et al. [32] highlight the need for extensive worker training and change in management before peak performance can be reached.

These barriers include the need for significant computing power and issues with scalability [33]. Researchers like Abioye et al. [34] have highlighted the high initial cost associated with deploying wearable technologies, robotics and machine learning systems, stating that investing in these technologies sometimes comes with hefty upfront expenses and the maintenance requirements for such solutions must also be considered. Roy et al. [35] and Igual et al. [36] reported performance limitations in real-life conditions, complexity of use, and limited acceptance.

Bughin et al. [37] also expressed the hinderance of cost, stating that most subcontractors and small enterprises, which make up a significant percentage of the construction sector, may be unable to pay the required amount for these technologies. According to EY and MIT [38], currently, there is a global lack of AI engineers with the necessary abilities to spearhead substantial advancement across industries. Recruiting engineers with construction industry experience to develop specialised solutions to address the sector's myriad issues is challenging [34].

Furthermore, other researchers like Winfield and Jirotko [39] believe that the ethics and governance associated with rolling out DTs in the construction sector is unclear. They stated that establishing and maintaining public trust in technologies like AI requires participatory, transparent, and agile governance. This is a critical issue that affects the entire society. While these technologies offer potential benefits, they can also threaten construction workers if they are not properly governed. However, studies have suggested that involving clients can help enhance technology acceptance in construction H&S management [19].

3. Materials and Methods

A systematic literature review (SLR) was utilised in the current study to examine the body of knowledge regarding the junction of the terms "Virtual reality", "Augmented reality", "Digital technology", "Machine learning", "Artificial Intelligence", "Health and safety", and "Construction Industry". According to Moher et al. [40], SLR entails the persuasive compilation of all data pertinent to a specific field of study to find answers to research questions. Using straightforward techniques, a systematic review reduces prejudice by identifying gaps and new directions for further research, according to Abam et al. [41]. SLR is an effective tool for distilling built environment research. Topics like status

and emerging research trends in construction safety, as in the work of Akinlolu et al. [2], lean-offsite-simulation nexus for housing construction, reported in the work of Daniel and Oshodi [42], and digital technologies in the architecture, engineering and construction (AEC) industry, such as in the work of Manzoor et al. [43], have all made use of SLR. Due to the significance of the reproducibility of results, SLR is suitable for answering the research question presented in this paper's introduction.

The steps of the SLR used in this study include identifying relevant keywords, searching relevant databases, filtering search results based on inclusion criteria, and content analysis of the papers that satisfied the inclusion criteria. The data collected from the fourth stage addressed the study question mentioned in the introduction.

Figure 1 represents a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram, which shows the procedure utilised for the SLR. The PRISMA flow diagram is a commonly used tool in systematic reviews and meta-analyses to depict the research selection process [44]. It gives a clear visual picture of the literature search and screening process. The PRISMA flow diagram generally consists of four major sections:

Identification: this section displays the number of records found via database searches and other sources.

Screening: it shows the number of records after duplicates are deleted, as well as the number of records that were screened and excluded.

Eligibility: this section indicates the number of full-text articles evaluated for eligibility and the number that were excluded, along with their explanations.

Included: The last part provides the number of studies included in the qualitative synthesis and, if relevant, the quantitative synthesis (meta-analysis). Haddaway et al. [45] also expressed that the figure explains how researchers selected their final set of included papers, ensuring transparency and reproducibility in the review process.

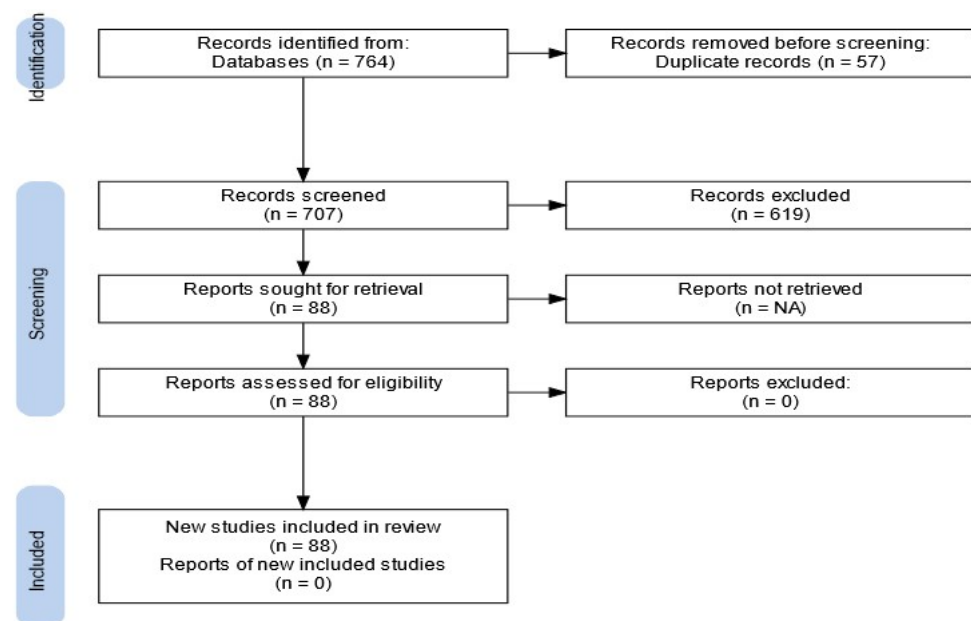


Figure 1. PRISMA flow diagram.

3.1. Search Keywords: Identification

Seven keywords were initially determined for the database search based on the study topic, i.e., ("Virtual reality", "Augmented reality", "Digital technology", "Machine learning", "Artificial Intelligence", "Health and safety", and "Construction Industry"). Various terms (such as immersive technology and serious gaming) are used interchangeably with virtual and augmented reality in digital technology for construction H&S management literature. The keywords used for searching relevant databases were based on similar phrases

and synonyms for the construction sector and occupational H&S that were identified in earlier literature review investigations [2,46–49]. Table 1 displays the search terms used for the database search.

Table 1. Keyword search combination.

Keyword Combination	Scopus Number of Papers	WoS Number of Papers
“digital technology” AND “health and safety” AND “construction industry” OR “building industry” OR “construction sector” OR “construction company”	22	7
“virtual reality” OR “augmented reality” AND “health and safety” AND “construction industry” OR “building industry” OR “construction sector” OR “construction company”	35	255
“machine learning” OR “artificial intelligence” AND “health and safety” AND “construction industry” OR “building industry” OR “construction sector” OR “construction company”	52	393
Total	109	655

3.2. Data Collection

A thorough search approach was used to search the relevant databases to ensure all pertinent studies were found. Scopus and Web of Science (WoS) were the databases used in this study. According to Pranckutė [50], WoS and Scopus are the most trustworthy and legitimate data sources and are multidisciplinary and selective bibliographic databases. Li et al. [51] and Dobrucali et al. [52] also stated that WoS and Scopus are extensive publications and citation databases and used them while conducting similar research. These two databases were enough to search for pertinent documents, ensuring this study’s results are replicable. Table 1 displays the keyword combinations that were utilised in the database search. Table 1 presents a summary of the search results. A total of 764 published studies from the WoS and Scopus databases were found after the search. According to the bibliometric search, the earliest paper on digital technologies in construction H&S was published in 2005 and 1997 for Scopus and Web of Science, respectively. Hence, the time range was limited to 2005 to the present in Scopus and 1997 to the present in WoS.

3.3. Filtering of Search Results

The inclusion and exclusion criteria were used to filter the first search results, like samples. Implementing this screening method guaranteed the sample to be free of irrelevant studies. There were two phases to the filtering procedure. Initially, each paper (i.e., 764 (109 from Scopus and 655 from WoS search) journal articles and conference proceedings papers) had its title and abstract read. The sample did not include 676 (351 journal articles and 325 conference proceedings) out of the 764 items found during the search phase. The following were the grounds for exclusion:

Overlapping results from the Scopus and WoS searches; 57 (34 journal articles and 23 conference proceeding articles) duplicates were eliminated from the data obtained.

Purpose of the identified studies.

The current review focuses on using digital technology in H&S construction management. Studies that concentrated on using these approaches for other projects were therefore disregarded. Hence, 707 papers were screened and 619 articles (315 journal articles and 304 conference proceedings articles) were excluded because they were not directly relevant to digital technology in H&S construction management studies.

Therefore, 88 documents were analysed in this study at the end of the first filtering stage (56 journal articles and 32 conference proceedings articles). Secondly, the full text of the 88 articles was read to ensure that the inclusion criteria (i.e., the focus of the study) were met, which means that at the end of the filtering process, the 88 articles remained in the search results and were used for the research analysis.

The 619 studies that were not directly relevant to digital technology for H&S construction management domain were rather related to other aspects of the application of digital technology in construction and were categorised in Table 2, as carried out in a recent study by Çevikbaş and Işık Z [53].

Table 2. Categorisation of objectives of omitted documents obtained from Scopus Database and Web of Science Database.

Objectives of Digital Technology in Construction	Number
Building Information Modelling (BIM)—Improve project coordination	115
Building Information Modelling (BIM)—Enhance visualisation	122
Internet of Things (IoT)—optimise energy consumption	119
Artificial Intelligence (AI) and Machine Learning—Predict project outcomes	48
Artificial Intelligence (AI) and Machine Learning—Automate repetitive tasks	43
Artificial Intelligence (AI) and Machine Learning—Optimise resource allocation	38
Virtual and Augmented Reality (VR/AR)—Enhance design visualisation	40
Virtual and Augmented Reality (VR/AR)—Facilitate remote collaboration	31
Robotics and Automation—Increase productivity	10
Robotics and Automation—Improve quality control	6
3D Printing and Additive Manufacturing—Reduce material waste	9
3D Printing and Additive Manufacturing—Enable complex geometries	4
3D Printing and Additive Manufacturing—Accelerate prototyping and production	7
Drones and Unmanned Aerial Vehicles (UAVs)—Conduct site surveys	10
Drones and Unmanned Aerial Vehicles (UAVs)—Monitor progress	6
Big Data Analytics—Improve decision-making	5
Big Data Analytics—Optimise project planning	3
Cloud Computing and Mobile Technologies—Enhance project management	3
Total	619

3.4. Qualitative Content Analysis of Search Results

A thorough qualitative content analysis was conducted on the 88 relevant articles. The predetermined study objectives mentioned in the introduction were considered when analysing the qualitative content data. The qualitative content analysis started by giving code numbers (i.e., 01 to 88) to papers that met the selection criteria. The coded papers were read to address the research objectives. For improved visualisation, a portion of the qualitative content results were quantified; more specifically, Figures 2 and 3 provide a summary and presentation of the study's findings, which are discussed in Section 5.

Developed and Developing

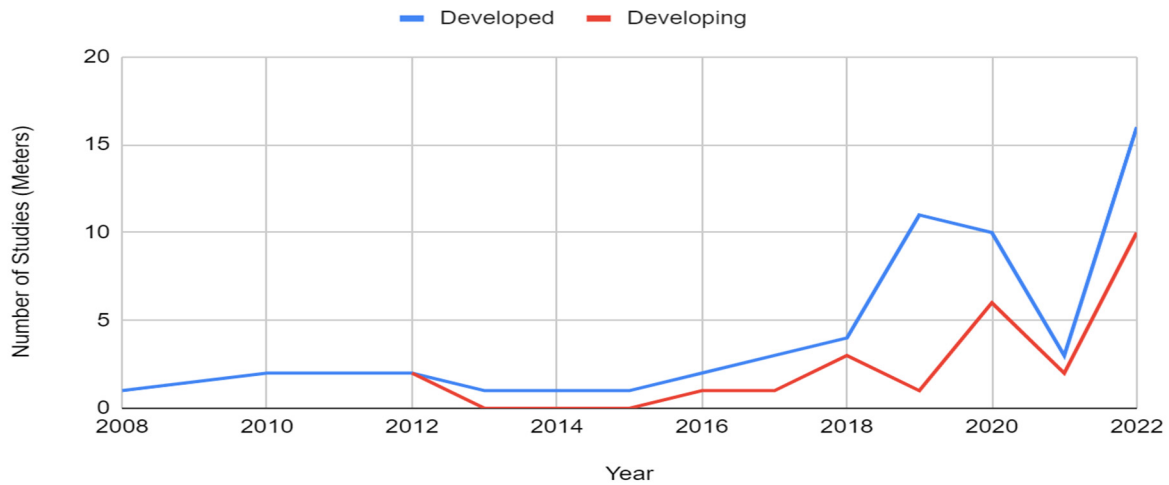


Figure 2. Distribution of digital technologies studies in health and safety management in developed and developing countries.

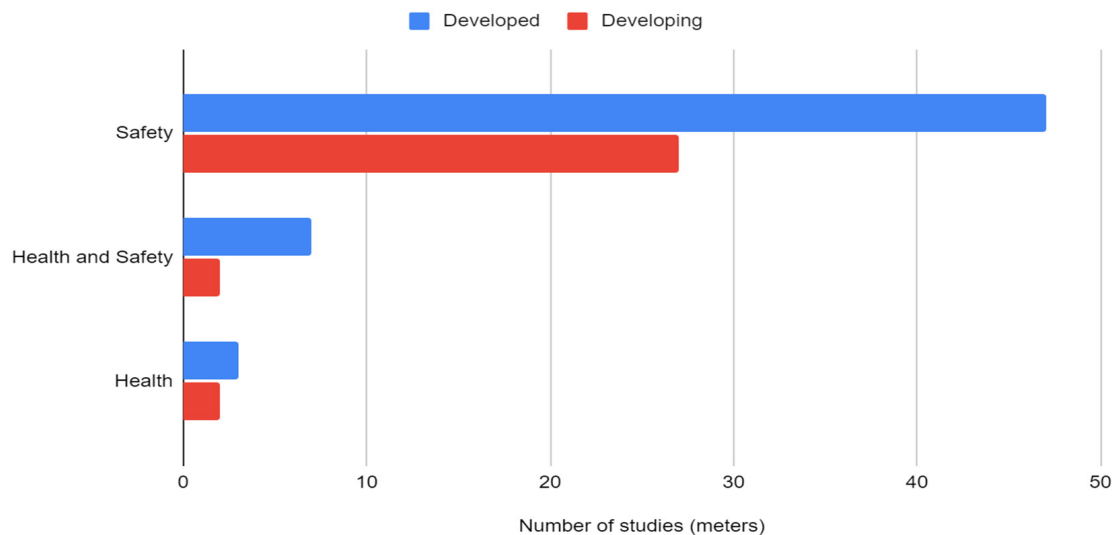


Figure 3. Distribution of study focus area in the application of digital technology in construction health and safety management; developed and developing countries.

Additionally, Figure 4 represents a thematic mapping of the barriers in developed and developing countries from the results of Section 4. This was carried out through developing themes, i.e., thematic analysis. According to Braun and Clarke [54], thematic analysis entails finding, analysing, and reporting patterns (themes) in data. It is very beneficial for analysing and making sense of big qualitative datasets. Various techniques, such as inductive (data-driven) or deductive (theory-driven), can be used in interpreting the data [54–57]. This method was therefore used to identify and group the various barriers in the relevant articles through a systematic review and thematic analysis as seen in Sections 4.1 and 4.3. The list of authors and publication year for each article (88) are presented in the Appendix A, with Table A1 for developed and Table A2 for developing countries.

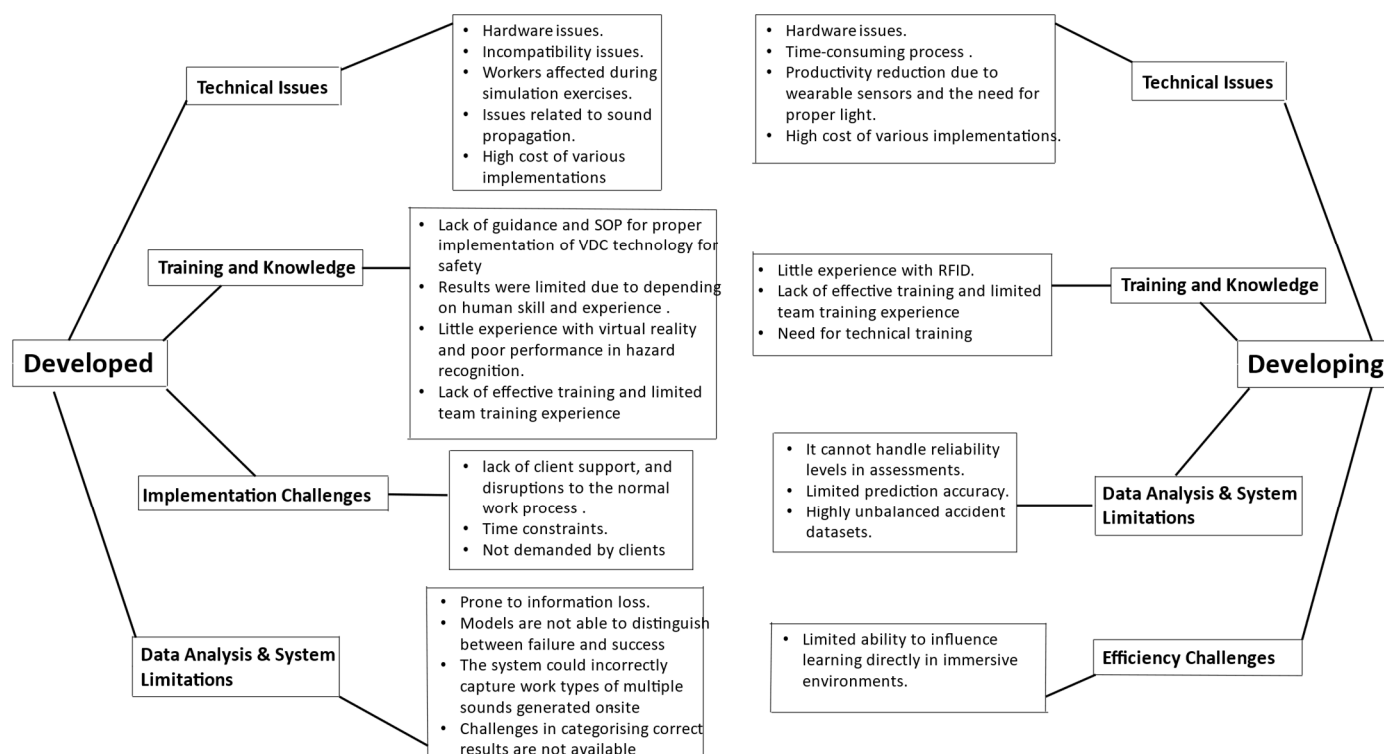


Figure 4. Mapping of the barriers to DT application in construction health and safety management in developed and developing countries.

4. Results

4.1. DT in Health and Safety Management Studies in Developed and Developing Countries

Figure 2 shows the distribution of the growth DT studies in developed and developing countries. Figure 2 reveals that although the publication on DT started about 2008 it was not until 2012 that DT studies begin to gain attention in developing countries. The figure also revealed that the studies on the use of DT has been on the increase post-covid in both developed and developing countries.

4.2. Barriers to Applying DT in Health and Safety Management in Developed Countries

These barriers in developed countries include technical issues, training and knowledge, implementation challenges, data analysis and systems limitations.

4.2.1. Technical Issues

Various technical barriers relating to virtual reality technology were identified as one of the primary barriers developed countries face in applying DT in construction health and safety management. This was noted in a study by Nykänen et al. [58], who opined that during simulation tests, hardware issues like the VR headset and the computers interacting with them could be incompatible due to their different service providers. Also, Klempous et al. [18] highlighted issues relating to poor sound propagation and reflection in a 3D environment, stating the need for appropriate implementation of physical properties in virtual environments to represent real-world settings and the right solutions to the problem of acoustic waves in a virtual environment.

Technical issues related to the well-being of workers were also noted. Li et al. [59] and Getuli et al. [10] stated that workers are affected during simulation exercises and are at risk of dizziness and vertigo during more extended hours of using the VR software, which poses a risk to their performance output and a barrier to technology use. Furthermore, other researchers highlighted technical issues relating to the cost of implementation. According to You et al. [60], regardless of the benefits that improved site automation could offer to

such a labour-intensive sector, the high implementation cost of human–robotics interaction tests and training in a virtual environment limits their adoption. At the same time, Azhar [61] highlighted the additional cost of developing a BIM model while presenting case studies that investigated the effectiveness of visualisation technologies in developing communication and implementation of construction site safety plans.

4.2.2. Training and Knowledge Barrier

The training and skill acquisition needed to appropriately use digital technologies in construction health and safety in developed countries has become a significant hurdle for construction workers. It has been highlighted by various researchers in the literature. Rwamamara et al. [17] stated that while using testing visualisation technologies for designing and planning a healthy construction workplace in Sweden, the results were limited due to the dependence on human skills and their inexperience with digital technologies. Secondly, Peña and Ragan [62] stated that, at the moment, the majority of construction workers are accustomed to standard mouse and keyboard interfaces but have limited experience when it comes to virtual reality for safety training. Also, Shafiq et al. [63] stated that there is a lack of knowledge and adequate training regarding digital technologies like virtual design construction (VDC), which impedes the use of these technologies to improve job-site safety and expressed the need for construction industries in regions like the United Arab Emirates (UAE) to push the training and education aspects of these technologies. Lastly, Wolf et al. [64] stated that during the implementation and testing of technologies like an augmented virtuality (AV) environment, the results showed that many participants performed poorly during hazard recognition and overestimated their safety performance due to their lack of experience handling this system and expressed the need for assisting workers with step-by-step training to identify hazards.

4.2.3. Implementation Challenges

The need to use digital technologies in construction health and safety has been frequently highlighted in the literature. Nevertheless, sometimes, these technologies have various complexities that might hinder their adoption, and various researchers have expressed this. According to Shafiq et al. [63], one of the primary reasons for the limited implementation of digital technologies in construction safety is the lack of demand from clients. It was stated that when these technologies do not have their technological implications reinforced, stakeholders will not be actively involved in its execution. Hoang et al. [65] stated that time constraints related to the complexity of virtual reality training exercises, like fear arousal, limit the completion of various related tasks for training and analysis of worker's skills in Australia, which limits its adoption by workers and sometimes corporations. Furthermore, McKinsey [66] noted that workers believe that these digital technologies caused a disruption to normal working processes, which, in turn, majorly hinders adoption.

4.2.4. Data Analysis and System Limitation

Digital technologies in construction health and safety management are efficient tools for producing reliable and effective results during application, analysis or testing. Nevertheless, sometimes, these technologies do not perform as expected or are prone to unreliable data. According to Jeon and Cai [67], digital technologies like an electroencephalogram (EEG) are effective tools for reducing data size and visualising high-dimensional data in an easy-to-understand way. Nonetheless, they are prone to information loss because they frequently overestimate feature similarity while underestimating the extent of extrapolation [68]. In a study conducted by Lee et al. [69], while looking at an audio-based system that pre-notifies on safety issues and detects accidents on construction work sites, they quickly noted that the technology classifies sounds that are similar to each other, hampering sound classification due to different brands and manufacturers of equipment for the same tasks making different noises, which led to the system incorrectly capturing work types of multiple sounds generated on-site, hindering reliable accident predictions. Also,

Zhang et al. [70] noted, while applying machine language to analyse construction accident reports in text format successfully, that misclassification was a problem, stating that due to the dynamic characteristics of the natural language, sentences of the same meaning can be expressed differently and therefore developing exhaustive rules to cover all variations is not feasible leading to consequences like particular objects in the documents going missing and some extracted objects not being legitimate. Vagueness in natural language is typical in the results, and it was challenging for humans to identify the object which caused the accidents in some cases.

4.3. Barriers to the Application of DT in Health and Safety Management in Developing Countries

These barriers in developing countries include technical issues, training and knowledge barrier, data analysis and system limitations and efficiency challenges.

4.3.1. Technical Issues

Various technical barriers relating to digital technology were identified as one of the primary barriers developing countries face in applying DT in construction health and safety management. Yang et al. [22] expressed the cost relating to technologies like health quick response (QR) code adoption in China during the COVID-19 pandemic, stating that the high initial cost of the health QR codes software and hardware, in addition to their implementation cost, was a significant barrier to its adoption. Other researchers like Tabatabaee et al. [71] noted physical discomfort in construction workers with certain digital technologies; in their study, they stated that while construction workers made use of wearable safety technologies, they experienced awkward working postures, which led to non-fatal occupational injuries, which, in turn, resulted in poor construction productivity, hence affecting the overall project performance negatively. Also, in a study conducted by Costin et al. [72], where they focused on an IOT-based indicator for construction safety, the authors highlighted the fact that this field of study is still emerging and there is a lack of standardisation efforts, which has led to a limitation on both hardware and software applications. Furthermore, in a study carried out by Sarkar et al. [21], while focusing on predictive models for the prediction of the occurrences of slip-trip-fall (STF) accidents in construction work sites, the authors stated that at the data pre-processing stage, extensive human labour is needed to sanitise the data for analysis, which is a time-consuming process limiting its adoption.

4.3.2. Training and Knowledge Barrier

While speaking on the opportunities and challenges associated with adopting digital technologies in health and safety management in the South African construction industry, Malomane et al. [13] noted that the lack of experience associated with implementing digital technologies for health and safety among construction professionals is one of the primary reasons these technologies are rarely adopted in the industry. Osunsanmi et al. [73] also noted that although digital technologies like RFID help in monitoring the safety of construction workers, the low level of technical experience has hampered its adoption. This view was shared by Ikuabe et al. [74], who claimed that there is still a lack of knowledge about digital technologies in the building industry. Okpala et al. [8] asserted that proper technical training for workers and owner involvement are required to work safely with sensor functions.

4.3.3. Data Analysis and System Limitation

Various researchers highlighted the limitations of implementing machine language-based models in managing construction health and safety. In a study by Sadeghi et al. [75], where they looked at a predictive safety risk assessment model to assess the OHS risks related to workers on construction sites in Malaysia, the authors noted that although the model can account for expert perceptions of uncertainty, it is unable to account for the degree of reliability in the evaluations that the corresponding safety experts provide,

which is a significant limitation to the model's adoption. In Gan et al.'s [9] study, while exploring an automated machine language (ML) system that automatically trains and evaluates different ML to select the most accurate ML-based construction accident severity predictors for the use of construction professionals, the authors stated that the automated severity classifiers experiment with highly unbalanced accident datasets. They noted that this reduces or limits the prediction accuracy. Also, in Koc et al.'s [76] study, the authors stated that they experienced limited prediction accuracies while trying to predict occupational accident outcomes based on national data using ML coupled with several resampling strategies.

4.3.4. Efficiency Challenges

There have been a few limitations regarding the usefulness of digital technologies like VR in construction health and safety management in developing countries. Md et al. [77] expressed their concern regarding virtual reality immersion, stating that although virtual reality simulation is beneficial by being immersed in the simulation and encourages engagement that could lead to improvements in procedural skills and knowledge, the learning process for construction workers is unable to be mediated by immersion due to immersion being misinterpreted, especially by first-time users of VR, concluding that immersion may not be able to encourage active learning because it focuses on passive learning or simulation.

5. Discussion

5.1. Growth of DT in Construction Health and Safety Management Studies in Developed and Developing Countries

Figure 2 presents a dataset showing the number of studies published on DT, such as virtual and augmented reality, wearables, BIM, etc., in H&S management in construction engineering and management in developing and developed countries over 15 years. These data indicate the growing interest in integrating DTs in the construction industry, especially in H&S management. From the data, it is evident that there is a significant increase in the number of studies published on DT in the construction industry, particularly in developed countries. In 2019, 11 studies were published in developed countries compared to only 1 in developing countries. The trend continues to increase, with 16 studies published in developed countries in 2022 compared to 10 in developing countries. This may indicate that developed countries are more advanced in using DT in the construction industry and conduct more research in this area. The emergence of COVID-19 in this period also contributed to increasing the volume of research on the use of DT. According to Elrefaey et al. [78], COVID-19 served as a catalyst for the use of various types of innovative technology in the construction sector.

Another significant trend to note is the narrowing gap between the number of studies published in developed and developing countries. In 2020, the difference was only four, indicating a more balanced distribution of research efforts. This could be attributed to the increased use of DT in developing countries and the growing recognition of its potential benefits in the construction industry. A noteworthy observation is the dip in studies published in developed countries in 2015 and 2016, which could be a result of the global economic crisis impacting research funding. However, the number of studies quickly rebounded in the following years, underscoring the resilience and importance of DT research in the construction industry.

Furthermore, the data show that most studies are conducted in developed countries, even though the construction industry is one of the fastest-growing industries in developing countries [77,78]. This could be attributed to the fact that developed countries have more resources and expertise in conducting research and a higher demand for innovative technologies to improve the efficiency and safety of their construction projects. Also, developed countries are quicker at adopting innovation and new technologies. These data suggest a growing interest in integrating DT for H&S management in the construction industry.

However, there is still a significant gap between the studies conducted in developed and developing countries. This underscores the urgent need for more research in developing countries to bridge the knowledge and technology gap in the construction industry.

5.2. Distribution of Research Focused on Applying Digital Technology in Construction in Developed and Developing Countries

Figure 3 compares the number of studies in developed and developing countries that focused on digital technologies being used to manage the health, safety or the health and safety of construction workers in the construction industry. The data show that developed countries dominate in either of the focus areas, with 47 related studies, while developing countries have 27. Developed countries have three associated studies focusing on digital technology for construction health management. In contrast, developing countries have two, and for studies focused on digital technology used for construction health and safety management, developed countries have seven related studies while developing countries have two. Developed countries dominating this study focus area may be partly due to developed countries generally conducting more research, as shown in Figure 2.

Figure 3 shows that both developed and developing countries placed a greater emphasis on safety than health or a combination of both. This could be due to global statistics highlighting more safety concerns, such as incorrect posture, heavy machinery accidents, and falls from heights, compared to health issues like fever or mental exhaustion among construction workers [23,24]. However, this does not mean that managing construction health is not essential, as worker productivity is also affected when they are not in good health. Mental exhaustion during prolonged use of equipment is a common cause of accidents, leading to decreased productivity and even severe injuries or fatalities on construction sites [10]. Thus, future research must focus on utilising digital technologies to manage the health and well-being of construction workers. Additionally, there is no significant difference between developed and developing countries regarding their focus on either health and safety or solely health. This suggests that both countries have similar approaches to studying these areas. Nevertheless, there is a need for more research on the combination of health and safety as they are closely intertwined, and effectively managing both is crucial for economic growth, productivity, and high standards within the construction industry.

5.3. Barriers to Applying DT for Health and Safety Management in the Construction Sector of Developed and Developing Countries

The barriers to adopting DT for health and safety management differ between developed and developing countries, as shown in Figure 3. While both face technical challenges, developing countries encounter more financial and infrastructural limitations. Knowledge gaps impede implementation across contexts, though training deficiencies are more pronounced in developing regions [13,73]. Data reliability issues emerge in both settings, yet developing countries report lower prediction accuracies, likely reflecting poorer quality inputs [75,79].

Technical obstacles arise in developed and developing contexts, including incompatible hardware, software costs, and worker discomfort [18,22,68,69]. However, developing countries report more financial barriers to acquiring and implementing technologies. The high cost of software, hardware, and system integration expenses strain budgets [21,22]. Insufficient standards also hinder developing countries' adoption of newer innovations like wearables and IoT sensors [69]. Given their more robust economic standing, advanced economies may better absorb these expenditures.

Training and knowledge gaps impede the use of DT in both settings. Developed countries face inexperience with newer interfaces like virtual reality [58,63]. Meanwhile, developing regions lack digital literacy among construction professionals [13,74]. This likely reflects poorer access to technology education. While training programs could close these gaps, developing countries may struggle to implement comprehensive upskilling.

Data analysis and prediction issues emerge across contexts. However, studies suggest lower reliability in developing country applications. Data deficiencies reflect their poorer data infrastructure, yielding insufficient quality or coverage inputs to train predictive models well [9,76]. Developed regions still encounter issues like sound misclassification, but their more robust data systems provide higher-quality training data [72,75].

Lastly, developed contexts question the learning value of immersive simulations, given the disorientation among new users [17,76] and the implementation challenges, such as lack of client demand and disruptions to workflow [65,66]. Meanwhile, developing countries report uncertainty about virtual reality's implementation benefits and struggle more with efficiency issues like passive learning in virtual environments, likely due to their limited exposure to pilot demonstrations [77]. While some implementation barriers are common across settings, developing countries face more pronounced economic and infrastructural limitations. Targeted financial assistance and training programmes could help narrow these digital divides.

6. Future Research Direction

Based on the systematic literature review of 88 articles, some potential future research directions to further advance the application of digital technologies for construction health and safety management were identified:

Developing targeted strategies to address context-specific barriers in developed vs. developing countries: This review highlighted vital differences in obstacles faced by advanced and emerging economies. Further research could identify approaches tailored to overcoming the unique technical, financial, knowledge, and data challenges faced in each setting [2,13,73]. This can enable appropriate capacity building.

Pilot and demonstration studies should be conducted: Limited exposure to real-world testing of new technologies hinders uptake, especially in developing regions. Additional on-site trials and demonstrations could provide the needed evidence to convince stakeholders of implementation benefits [10,75,77] and give insights into refining tools for greater efficiency and user comfort.

Examination of impacts on occupational health: The existing literature concentrates on safety management, but opportunities likely exist to use AI-based platforms to improve worker occupational well-being, fatigue, and ergonomics through biometric monitoring and predictive analytics [51,80,81]. This deserves more attention. Future research should emphasise integrating health management, including mental health and overall well-being, into DT applications. This involves exploring technologies that monitor and enhance workers' health conditions, such as wearable devices that track physiological parameters and predict health risks.

7. Conclusions

This systematic literature review aimed to identify the barriers to adopting digital technologies (DT) and enhancing construction health and safety management practices. After analysing 88 relevant articles, this study identified and categorised barriers to adopting DT into five categories: technical issues, training and knowledge, data analysis and system limitations, implementation and efficiency challenges. This study reveals that the barriers to DT in health and safety management in developed and developing countries occur under similar categories at the facial level. However, further analysis shows variations in how they manifest or occur in developed and developing countries.

The significant hurdles in developed nations included technical compatibility issues, high implementation costs, and a lack of client demand for newer digital interfaces, including knowledge gaps that required worker training programmes. On the other hand, developing countries faced even more significant challenges due to financial constraints and lower digital literacy levels among construction professionals, hindering technology adoption. Additionally, inadequate infrastructure and record-keeping in developing

countries amplified data quality issues, and equipment standardisation challenges further hindered progress.

The findings highlight the urgent need for targeted strategies to bridge the digital divide and promote the use of innovative safety tools globally. This includes providing funding mechanisms and comprehensive training programmes for developing countries and implementing change management programmes to promote technology acceptance. Additionally, pilot testing and demonstrations could showcase the benefits of digital technologies in construction health and safety. Despite the potential benefits of digital innovations, their adoption has been limited by context-specific barriers, which must be overcome through targeted interventions to fully realise their potential in safeguarding construction workers globally.

The systematic literature review provides valuable insights into the barriers hindering the application of digital technologies (DT) for enhancing construction health and safety management globally. This research highlights how obstacles differ across settings by comparing developed and developing world contexts. This enables targeted strategies to promote adoption worldwide.

A significant contribution is the comprehensive identification of critical barriers constraining innovative tools like virtual reality, wearables, and machine learning algorithms to prevent workplace accidents in the hazardous construction sector. This study analyses 88 relevant articles to categorise technical, training, implementation, efficiency, and data reliability challenges. The identified barriers would support future research in the use of digital technologies in health and safety management in the construction sector. For instance, the data aggregated in this would support future quantitative research via a questionnaire to identify critical barriers to DT applications in a given context.

Additionally, the research reveals pronounced barriers in developing countries, including financial and infrastructure limitations that obstruct technology acquisition and training. Developed nations also face knowledge gaps and data quality issues. However, developing regions exhibit lower digital literacy and predictability from poorer inputs. This study provides actionable insights to spur global progress by distinguishing key contextual differences. Developing countries require more financial assistance and training programmes to bridge digital divides. However, even advanced economies need targeted training and change management to address lingering adoption barriers.

However, this study is limited to the Scopus and Web of Science databases and is restricted to English-language publications. Future research should explore additional databases. More empirical studies should be undertaken to demonstrate the benefits that could motivate clients and owners to invest in using digital technology infrastructure for health and safety management in the construction sector. Furthermore, future research should explore the potential of DT in advancing worker health monitoring and fatigue prediction. Wearable sensors and machine learning models offer opportunities to improve occupational well-being.

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Data Availability Statement: Data are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Barriers in the application of digital technologies in construction health and safety management in developed countries.

Authors	Year of Publication
Nykanen, M; Puro, V; Tiikkaja, M; Kannisto, H; Lantto, E; Simpura, F; Uusitalo, J; Lukander, K; Rasanen, T; Heikkila, T; Teperi, AM	2020
Bokary, S; Connolly, TM; Bennett, P; de Vries, M; Lawrie, J; Wilson, N	2017
Roslón, J; Nical, A; Nowak, P	2018
Nykanen, M; Puro, V; Tiikkaja, M; Kannisto, H; Lantto, E; Simpura, F; Uusitalo, J; Lukander, K; Rasanen, T; Teperi, AM	2020
Lopez, JG; Lopez, AG	2014
Shafiq, MT; Afzal, M	2020
Albeaino, G; Brophy, P; Gheisari, M; Issa, RRA; Jeelani, I	2022
Li, WW; Huang, HK; Solomon, T; Esmaeili, B; Yu, LA	2022
Klempous, R; Kluwak, K; Idzikowski, R; Nowobilski, T; Zamojski, T	2017
Jacobsen, EL; Solberg, A; Golovina, O; Teizer, J	2022
Jeon, J; Cai, HB	2021
Peña A.M.; Ragan E.D.	2017
Mendes, E; Albeaino, G; Brophy, P; Gheisari, M; Jeelani, I	2022
Roofigari-Esfahan, N; Porterfield, C; Ogle, T; Upthegrove, T; Jeon, M; Lee, SW	2022
Soeiro, A; Martins, JP; Zavrski, I; Theodossiou, N; Meszaros, P; Sidani, A	2020
Mo, Y; Zhao, D; Du, J; Liu, WH; Dhara, A	2018
Bao, L; Tran, SV; Nguyen, TL; Pham, HC; Lee, DM; Park, C	2022
Eiris, R; Dover, K; Gheisari, M	2022
Ahn, S; Kim, T; Park, YJ; Kim, JM	2020
Wolf, M; Teizer, J; Wolf, B; Buekrue, S; Solberg, A	2022
Jeelani, I; Albert, A; Han, K	2020
Li, H; Chan, G; Skitmore, M	2012
Miller G.A.; Dawood N.N.; Kassem M.	2012
Getuli V.; Capone P.; Bruttini A.; Sorbi T.	2022
Getuli V.; Capone P.; Bruttini A.; Isaac S.	2020
Kurien M.; Kim M.-K.; Kopsida M.; Brilakis I.	2018
Hoang T.; Greater S.; Taylor S.; Aranda G.; Mulvany G.T.	2021
Hafsia M.; Monacelli E.; Martin H.	2018
Kelm A.; Meins-Becker A.; Helmus M.	2019
Rwamamara R.; Norberg H.; Olofsson T.; Lagerqvist O.	2010
Hallowell M.R.; Hardison D.; Desvignes M.	2016
Cooke T.; Lingard H.; Blismas N.; Stranieri A.	2008
Goldberg D.M.	2022
Baker H.; Smith S.; Masterton G.; Hewlett B.	2020
Yi W.; Chan A.P.C.	2015
Lee Y.-C.; Shariatfar M.; Rashidi A.; Lee H.W.	2020

Table A1. *Cont.*

Authors	Year of Publication
Yu Y.; Li H.; Yang X.; Kong L.; Luo X.; Wong A.Y.L.	2019
Yang Y.; Chan A.P.C.; Shan M.; Gao R.; Bao F.; Lyu S.; Zhang Q.; Guan J.	2021
Ajayi A.; Oyedele L.; Owolabi H.; Akinade O.; Bilal M.; Davila Delgado J.M.; Akanbi L.	2020
Ajayi A.; Oyedele L.; Akinade O.; Bilal M.; Owolabi H.; Akanbi L.; Delgado J.M.D.	2020
Esmaeili B.; Hallowell M.	2013
Fung I.W.H.; Tam V.W.Y.; Lo T.Y.; Lu L.L.H.	2010
Niu Y.; Lu W.; Xue F.; Liu D.; Chen K.; Fang D.; Anumba C.	2019
Palaniappan K.; Kok C.L.; Kato K.	2021
Poh, CQX; Ubeynarayana, CU; Goh, YM	2018
Abad, A; Gerassis, S; Saavedra, A; Giráldez, E; García, JF; Taboada, J	2019
Lee, BG; Choi, B; Jebelli, H; Lee, S	2021
Lee, JY; Yoon, YG; Oh, TK; Park, S; Ryu, SI	2020
Zhang, F; Fleyeh, H; Wang, XR; Lu, MH	2019
Zhang, F	2022
Kang, K; Ryu, H	2019
Jeon, JH; Cai, HB	2022
Bigham, GF; Adamtey, S; Onsarigo, L; Jha, N	2019
Rubaiyat, AM; Toma, TT; Kalantari-Khandani, M; Rahman, SA; Chen, LW; Ye, YF; Pan, CS	2016
Xie, YY; Lee, YC; Shariatfar, M; Zhang, ZJ; Rashidi, A; Lee, HW	2019
Jebelli, H; Choi, B; Lee, S	2019
Nabi, MA; El-adaway, IH; Dagli, C	2020

Table A2. Barriers in the application of digital technologies in construction health and safety management in developing countries.

Authors	Year of Publication
Gao, YF; Gonzalez, VA; Yiu, TW; Cabrera-Guerrero, G; Li, N; Baghouz, A; Rahouti, A	2022
Dobrucali, E; Demirkesen, S; Sadikoglu, E; Zhang, CY; Damci, A	2022
Yap, JBH; Lee, KPH; Wang, C	2021
Li, H; Chan, G; Skitmore, M	2012
Shamsudin, NM; Mahmood, NHN; Rahim, ARA; Mohamad, SF; Masrom, M	2018
Shamsudin, NM; Majid, FA	2019
Azhar, S	2017
Shamsudin, NM; Mahmood, NHN; Rahim, ARA; Mohamad, SF; Masrom, M	2018
Shamsudin, NM; Mahmood, NHN; Rahim, ARA; Mohamad, SF; Masrom, M	2018
Tabatabaee, S; Mohandes, SR; Ahmed, RR; Mahdiyar, A; Arashpour, M; Zayed, T; Ismail, S	2022

Table A2. Cont.

Authors	Year of Publication
Mazibuko N.; Smallwood J.	2022
Goulding J.; Nadim W.; Petridis P.; Alshawhi M.	2012
Majumder S	2022
Koc K.; Gurgun A.P.	2022
Pekel E.; Akschir Z.D.; Meto B.; Akleyek S.; Kilic E.	2018
Ayhan B.U.; Tokdemir O.B.	2019
Koc K.; Ekmekcioğlu Ö.; Gurgun A.P.	2022
Rijo George M.; Nalluri M.R.; Anand K.B.	2022
Sadeghi H.; Mohandes S.R.; Hosseini M.R.; Banihashemi S.; Mahdiyar A.; Abdullah A.	2020
Ugur O.; Arisoy A.A.; Can Ganiz M.; Bolac B.	2021
Togan, V; Mostofi, F; Ayoezen, YE; Tokdemir, OB	2022
Koc, K; Ekmekcioglu, O; Gurgun, AP	2021
Abbasianjahromi, H; Golafshani, EM; Aghakarimi, M	2022
Umer, W	2022
Nayak, NR; Kumar, S; Gupta, D; Suri, A; Naved, M; Soni, M	2022
Sarkar, S; Raj, R; Vinay, S; Maiti, J; Pratihar, DK	2019
Mostofi, F; Togan, V; Ayözen, YE; Tokdemir, OB	2022
Xu, G	2022
Chen, HN; Luo, XW	2016
Li, J; Li, H; Umer, W; Wang, HW; Xing, XJ; Zhao, SK; Hou, J	2020
Xu, YQ; Wang, GB; Xia, C; Cao, DP	2020

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