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Review Article

Adoption of Digitalization in Construction Safety: A TCCM-based Literature Synthesis and Development of the DSRAO Framework

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Abstract *- Digitalization has been increasingly portrayed as a game-changing approach to enhancing construction safety through the adoption of technologies like Building Information Modelling (BIM), sensors, Artificial Intelligence (AI), and data analytics-based safety tools. While research interest and adoption of digital safety technologies have been increasing, the evidence of long-term improvement in safety performance is unclear. To understand this challenge, this research adopts a systematic review approach to critically synthesize the existing research on digitalization for construction safety, using the Theory-Context-Characteristics-Methodology (TCCM) framework. The review examined 120 peer-reviewed journal articles published from 2010 to 2026 to map research patterns, structural gaps, and cross-dimensional gaps. The results show a heavy emphasis on adoption-focused theories, location of studies in developed countries with little discussion of how they apply to developing construction settings, isolated technology-driven studies, and use of cross-sectional and perception-based research designs. These characteristics fuel a gap between digital technology adoption and safety outcomes. Drawing on the synthesis, this study develops the Digital Safety Readiness-Adoption-Outcome (DSRAO) framework, which conceptualizes digitalization in construction safety as a mediated and outcome-focused process. It places the organizational digital safety readiness as a key explanatory factor connecting contextual enablers and barriers, digital technology adoption, and explicit safety outcomes. The research contributes to the body of literature on digital construction safety by moving beyond descriptive synthesis and adoption-focused explanations, and providing an evidence-based and structured framework that explains how digitalization can enhance construction safety outcomes.*

Keywords *- Construction safety, Digitalization, TCCM framework, Digital readiness, Developing economies, Safety outcomes, Technology adoption.*

1. Introduction

Construction is one of the world's most dangerous industries, consistently contributing disproportionately to the number of accidents, injuries and deaths [53]. Despite regulatory reforms and improvements to safety management, construction safety has only improved marginally, especially in labour-intensive and complex projects [63, 132]. To address these ongoing challenges, digitalization like Building Information Modelling (BIM), sensing technologies, artificial intelligence, data analytics, wearables and immersive technologies – has increasingly been advocated as a disruptive approach to enhance construction safety performance [18, 124]. In the last decade, there has been an increasing focus on the use of digital technologies in construction safety, covering areas such as hazard identification, real-time monitoring, unsafe behaviour detection, training and safety planning [19, 29, 37, 89]. More recent research has extended this to explore behavioural and organisational factors affecting the uptake of digital safety technologies, often building on existing theories of technology acceptance and diffusion [59, 61, 80, 117]. Taken together, this body of work indicates that there is considerable promise for digitalization to improve construction safety management [4, 106].

Despite the burgeoning research on digital safety and growing adoption of technology in construction, the evidence of consistent and lasting improvement in safety performance is mixed [69, 128]. A number of systematic reviews have identified the growth in the number of digital safety tools and applications but also reported a lack of empirical evidence of the link between technology adoption and safety performance [10, 21, 22, 30, 47]. This lack of digital investment to safety performance suggests that the field may be suffering from structural constraints in the conceptualisation, research, and practice of digitalisation for construction safety [4, 17].

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Despite this expanding body of work, existing reviews of digital construction safety have largely catalogued available technologies and their adoption determinants without systematically explaining why increased adoption has not translated into consistent safety performance improvement. No prior review has applied an integrative, multi-dimensional lens - spanning theory, context, technology characteristics and methodology simultaneously - to explain, rather than merely describe, this persistent adoption-outcome disconnect.

This represents a clear and unaddressed research gap. Left unaddressed, it leaves both researchers and practitioners without a structured basis for understanding when and why digital investment translates into measurable safety gains, which is the problem this study sets out to address.

This research fills this gap by conducting a systematic literature review to critically synthesize the body of research on digitalization for construction safety through the Theory-Context-Characteristics-Methodology (TCCM) framework [83]. The TCCM framework offers a structured approach to detecting dominant patterns, structural constraints and gaps across four dimensions: theory, context, technology and methodology. This framework allows the study to go beyond descriptive synthesis to understand how patterns across these dimensions impact the field's capacity to explain and enhance safety outcomes.

This study answers the following research questions: RQ1: What are the key theoretical perspectives in digitalization research for construction safety and how do they influence the capacity to explain safety outcomes? RQ2: How do contextual variables, especially economic differences between developed and developing countries, affect the adoption of digital safety technologies? RQ3: What are the characteristics of technology and its implementation, and how does technology fragmentation impact research and practice? RQ4: Which research methods are most common in the field, and what are the implications for causal inference of digitalization on safety outcomes? RQ5: What are the cross-dimensional gaps resulting from the interplay between theory, context, characteristics and methodology, and how can they be addressed with an integrated approach?

The main contribution of this study is the development of the Digital Safety Readiness-Adoption-Outcome (DSRAO) framework, which reconceptualizes digitalization in construction safety as a readiness-mediated and outcome-oriented process. The framework positions organizational digital safety readiness as a central explanatory construct linking contextual enablers and barriers, technology adoption depth, and explicit safety outcomes. By integrating insights across the TCCM dimensions, the DSRAO framework provides a theoretically grounded and empirically testable structure to guide future research and practice [6, 16]. This positions DSRAO as distinct from prior adoption-centric or technology-specific frameworks summarised in Table 3 (e.g., TOE-based adoption assessment models, technology-specific maturity models), which largely treat adoption itself as the terminal outcome of interest; DSRAO instead separates readiness, adoption depth and safety outcomes into distinct, sequentially linked constructs, offering an explanatory mechanism that existing frameworks do not provide. Numerous past studies have been considered for this paper, but there has not been a TCCM based synthesis of literature studied or presented before. This study aims exactly at this aspect. Moreover, a DSRAO framework has been proposed which is the very novelty of the present study.

2. Literature Review

Research on digitalization in construction safety has developed along several inter-linked strands. An initial, technology-driven strand examined specific tools - Building Information Modelling (BIM), sensing and computer-vision systems, wearables and immersive technologies - and their direct applications to hazard identification and monitoring. A second, behavioural strand drew on established technology-adoption theories to explain why practitioners and organisations take up these tools. A third, contextual strand examined how economic and institutional conditions, particularly the developed–developing economy divide, shape adoption patterns. A smaller, more recent strand has begun to interrogate whether adoption of these technologies is empirically associated with improved safety outcomes, rather than assuming this link. The following subsections synthesise each of these strands in turn (Sections 2.1–2.5) to provide the theoretical and empirical grounding for the TCCM-based analysis presented in Sections 4–6.

2.1. Digital Technologies in Construction Safety

Over the last 20 years, the use of digital technologies for construction safety management has garnered significant research attention due to the ongoing need to minimize the number of injuries and fatalities in one of the world's most dangerous professions [53, 130]. The research of Zhou et al. [130] was a precursor to the study, which presented some of the initial work examining advanced technologies to improve safety management, showing potential for significant improvements in hazard awareness and incident response through the use of sensor-based monitoring and computer vision and information management systems. Taking this further, Cheng and Teizer [18] showed how to use RTLD for resource tracking and proactive safety monitoring, laying the groundwork for future sensor-integrated safety research.

The use of BIM in construction safety has proven to be a significant application, with researchers highlighting the benefits of hazard identification, 4D simulation of safety [127], and automated rule checking and documentation of safety throughout the construction lifecycle [21, 22]. Zhang et al. [127] established an influential framework for BIM-based fall hazard identification during construction planning, while

Collinge et al. [21, 22] extended this to develop and deploy an industry-ready safety risk library. The versatility of BIM for safety applications - encompassing design-stage prevention, site coordination and regulatory compliance - has made it the most extensively studied digital technology in the domain [73, 98, 99].

The last decade has seen rapid diversification of digital safety tools. Fang et al. [37] examined the use of computer vision for detecting unsafe behaviours on construction sites, demonstrating the potential of automated monitoring systems to identify PPE violations and proximity hazards in real time. Guo et al. [29] investigated a real-time control approach based on intelligent video surveillance for construction-worker violations, demonstrating the potential of automated monitoring and analysis for construction safety management. The work was furthered by Chi et al. [19] who examined the multi-dimensional real-time safety management with wearable physiological sensors and environmental monitoring. Together, these contributions laid the groundwork for a stream of research for digitalization in the construction industry, today known as construction safety digitalization [8, 10, 47].

There has been a complementary strand of IoT and sensor technologies that now allow for real-time monitoring of conditions at the site level, including environmental and worker conditions. Häikiö et al. [50] examined IoT-based safety monitoring from the perspective of construction-site workers, highlighting worker acceptance, trust, privacy, and the use of wearable technologies in construction safety. Elrifaee et al. [36] did a detailed review of IoT contributions to construction site safety highlighting the progress in gas detection, proximity warning and monitoring of structures as well as highlighting significant challenges of integration and data governance. These studies provide a clear indication that IoT platforms are maturing and yet, there is a need for a systematic integration with safety management systems [3, 64].

2.2. Technology Adoption Theories in Construction Safety

As empirical evidence of the effectiveness of digital safety tools grew, the parallel stream of research began to investigate the 'how' and 'why' of the use of digital tools by practitioners. Lu and Deng [59] examined construction practitioners' acceptance of intelligent surveillance systems using an extended Technology Acceptance Model and found that perceived usefulness, perceived ease of use, cost savings, training, technical support, and other contextual factors influenced acceptance. Hire et al. [61] examined BIM adoption for safety in the Indian construction sector, highlighting both the potential safety benefits of BIM and important barriers to adoption. Park et al. [80] investigated how construction supervisors adopted AI-based safety monitoring systems by using the Unified Theory of Acceptance and Use of Technology (UTAUT) framework [115] and found that the three factors of performance expectancy, effort expectancy, and social influence play a role in determining adoption. In addition, Rogers's Diffusion of Innovations theory [90] has been extensively cited to describe patterns of technology adoption in the construction industry, focusing on relative advantage, compatibility, and observability as factors influencing the adoption of digital safety tools within companies and projects. The Technology-Organisation-Environment (TOE) framework has proved particularly useful for explaining organisational-level adoption decisions, with studies by Yap et al. [122, 123] and Xu et al. [120] demonstrating how the interplay of technological characteristics, organisational capability and external environmental pressures shapes adoption outcomes in both developed and developing economy contexts.

Although these theoretical frameworks are useful, a recurring problem for adoption studies is that they tend to measure intention to adopt and actual uptake, but not the extent to which adoption is implemented or the effects of such implementation on safety performance. Waqar et al. [117] listed the success factors in introducing AI into health and safety management systems, but noted that this needs to be sustained organisational commitment and capability development that are not sufficiently captured and addressed by existing models to make measurable improvements in safety. The discrepancy between adoption theory and safety outcomes is an impetus for a more integrative theory as was used in the current study.

2.3. Contextual Factors and Developing Economy Perspectives

A considerable amount of work has been done on the context conditions influencing the adoption of digital safety. In the United States, Nnaji et al. [75] reported a high awareness of the digital technology use for safety, but frequent gaps in implementation are related to skills, lack of ROI and costs. Their work highlighted the importance of the role of organisational culture and management commitment as the drivers, which is confirmed in many other subsequent studies [22, 51, 97]. Studies in developing countries show a different structure of the adoption environment. Yap et al. [108] examined barriers to the adoption of new safety technologies in the Malaysian construction industry and identified regulatory/legislative gaps, technological limitations, organizational commitment, cost, safety culture, and privacy/data-security concerns as major barriers. In the literature, there is little discussion on the need to design safety monitoring systems that are context-specific to resource-constrained environments, and the study by Chathuranga et al. [16] in Sri Lanka demonstrated this for low-cost, camera-based safety monitoring systems. Akram et al. [6] studied BIM applications in safety management in developing countries such as Pakistan, Qatar and India and suggested the need for an automated hazard analysis tool developed based on local constructions types, local regulations and codes. Together,

these studies have shown that technology frameworks designed in advanced economy environments have trouble adapting their product without modification to develop economy environments [65].

2.4. Safety Climate, Organisational Factors and the Adoption-Outcome Gap

The other, though smaller, body of literature explores the mediating role of organisational and cultural factors between the adoption of digital technology and safety outcomes. Tezel et al. [107] studied the relationship between safety culture and technology implementation fidelity and the respective safety performance results, concluding that high performing safety cultures resulted in higher technology implementation fidelity and improved safety performance results. That means that enhancing safety through technology is not sufficient, but it requires the organizational readiness and organizational culture — which is in line with the socio-technical systems perspectives [3, 20].

Recent evidence reinforces the adoption–outcome gap. Daniel et al. [69], in a systematic review of digital technologies in construction safety, found that research remains concentrated on technology development, models and simulations, while implementation and evidence of safety impacts remain comparatively limited. Zhang et al. [128] further examined mechanisms for implementing Construction 4.0 technologies in construction organizations, reinforcing the importance of organisational mechanisms in translating technology adoption into safety improvements. Together, these contributions reinforce the importance of explicitly modelling readiness, adoption depth, and safety outcomes, which is what the DSRAO framework proposed in this study aims to address.

2.5. Systematic Reviews and Research Methodology

Systematic Literature Reviews (SLRs) are an important methodological tool to synthesize the huge amount of digitalization and construction safety literature. Tranfield et al. [113] laid out the principles for carrying out SLRs in management and organisational research with the aim of providing a basis for conducting SLRs with transparency, explicit inclusion and exclusion criteria and rigorous quality appraisal. Booth et al. [12] later extended the methodology of systematic review to the health and social sciences, offering guidelines for designing search strategies, extracting and synthesizing data that are popularly used in other disciplines such as engineering and construction management. In the last decade, numerous systematic and bibliometric reviews have been undertaken in the field of digital construction safety, consistently highlighting the immense development of the field and the structure's limitations. Guo et al. [47] have conducted a critical review of the computer vision technology for construction safety, including the fact that most studies have been on the technical performance metrics instead of safety outcome validation. Daniel et al. [24, 25] conducted a systematic review and found that digitalization for health and safety management was progressing rapidly with the development of new tools, but few empirical studies had been conducted to prove the improvement in the safety performance. Dobrucali et al. [30] utilised bibliometric analysis to identify the major trends and the intellectual framework of the area through analysing the field. The study showed that the field's focus has shifted to greater prominence of themes of AI, BIM and IoT, as well as showed the lack of cross-disciplinary interaction with themes of safety science and organisational theory. As a whole, these reviews show how the structural adoption-outcome gap exists, and how it can be explained and addressed with the DSRAO framework developed in this study.

3. Methodology

This research employed a hybrid Systematic Literature Review (SLR) approach that combined a pre-identified body of literature with additional searches across databases to achieve a comprehensive and timely review of the digitalization in construction safety domain. The study adhered to rigorous and transparent SLR guidelines [113], and PRISMA principles. The core was 90 research articles (2010–2026) sourced through SLR in Scopus database. Researchers complemented the search with supplementary Google Scholar searches.

The total search involved a combination of construction safety keywords (e.g., "construction safety", "occupational safety") and digitalization-related terms (e.g., "BIM", "artificial intelligence", "IoT", "wearables", "computer vision", "VR/AR", "drones", "sensors", "digitalization") through Boolean operators. The complementary search identified 53 papers, bringing the total number of papers to 143 (90 initial + 53 supplementary). Please refer Figure 1 for the PRISMA analysis. (see Appendix A for full search strings and the quality-appraisal rubric).

Title/abstract and full-text evaluations were made against inclusion criteria (digitalization in construction safety, peer-reviewed, English, 2010–2026, and empirical or theoretical), yielding a final set of 120 papers for analysis. While 143 papers satisfied initial inclusion criteria, a second pass was made to filter for analytical fit with the TCCM framework [83] and the research purpose of explaining the adoption-outcome gap. Studies were included if they showed conceptual centrality to adoption, implementation, readiness or safety outcomes; explicit theoretical anchoring or methodological rigor; and substantive information to allow structured coding for TCCM dimensions. Technical or redundant studies without conceptual insights were removed to ensure analytical rather than descriptive focus. At this stage another 23 papers were removed, leaving 120 papers for analysis/evaluation. Extraction focused on the theory, context (geographical and economic), characteristics of the technology, methodology, outcome measures and gaps.

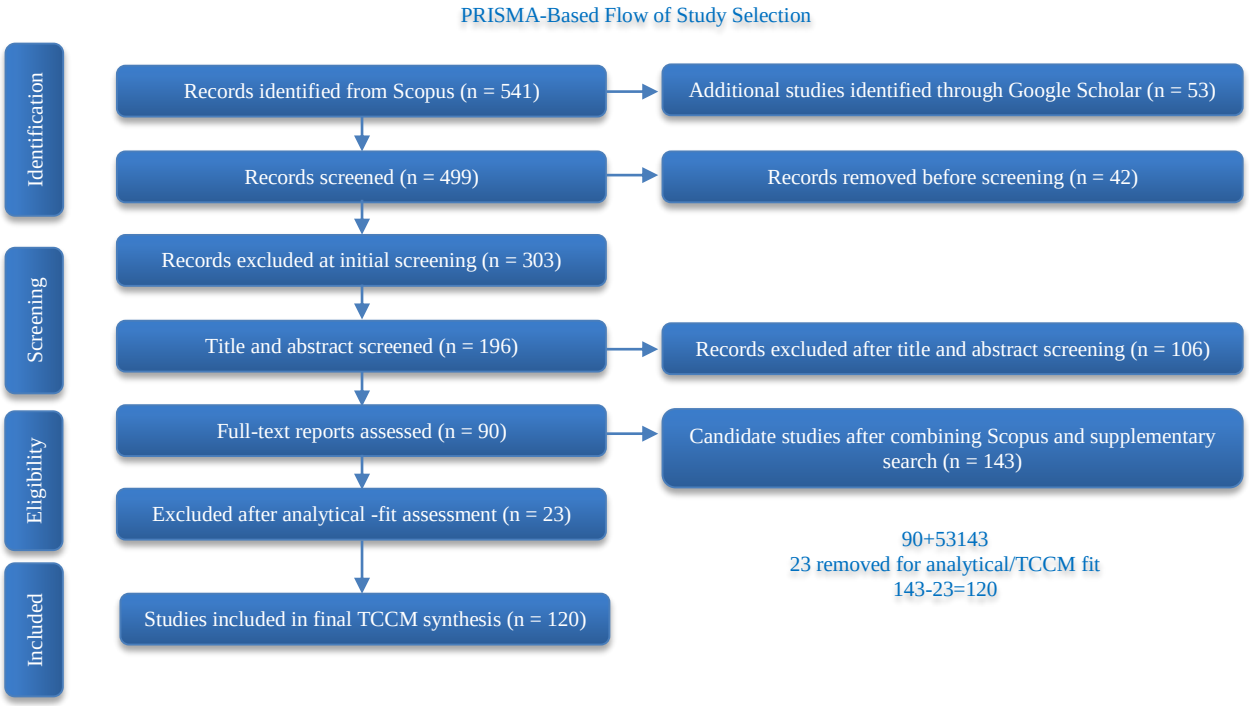


Fig. 1 PRISMA flow diagram for the systematic literature review (Source: Compiled by author)

To make the eligibility criteria explicit and reproducible, studies were retained if they satisfied all of the following inclusion criteria: (i) published in a peer-reviewed journal or peer-reviewed conference proceeding in English; (ii) published between 2010 and 2026; (iii) substantively addressed digital technology in the context of construction safety, occupational health and safety, or site risk management, rather than construction digitalization in general; (iv) reported empirical findings (quantitative, qualitative or mixed-methods) or a clearly articulated conceptual/theoretical contribution; and (v) provided sufficient methodological or conceptual detail to permit coding against the four TCCM dimensions.

Studies were excluded if they: (i) addressed construction digitalization without a specific safety, health or risk-management application (e.g., cost estimation, scheduling); (ii) were editorials, non-peer-reviewed reports, or conference abstracts without accessible full text; (iii) substantially duplicated findings already captured in a more comprehensive included study by the same author(s); or (iv) lacked sufficient methodological detail for TCCM coding.

This scope was deliberately balanced rather than restricted to emerging technologies: studies addressing traditional/procedural safety measures, technology-integration challenges with existing safety management systems, and regulatory or compliance-driven digitalization were equally eligible under the above criteria, and are discussed alongside technology-specific studies in Sections 4 and 5, so that the review's coverage extends beyond a narrow adoption/technology focus.

4. Descriptive Overview of Literature

The systematic review analysed 120 peer-reviewed publications between 2010 and 2026, with a significant surge in papers published since 2018. Some 71% of the studies (85 articles) were published from 2020 to 2026, showing an increase in interest in digitalization for construction safety [4, 30]. This trend suggests digital construction safety is an emerging research area, with a surge in research activity in recent years.

4.1. Geographical Distribution

The studies showed a high level of geographical concentration: 65% of the studies have been conducted in developed economies like the United States, United Kingdom, Australia, South Korea, and Western European countries [22, 51, 75, 97]. These studies tended to focus on the use of advanced technologies in environments with well-developed digital infrastructure and regulatory regimes. Contexts in emerging and developing economies (China, Malaysia, Nigeria, Sri Lanka, Pakistan and Middle Eastern countries) represented about 25% of studies [2, 6, 16, 120, 122, 123]. The remaining 10% were comparative studies across multiple countries or without any geographical context. This suggests under-representation of developing country contexts where the challenges of construction safety are often greatest [65].

4.2. Technology Focus

A variety of digital technologies were discussed in the literature. BIM was the most commonly researched technology (around 30% of studies) due to its widespread use and applications for safety, including hazard detection, safety planning and safety risk libraries [21, 22, 44, 73, 98-100, 105]. Computer vision and AI/machine learning systems represented 25% of studies, with a recent focus on deep learning for automatic hazard recognition, PPE compliance, and unsafe behaviours [5, 7, 8, 10, 47]. IoT and sensor technologies accounted for 20% of studies [13, 36, 50, 64]. Wearables accounted for 12%, virtual and augmented reality for 10% [33, 43, 77, 87, 102] and drones/UAVs for 8% [5, 67].

4.3. Research Focus Areas

Studies predominantly addressed technology development and adoption factors rather than safety outcomes. Approximately 40% focused on technology development, testing, or technical performance evaluation [7, 10, 47]. Another 35% examined adoption factors, barriers, and enablers using survey-based approaches [75, 108, 117, 120, 122, 123]. Systematic and bibliometric reviews accounted for 15% [4, 17, 21, 22, 30]. Only approximately 10% explicitly measured safety outcomes or impact, representing a significant adoption-outcome gap in the literature [45, 69, 128].

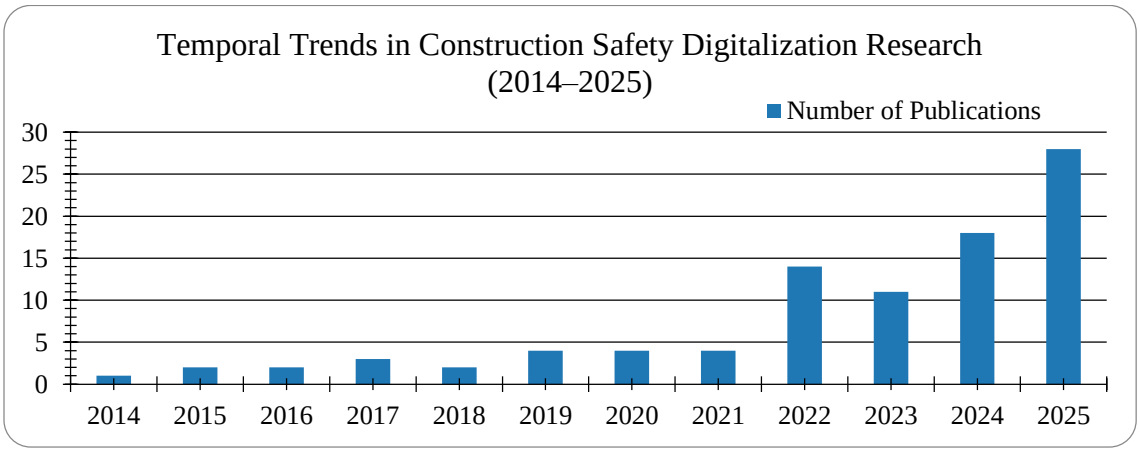


Fig. 2 Temporal trends in safety digitalization research (Source: Compiled by author)

Table 1. Distribution of studies by technology type and research focus

Technology Type	Development/Technical	Adoption Factors	Reviews	Outcome Evaluation	Total
BIM	12	15	5	4	36
Computer Vision/AI	18	6	4	2	30
IoT/Sensors	10	8	3	3	24
Wearables	5	6	2	1	14
VR/AR	3	7	2	0	12
Drones/UAVs	0	3	2	0	5
Unique studies	48	42	18	12	120

Note: The final TCCM synthesis comprises 120 unique studies. Technology-type counts are category-level counts and are not intended to represent an additional unique-study total; a study addressing more than one technology category may therefore contribute to more than one technology count. The research-focus totals are mutually exclusive and sum to 120.

It is clear from Table 1 that there is a huge imbalance in the literature. Only 12 of the 120 studies reviewed focus primarily on the safety outcomes, 48 study the primary focus on technical development, and 42 study the focus on adoption determinants. This distribution shows that fewer than 10% of the literature contain empirical proof that digitalization leads to measurable benefits to safety performance. This disparity is most pronounced in research on AI and VR, where most studies focus on how these technologies can be implemented and adopted instead of on their validated outcomes. Figure 2 indicates Construction safety digitalization research remained relatively limited between 2014 and 2021, with only a gradual increase in the number of publications. From 2022 onward, the field experienced rapid growth, reaching its highest publication output in 2025, reflecting increasing global interest and research activity in digital technologies for construction safety. Figure 3 shows that Computer Vision/AI dominates research on technical development, while BIM is the most extensively studied technology for adoption factors. In contrast, outcome evaluation receives comparatively less attention across all technologies, indicating a gap in assessing the real-world effectiveness of digital safety solutions. These results support the existence of a structural adoption–outcome gap, and further justify the adoption of an outcome-oriented and readiness-mediated explanatory framework.

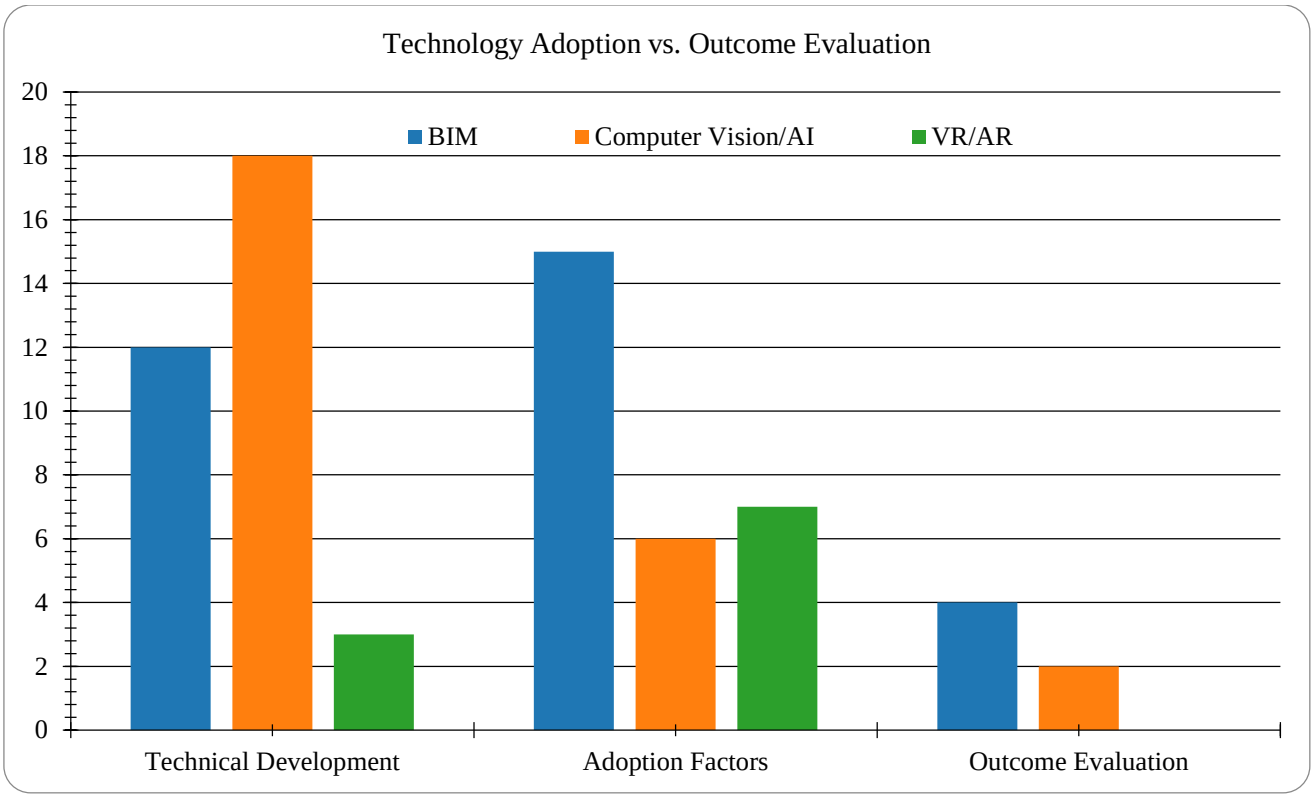


Fig. 3 Technology adoption vs. outcome evaluation (Source: Compiled by author)

5. TCCM-based Analytical Synthesis

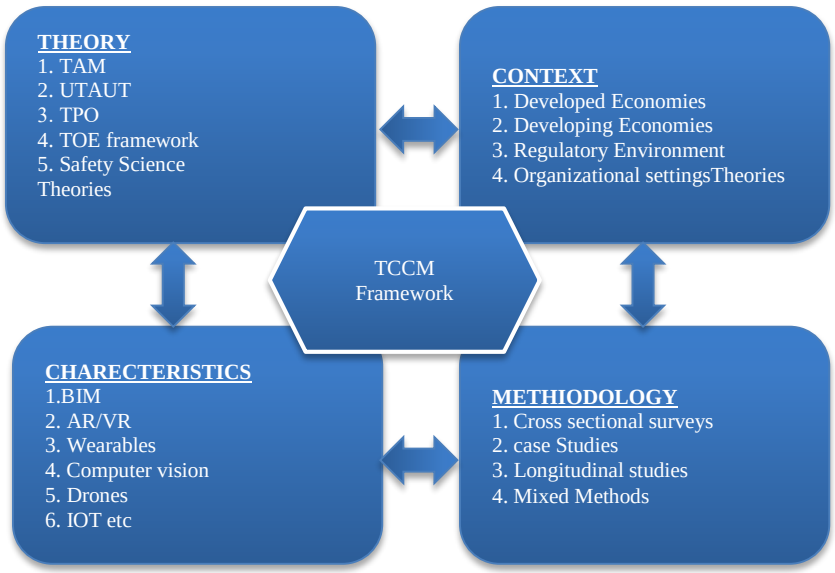


Fig. 4 The TCCM framework (Source: Compiled by author)

The TCCM framework (Figure 4) conceptualizes digitalization in construction safety research across four interconnected dimensions-Theory, Context, Characteristics, and Methodology-highlighting how each shapes the understanding of adoption and safety outcomes. By integrating these dimensions, the framework provides a structured lens to identify dominant patterns, structural gaps, and cross-dimensional imbalances within the existing literature.

5.1. Theory Dimension: Adoption-Centric Theories and Limitations

The field of digitalization in construction safety is dominated by adoption-focused theories that address the

question of why technologies are adopted and used, but do not provide much guidance on how it affects safety. The most common theoretical approaches include the Technology Acceptance Model (TAM), Unified Theory of Acceptance and Use of Technology (UTAUT), Technology-Organization-Environment (TOE) framework and the Diffusion of Innovations (DOI) theory [59, 61, 80, 90, 115].

TAM and UTAUT focus on individual factors (e.g., perceived usefulness, perceived ease of use, performance expectancy, effort expectancy) as key predictors of technology acceptance [115]. Research using these theories to investigate construction safety technologies consistently find these constructs to be key determinants of adoption [59, 80].

The TOE framework builds on this by adding organizational (e.g., top management support, organisational readiness, firm size, resource availability) and environmental (e.g., regulatory pressure, competitive pressure, industry norms, institutional support) factors [100, 120, 122, 123]. DOI theory adds relative advantage, compatibility, complexity, trialability and observability, attributes of innovation, are added to the standard list of attributes of innovation as provided by DOI theory [90]. Although adoption-focused theories are effective in explaining variance in the intention and behaviour of adoption, they have three key limitations.

First, they consider technology adoption as the dependent variable rather than safety performance, leading to a theoretical disconnect between technology acceptance and safety [69, 128]. Second, they insufficiently consider implementation capacity and readiness issues that intervene between adoption and use [22, 117]. Third, they offer little guidance for analysing contextual factors that influence relationships between adoption and outcomes in different economic and institutional settings [2, 6, 16].

A minority of studies have started to take different theoretical perspectives. Safety climate theory and safety culture models have been used to explore the impact of safety priorities on the adoption and use of digital technologies [60, 107]. Socio-technical systems theory has been used to understand dynamic relationships between technology, individuals and processes [3, 20].

Human factors and ergonomics approaches have guided research on acceptance of wearable technology [50, 97, 133]. Institutional theory has been used to examine the influence of regulation and industry standards on digitalization [63]. Yet, these perspectives are underused and have not been synthesised with adoption theories to develop robust explanatory models.

There is a lack of holistic theories that explicitly connect the factors influencing adoption, readiness, implementation and safety in a single framework. This prevents the field from explaining the variable impacts of safety outcomes in different organisational and contextual settings despite the use of similar technologies [69, 128].

5.2. Context Dimension: Developed vs. Developing Economies

The evidence of contextual elements in the adoption and use of digital safety technologies is crucial; however, the research field has a high level of geographical bias and lacks contextualisation to emerging and developing economies. Research in developed economies generally assumes a high level of digital infrastructure, access to skilled professionals, enforcement of regulations and organisational resources [22, 51, 75, 97]. These studies tend to investigate the application of the newest technologies, integration, and evolutionary improvements of current safety management practices.

The few studies from developing economies show different contextual factors. Research from Nigeria, Sri Lanka, Malaysia, Pakistan, and Middle Eastern nations consistently report that cost, skills, lack of digital infrastructure, regulatory enforcement, and organisational capacity are main barriers to adopting digital safety technologies [2, 6, 16, 108, 122, 123].

Nigerian construction companies identify costs, technical skills, infrastructure, and awareness barriers to even basic digital technologies for safety [2]. Sri Lankan studies advocate low-cost, camera-based frameworks tailored to low-resource settings [1, 16]. Malaysian studies highlight the importance of government, industry standards, training and financial incentives [108, 122, 123]. Pakistani studies of BIM for safety in developing countries call for automated hazard assessment tools tailored to local construction contexts [6].

Institutional and regulatory environments have an impact on digitalization. More stringent standards are often present in advanced economies, which may require mandatory reporting of safety, enforce it, and support digital innovation initiatives [63, 75]. In comparison, emerging economies might not have digital safety regulations, protocols, interoperability standards, and enforcement [2, 6, 16]. The literature on this topic focuses on developed economies and, as such, limits the transferability of research results. This is particularly worrisome because developing economies comprise the majority of construction activity in the world, and most of the largest accident and mortality rates worldwide.

Figure 5 illustrates that the adoption of digital safety technologies is influenced by five key contextual dimensions: economic landscape, infrastructure, government policy, regulatory environment, and human capital. Together, these factors determine an organization's readiness and capability to successfully implement digital technologies for improving construction safety.

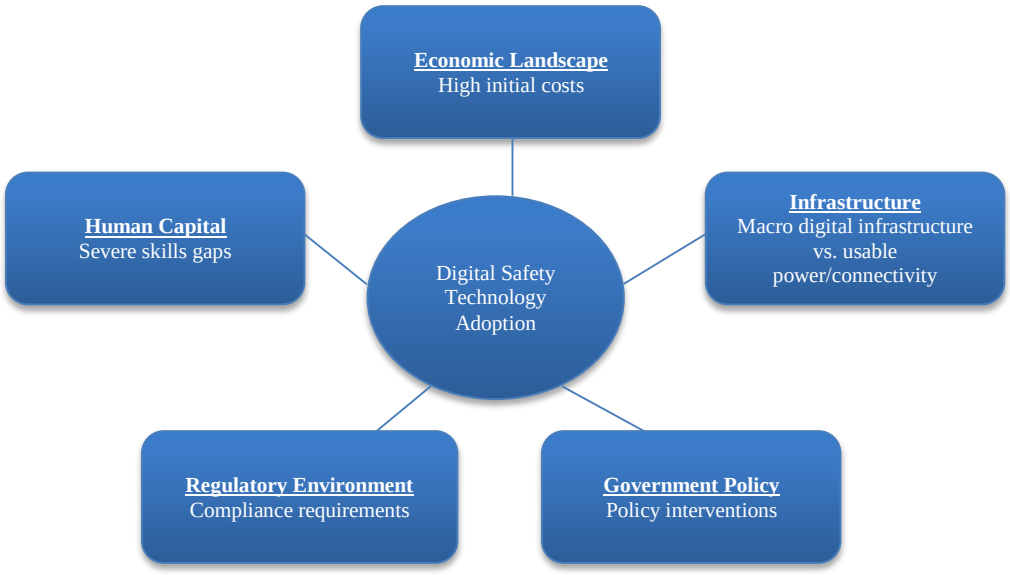


Fig. 5 Factors influencing digital safety technology adoption (Source: Compiled by author)

5.3. Characteristics Dimension: Technology Type and Fragmentation

Research investigates a variety of digital technologies to support construction safety, but due to their diversity, they have been the focus of isolated, technology-specific studies, which limit the possibility of a comprehensive understanding of how technologies interact and are best suited to different contexts. BIM has become the most researched technology, applied throughout the project lifecycle for hazard identification, safety planning, 4D simulation, automated rule checking, safety risk libraries, and documentation management [21, 22, 44, 73, 98, 99, 105].

AI and computer vision have seen significant advances with applications in hazard detection, PPE compliance, unsafe behaviour monitoring, proximity detection and predictive safety analytics [5, 7, 8, 10, 47]. IoT technologies allow for real-time monitoring of workers, machinery, and environmental factors through sensor networks [13, 36, 50, 64]. Wearable construction safety technologies encompass smart helmets, vests, watches and glasses [97, 133]. VR/AR are mainly used for safety training and site safety inspections [23, 33, 43, 77, 87, 102]. Drones allow remote site assessment, progress tracking, and hazard identification [5, 67].

Current research focuses more on specific technologies rather than integrated systems, technology comparisons and technology portfolios [21, 22, 67]. More recent research has begun to highlight the significance of integration and interoperability [3, 22, 64, 111]. For instance, BIM-IoT integration supports real-time safety monitoring in digital models [3, 64], and digital twin technologies exemplify integration of multiple technologies into cyber-physical systems [3, 26, 111]. But technical, organisational and institutional integration barriers persist [22, 36].

5.4. Methodology Dimension: Research Designs and Gaps

This study reveals a dominance of cross-sectional, perception-based, and technology-focused research, with few longitudinal, experimental or outcome-oriented research designs that can demonstrate causal effects of digitalization on safety outcomes. Some 35% of studies use cross-sectional questionnaire surveys to investigate adoption factors, barriers, perceptions and intentions [75, 117, 100, 108, 120, 122, 123]. Another 30% concentrate on technology development and technical evaluation [5, 7, 10, 47, 57]. Systematic and bibliometric reviews account for approximately 15% [4, 17, 21, 22, 30, 65]. Case studies and qualitative research account for around 12% [22, 44]. Only around 8% use longitudinal, quasi-experimental or intervention designs that explicitly examine changes in safety outcomes over time [45, 69, 101].

There is a limited use of objective safety outcome measures such as injury rates, near-miss rates, lost-time incident rates or workers' compensation claims [45, 69]. Even when outcomes are measured, they commonly use subjective perceptions of improving safety rather than real safety performance outcomes [69]. This is a major methodological bottleneck that hampers evidence-based practice and leaves uncertainty about the safety outcomes of digital technologies.

Recent reviews recommend more longitudinal studies that track technology uptake and safety outcomes over time, quasi-experimental studies that compare sites or organisations with and without digital technologies, mixed-method studies combining quantitative outcome measures and qualitative insights, standardised outcome measures to allow comparisons across studies and meta-analysis, and intervention studies to assess the impact of specific strategies [21, 22, 69, 128].

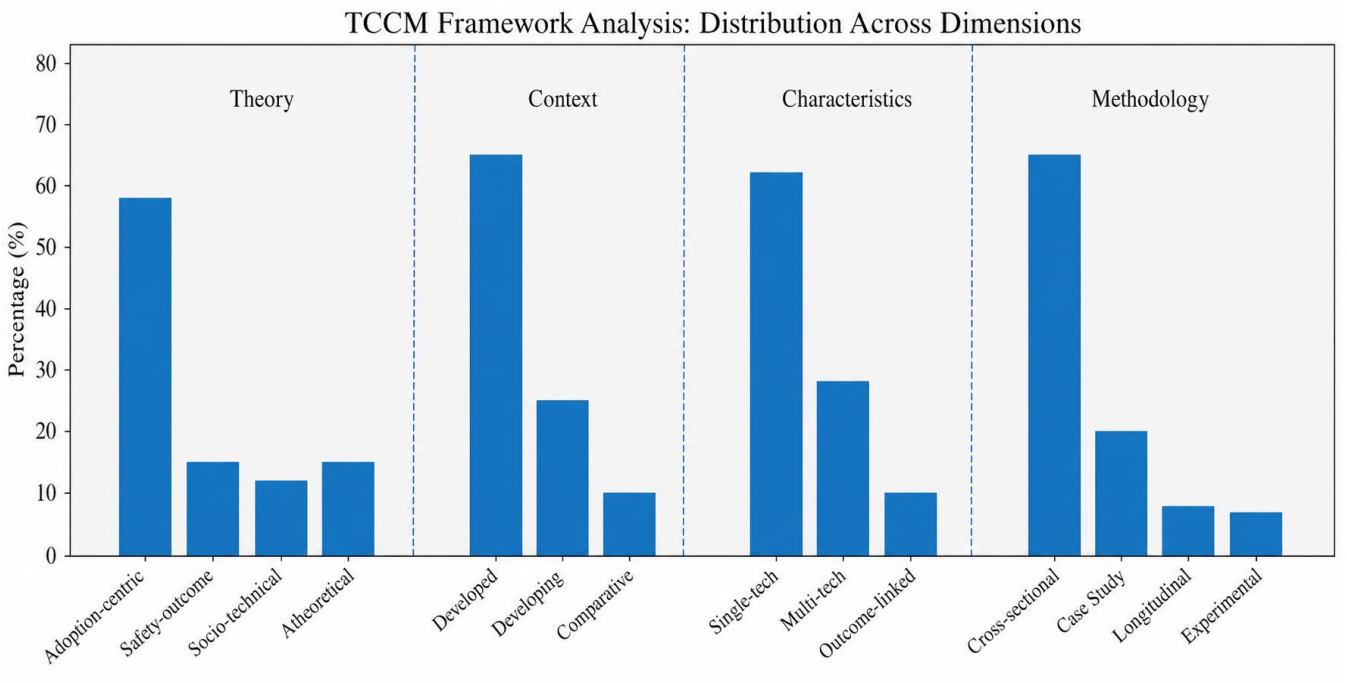


Fig. 6 TCCM framework analysis: distribution across dimensions (Source: Compiled by author)

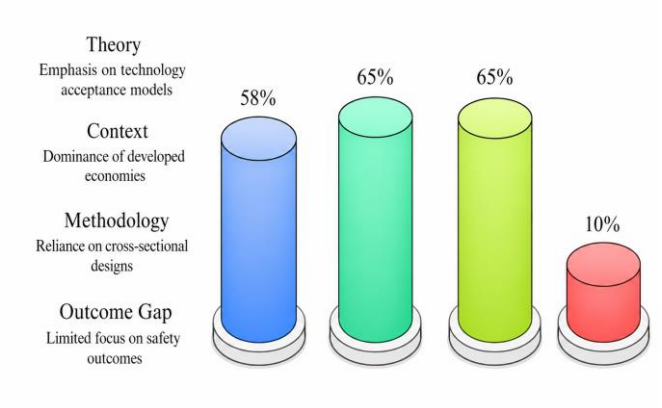


Fig. 7 Structural imbalances in literature review (Source: Compiled by author)

6. Cross-Dimensional Gap Analysis

The TCCM synthesis shows that the gaps in each dimension interact to create cross-dimensional gaps that limit the ability of the field to explain and enhance safety outcomes through digitalization. These cross-dimensional gaps are structural factors that contribute to the adoption-outcome disconnect.

Theory-Context Gap: Adoption theories developed in contexts of developed economies may not explain adoption patterns in resource-constrained contexts where the infrastructure, skills, institutional support and organisational capacity is considerably different [2, 6, 16]. Theoretical frameworks that are adaptable to different levels of digital infrastructure, institutional capacity and resource constraints are missing from the literature. In Figure 6 the TCCM analysis indicates that existing research is predominantly adoption-centric**,** conducted in developing-country contexts**,** focused on single technologies**,** and primarily uses cross-sectional research designs. Comparatively fewer studies emphasize safety outcomes, comparative analyses, multi-technology integration, longitudinal research, or experimental methodologies, highlighting important directions for future research. Figure 7 highlights that current research is largely grounded in technology acceptance theories (58%)**,** focuses on developed-country contexts (65%)**,** and predominantly employs cross-sectional methodologies (65%)**.** In contrast, only 10% of studies evaluate actual safety outcomes, revealing a significant gap in evidence on the practical effectiveness of digital safety technologies.

Theory-Methodology Gap: Adoption theories aim to explain variance in the intention to adopt, but prevalent cross-sectional designs cannot determine if adoption results in better safety outcomes [69, 128]. The adoption-focused theories are supported by studies that focus on measuring adoption rather than outcomes, forming a feedback loop that drives the adoption-outcome gap.

Context-Characteristics Gap: The technology characteristics examined in developed economies may not be suitable or affordable for developing economy contexts, where limited resources and capabilities are prevalent due to cost, infrastructure, human resource, and institutional constraints [1, 6, 16].

Table 2. Primary barriers and enablers for developed and developing economies

Dimension	Developed Economies	Developing Economies	Key Sources
Primary Barriers			
Cost & Financial	High initial costs relative to uncertain ROI; opportunity costs; client unwillingness to pay premium	High implementation and maintenance costs as absolute constraint; limited financial resources; lack of investment capital; cost ranked as top barrier (RII=0.69 in Sri Lanka)	Yap et al. (2022); Chathuranga et al. (2025); Daniel et al. (2025)
Skills & Training	Shortage of specialized expertise; need for continuous upskilling; resistance from experienced workers	Severe skills and training gaps across workforce; limited technical education; skills gap ranked highest barrier (RII=0.71 in Sri Lanka); 70.6% lack prior digital training	Chathuranga et al. (2025); Akram et al. (2022); Yap et al. (2022); Younghan Jung et al. (2025)
Infrastructure & Connectivity	Data management and privacy concerns; interoperability issues; system integration challenges	Inadequate network connectivity; unreliable power supply; poor digital infrastructure; limited on-site expertise; insufficient vendor support	Ting et al. (2024); Yap et al. (2022); Desai et al. (2025); Daniel et al. (2025)
Organizational	Resistance to change in the experienced workers; lack of client demand; unclear ROI; organizational inertia	Low top management commitment; weak organizational technology orientation; limited organizational capacity; cultural resistance to technology	Yap et al. (2022); Ting et al. (2024); Daniel et al. (2025)
Technical	Technical compatibility issues; integration with existing systems; data quality and reliability; cybersecurity concerns	Technology maturity concerns; sensor reliability; limited integration capabilities; lack of local technical support; adaptation to local conditions	Daniel et al. (2025); Mariam Akinlolu (2025); Xu et al. (2024)
Institutional	Lack of industry standards; insufficient client requirements; limited contractual incentives	Weak regulatory frameworks and enforcement; absence of digital technology standards; limited professional certification; institutional voids; insufficient government support	Chathuranga et al. (2025); Akram et al. (2022); Yap et al. (2022)
Primary Enablers			
Regulatory & Institutional	Strong regulatory frameworks; established enforcement mechanisms; comprehensive safety regulations; industry standards (e.g., BIM standards); legal frameworks for data governance	Government support and policy interventions (critical enabler); regulatory development; industry standards development (RII=0.78 in Sri Lanka); enforcement mechanisms	Chathuranga et al. (2025); Yap et al. (2022); Smithies et al. (2025)
Organizational Leadership	Strong top management commitment; organizational innovation culture; strategic digital priorities; established change management	Top management commitment (key predictor); organizational technology orientation; leadership support; contractor awareness	Yap et al. (2022); Ting et al. (2024); Smithies et al. (2025)
Capacity Building	Availability of skilled workforce; established training programs; professional development opportunities; mature education systems	Research and development support (RII=0.79, top facilitator in Sri Lanka); education and training programs (RII=0.78); targeted capacity building; knowledge development	Chathuranga et al. (2025); Yap et al. (2022); Frédéric Gardeux al. (2025)
Technical Support	Mature vendor ecosystems; comprehensive technical support;	International development assistance; knowledge transfer;	Abdullah et al. (2025); Chathuranga et al.

	established best practices; technology maturity	demonstration projects; affordable technology solutions; remote expertise access	(2025); Akram et al. (2022)
Market Factors	Client requirements and contractual incentives; competitive pressures; industry norms favoring innovation; established ROI evidence	Industry associations facilitating knowledge sharing; peer learning; demonstration of feasibility; success stories building confidence	Smithies et al. (2025); Salzano et al. (2024); Ghosh et al. (2025)
Technology Characteristics	Advanced integrated systems; established interoperability; comprehensive features; proven reliability	Affordable and appropriate technology solutions; camera-based low-cost systems; adapted frameworks; scalable solutions; reduced technical complexity	Abdullah et al. (2025); Akram et al. (2022); Chathuranga et al. (2025)

Note: RII = Relative Importance Index from survey research. Higher values indicate greater importance/severity. Table 2 presents the primary Barriers and Enablers for developed and developing economies. Key sources for the same have been identified and tabulated as well.

Characteristics-Methodology Gap: Technology-specific research assesses technical performance indicators (e.g., detection rates, system reliability) as opposed to safety outcome indicators (e.g., injury reduction, hazard prevention) [10, 47]. Context-Methodology Gap: Most research is conducted in developed economies using approaches suited to those settings, which limits understanding of digitalization patterns and challenges in developing economies [2, 6]. Cross-country studies of how contextual factors moderate the effect of adoption on outcomes are scarce [65].

The reviewed studies are not fully consistent in how they characterise the adoption–outcome relationship, and this divergence is itself informative. Daniel et al. [69] found that digital technology research in construction safety remains concentrated on technology applications, models, and simulations, with implementation and evidence of safety impacts still limited. In contrast, Tezel et al. [107] found a more direct relationship between technology implementation and safety performance where safety culture and implementation fidelity were strong. Read together, these findings suggest that organisational readiness and implementation conditions may be critical in determining whether technology adoption translates into measurable safety outcomes, which is precisely the mediating role that digital safety readiness is positioned to play within the DSRAO framework proposed in Section 7.

Taken together, the cross-dimensional gaps result in an integrated gap: while the industry knows what technologies are available, how they technically operate, and why firms adopt technologies, it does not know how adoption affects safety outcomes, or when digitalization leads to better safety performance [21, 22, 69, 128].

Figure 8: The figure illustrates a reinforcing cycle in which theoretical models developed in Western contexts and technology-centric research approaches fail to address local safety challenges**,** creating gaps between theory, context, methodology, and practical outcomes. As a result, digital technology adoption increases, but corresponding improvements in construction safety remain limited, highlighting the need for context-specific, outcome-oriented research.

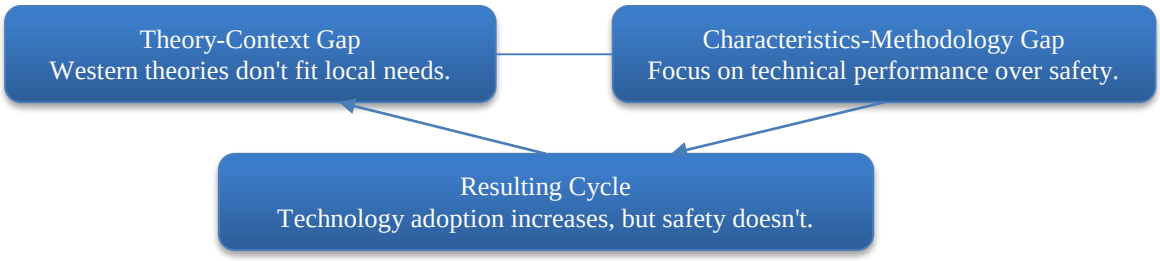


Fig. 8 The integrated adoption - outcome gap cycle (Source: Compiled by author)

7. DSRAO Framework Development

Based on the cross-dimensional gap analysis, this research introduces the Digital Safety Readiness-Adoption-Outcome (DSRAO) framework, which reframes digitalization of construction safety as a readiness-moderated and outcome-focused process. It conceptually links contextual factors, firm-level capability, adoption intensity and explicit safety outcomes in an empirically testable framework. Instead of adoption as the final outcome, DSRAO identifies improvement in safety performance as the final dependent variable and outlines how digitalization drives that improvement. DSRAO is underpinned by four insights from the TCCM synthesis. First, contexts play a vital role in shaping the digitalization process but are rarely specified explicitly.

Second, while organisational capability is talked about, it is rarely conceptualised in a coherent way. Third, the term adoption is used more as a binary outcome than a measure of implementation depth. Fourth, safety outcomes are often proxied rather than explicitly measured. To overcome these challenges, DSRAO draws on digital safety readiness as the key construct that mediates the relationship between context, adoption, and safety performance [6, 14, 104]. Contextual enablers and barriers include institutional factors such as regulatory frameworks and enforcement capacity [63], economic conditions such as market maturity and resource availability [65], infrastructure conditions including digital connectivity and technical support [2, 14], and cultural elements such as safety culture and innovation culture [107, 122, 123]. At the heart of the framework is organisational digital safety readiness, defined as a multidimensional capability that includes: technological infrastructure [19, 107]; organisational readiness and change management [89, 109]; human capital readiness [2, 104]; process maturity and data governance [19, 40]; and strategic alignment and continuous improvement mechanisms [17, 90].

The framework also extends the literature by conceptualizing the depth of technology adoption as a multidimensional construct reflecting the diversity of technologies adopted, integration with safety management systems, level of use, and ongoing adaptation [3, 50, 75, 97, 101]. Safety outcomes are defined explicitly at different levels. Leading indicators include hazard and near-miss reporting [53], lagging indicators include injury and incident rates [41, 118], and process indicators include safety compliance and culture [60, 69]. Figure 9 presents the proposed Digital Safety Readiness-Adoption-Outcome (DSRAO) Framework, illustrating that institutional environment, organizational context, project characteristics, and economic development collectively influence an organization's digital safety readiness**.** This readiness determines the level of technology adoption—symbolic, functional, or transformative-which subsequently affects construction safety performance through leading indicators, lagging indicators, safety culture metrics, and compliance levels, with a feedback loop enabling continuous improvement in readiness and adoption.

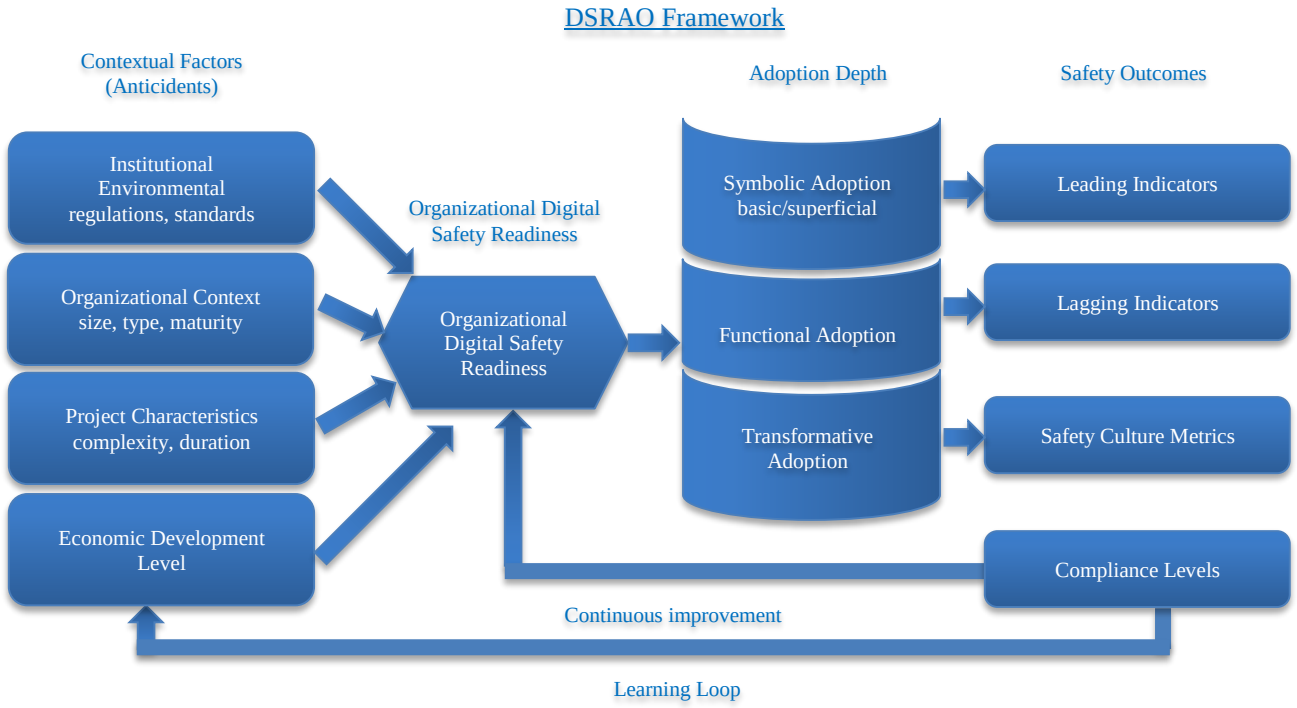


Fig. 9 Structural imbalances in literature review (Source: Compiled by author)

Table 3. Existing digital frameworks and the proposed DSRAO framework

Framework/Model	Authors & Year	Theoretical Basis	Key Components/Dimensions	Context	Main Contribution	Limitations
TOE-based Adoption Assessment Model	Xu et al. (2024)	Technology-Organization-Environment	Four criterion groups: (1) Organizational factors, (2)	China; construction safety management	Empirically identifies and prioritizes adoption factors	Adoption-centric; does not specify outcome

		(TOE) framework	Technological factors, (3) Individual factors, (4) External factors. Technology factors most influential.		in developing-economy context; uses fuzzy composite evaluation	pathways; cross-sectional design limits causal inference
Four-Dimensional Adoption Predictor Model	Yap et al. (2022)	Expectancy theory; multi-factor adoption models	Four dimensions from EFA: (1) Organizational commitment/technology orientation, (2) Supporting technological attributes, (3) Personal perception/performance expectancy, (4) Government support	Malaysia; 133 construction professionals	Identifies key predictor dimensions specific to developing-economy context; empirically derived factor structure	Adoption intentions only; no outcome measurement; limited to Malaysian context; requires validation
BIM-driven Safety Management Framework	Akram et al. (2022)	Socio-technical approach	Lifecycle BIM integration for: design-stage hazard identification, 4D simulation, automated rule-based checking, visualization. Adapted for developing countries.	Developing countries (Qatar, Pakistan, India, UAE, USA, Australia)	Proposes systematic BIM framework adapted to developing-country constraints; mixed-methods validation	Conceptual framework requiring full empirical validation; limited automated hazard datasets
Conceptual Framework for Digital Safety Implementation	Chathuranga et al. (2025)	Organizational readiness model	Prioritizes impactful technologies (BIM, VR, AR, GIS, Serious Games); identifies barriers (skills gap, cost) and facilitators (R&D, education, standards)	Sri Lanka; 101 construction professionals	Comprehensive country-level framework; empirically identifies barriers and enablers with RII analysis	Conceptual framework requiring implementation and validation; country-specific; limited operational detail
Digital Transformation Blueprint	Smithies et al. (2025)	Organizational transformation; predictive analytics	Unified technology system; predictive analytics and ML integration; cultural change; strategic evolution over 7 years (2016-2023)	UK; Principal Company case study	Demonstrates sustained transformation with strong outcomes (23% safety improvement, AFR 0.17→0.026); longitudinal perspective	Single leading firm; high resource requirements; limited transferability to SMEs or developing economies
BIM Integration for Risk Management	Sufiana Safiena et al. (2024)	BIM-based risk management	Lifecycle BIM integration for safety management; comparative analysis with	Italy, Switzerland; CERN and heritage	Demonstrates BIM superiority in risk mitigation; validated	Developed-economy context; advanced projects;

			traditional methods; stakeholder validation	building cases	through stakeholder feedback; comparative methodology	requires mature BIM capabilities
DSRAO Framework (Proposed)	Current study (2026)	Extension of adoption theories; organizational readiness; socio-technical systems; contingency theory	Five components: (1) Contextual enablers/barriers, (2) Organizational digital safety readiness (6 dimensions), (3) Technology adoption depth, (4) Safety outcomes (leading/lagging), (5) Feedback loops	Cross-contextual; explicitly addresses developed vs developing economies	Outcome-oriented; readiness as central mediator; context-sensitive; addresses adoption-outcome gap; empirically testable; integrates TCCM insights	Requires empirical validation; operationalization needed; complexity may challenge implementation

Table 3 synthesizes existing digital safety frameworks, highlighting their theoretical bases, construct focus, contextual scope, and limitations. Prior models are predominantly adoption-centric, grounded in TOE, expectancy, or socio-technical perspectives, with emphasis on identifying adoption determinants. Most lack explicit outcome linkages and rely on cross-sectional designs. In contrast, the proposed DSRAO framework integrates contextual factors, organizational readiness, adoption depth, and measurable safety outcomes within a unified, readiness-mediated structure, directly addressing the adoption–outcome gap.

Table 4. DSRAO framework constructs and measurement

Construct	Dimensions	Example Indicators
Contextual Enablers/Barriers	Institutional, Economic, Infrastructure, Cultural	Regulatory stringency, enforcement capacity, digital infrastructure quality, industry standards maturity, competitive pressure, economic development level, safety culture strength
Digital Safety Readiness	Technological, Organizational, Human Capital, Process, Strategic	IT infrastructure maturity, system integration capability, management commitment, resource allocation, workforce digital skills, training investment, SMS maturity, process standardization, digital strategy clarity, performance metrics
Adoption Depth	Breadth, Integration, Utilization, Adaptation	Number of technologies, technology diversity, system integration level, workflow integration, usage frequency, usage consistency, customization extent, continuous improvement
Safety Outcomes	Leading, Lagging, Process	Hazard identification rate, near-miss reporting frequency, safety audit scores, injury frequency rate, lost-time incident rate, fatality rate, compliance rate, training effectiveness

Table 4 operationalizes the DSRAO framework by defining its key constructs, dimensions, and indicators. It captures contextual factors, multidimensional organizational readiness, and adoption depth, linking them to measurable safety outcomes across leading, lagging, and process indicators, thereby enabling empirical assessment of the readiness-mediated adoption–outcome relationship.

7.1. Illustrative Application

To illustrate how DSRAO would be applied in practice, consider a hypothetical mid-sized contractor in a developing-economy setting that has recently invested in wearable safety sensors. Under an adoption-centric lens, the relevant question would be limited to whether workers accept and use the

devices. Under DSRAO, the same investment would first be assessed against digital safety readiness — e.g., whether the firm's process maturity and data-governance practices (Table 4) can absorb sensor-generated data, whether supervisors have the human-capital readiness to act on alerts, and whether the organisation has the change-management capacity to integrate the devices into existing safety procedures. Only once these readiness dimensions are addressed would adoption depth - the breadth and integration of the sensors with the firm's safety management system, rather than mere possession of the devices - be expected to translate into measurable leading and lagging safety outcomes (Table 4). This sequencing illustrates why two firms adopting the same technology can realise different safety outcomes, and it gives practitioners a diagnostic checklist (readiness → adoption depth → outcomes) rather than a single adopt/do-not-adopt decision.

7.2. Framework Contributions

The DSRAO framework contributes to the body of research and practice in digital construction safety in three major ways. First, it offers a theoretically based explanation of the heterogeneity in safety outcomes by locating readiness as a mediating variable that can justify why like technologies yield different outcomes in different organizations and settings [22, 117]. Second, it changes the emphasis on adoption as a final variable to adoption depth and safety outcomes as the final dependent variables, which directly resolves the adoption-outcome gap in the literature [69, 128]. Third, it has a context-adaptive framework that clearly describes differences in institutional capacity, resource access, and digital maturity between developed and developing economies [2, 6, 16]. This distinguishes DSRAO from the frameworks summarised in Table 3, none of which model readiness as an explicit mediating construct between context and outcomes.

8. Implications

8.1 Research Implications

The DSRAO framework offers a platform to more rigorous empirical investigation. Future studies ought to measure and prove the readiness construct with multi-dimensional measurement scales [22, 101]. Longitudinal designs to monitor readiness development, the depth of adoption, and safety outcomes over time and quasi-experimental designs to compare organizations or projects with various levels of readiness should be used to test the proposed relationships [69, 128]. The context-adaptive arguments in the framework should be validated by comparative studies that investigate contextual moderators in various economic and institutional settings [6, 65].

8.2. Practical Implications

To construction organizations, the results warn that digital investment and safety improvement cannot be equated. To achieve successful digitalization, a systematic preparation of the technological, organizational, human capital, process, and strategic levels, before and during the adoption of technology is required [22, 101, 117]. Organizations are encouraged to perform thorough preparedness evaluations, make investments in readiness-building a priority, adopt technologies in stages with a focus on integration and effective use, and develop organizational learning mechanisms to capture lessons learned.

This framework recommends that developing countries should prioritize creating basic preparedness before embarking on highly innovative technology use, explore low-cost, suitable-technology options that can fit local capacity and infrastructure [1, 16], invest in workforce training and skills development as a precursor to successful technology adoption [2, 55] and develop regional knowledge networks to share implementation experiences and best practices [16].

8.3. Policy Implications

To the policymakers and industry associations, the framework demonstrates the significance of institutional enablers. Recommendations include developing industry standards and guidelines for digital safety technology implementation that account for varying organizational capacities [122, 123], establishing regulatory frameworks that incentivize outcome-focused digitalization rather than mere technology adoption [63], investing in digital infrastructure and workforce development programs particularly in developing economies [2, 16], creating knowledge-sharing platforms and best practice repositories to facilitate organizational learning [20, 32], supporting research on context-appropriate, low-cost digital safety solutions for resource-constrained environments [1], and developing readiness assessment tools and capacity-building programs to support organizational digital transformation [101].

9. Limitations and Future Research Direction

There are a several limitations of this study. Being a literature review, it is limited by the range and quality of published literature. The gaps identified are indicative of limitations in the literature as opposed to conclusive findings on the effectiveness of digitalization in practice. The DSRAO framework is theoretical and needs to be proven by empirical methods of operationalization of constructs, development of measurement tools and testing of hypotheses with proper research designs. The literature search relied on peer-reviewed scholarly sources and might not comprehensively reflect the practices in the industry, proprietary technology, unpublished case studies, or recent advances not yet represented in published literature. The organizational readiness focus of the framework might undervalue the role of individual level elements, social processes and emergent implementation processes.

Future research ought to build on this basis along five priority directions, summarised in Table 5.

Table 5. Future research directions

Priority Direction	Focus	Key Citations
1. Empirical validation	Longitudinal and quasi-experimental designs testing the DSRAO framework, including mediation effects of readiness.	[69, 128]
2. Comparative contextual studies	Contextual moderating effects between developed and developing economies, regulatory systems, project types and organisational forms.	[6, 16, 65]
3. Standardized measurement tools	Validated instruments to assess digital safety readiness and safety outcomes comparably across studies and contexts.	[53, 69]
4. Readiness-building interventions	Studies testing the effectiveness of interventions that build organisational capacity for digital safety.	[101, 117]

10. Conclusion

This study aimed to synthesize the existing literature on digitalization in construction safety and address the persistent gap between technology adoption and tangible improvements in safety performance. Using a TCCM-based analysis of 120 studies published between 2010 and 2026, four structural patterns were identified: a dominance of adoption-focused theories that explain technology acceptance but not safety outcomes; a strong concentration of studies in developed economies with limited representation of developing-country contexts; fragmented, technology-specific treatment of digital safety tools; and a methodological reliance on cross-sectional, perception-based designs that cannot establish causal adoption–outcome links. In response, this study proposes the Digital Safety Readiness–Adoption–Outcome (DSRAO) framework, which repositions digitalization in construction safety as a readiness-mediated, outcome-focused process. By linking contextual enablers and barriers, a five-dimensional organisational readiness construct, adoption depth, and explicit safety outcomes within a single explanatory structure, DSRAO builds on — rather than replaces — existing adoption models, offering a more theoretically consistent basis for explaining heterogeneous safety performance across construction settings [22, 61, 80, 117].

Beyond the framework itself, this synthesis carries implications for how digitalization is understood and pursued in construction safety more broadly. By making explicit the distinction between adopting a technology and being ready to use it effectively, the DSRAO framework offers researchers, practitioners, and policymakers a common reference point for evaluating digital safety initiatives beyond simple uptake counts. It reframes the central question from whether organizations have adopted digital tools to whether they possess the organizational conditions necessary to translate that adoption into measurable safety gains. As construction firms across both developed and developing economies continue to invest in digital safety technologies, empirical testing and contextual refinement of the DSRAO framework will be essential to determine whether closing the readiness gap can, in practice, close the outcome gap.

Author Contribution

1. Abhijeet Sangapurkar conceived the study, designed and executed the systematic literature review (including database searching, screening, and TCCM-based coding of the 120 included studies), performed the formal cross-dimensional gap analysis, developed the proposed Digital Safety Readiness-Adoption-Outcome (DSRAO) framework, prepared all figures and tables, and wrote the original draft of the manuscript in its entirety. He also administered the overall project, including the revision process in response to peer review.

2. Babalu Rajput, as PhD supervisor, provided overall academic supervision and guidance on the study's conceptual direction and theoretical framing, critically reviewed and validated the content of the manuscript at each stage, contributed to revising and editing the manuscript, and provided the institutional resources (NICMAR University) that supported this work.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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Glossary of Key Terms

Term	Definition (as used in this study)	Source
TCCM	Theory-Context-Characteristics-Methodology framework used to structure the literature synthesis across four dimensions.	[83]
DSRAO	Digital Safety Readiness–Adoption–Outcome framework proposed in this study, linking contextual enablers, organisational readiness, adoption depth and safety outcomes.	This study
Digital safety readiness	A multidimensional organisational capability spanning technological, organisational, human-capital, process and strategic dimensions that precedes and enables effective technology adoption.	Section 7
Adoption depth	The extent of technology use, captured through breadth, integration with safety management systems, utilisation, and ongoing adaptation, rather than a binary adopted/not-adopted measure.	Section 7
Leading indicators	Proactive safety measures such as hazard and near-miss reporting rates.	[53]
Lagging indicators	Outcome-based safety measures such as injury and incident rates.	[41, 118]
Process indicators	Measures of safety compliance and safety culture strength.	[60, 69]
TAM / UTAUT	Technology Acceptance Model / Unified Theory of Acceptance and Use of Technology – individual-level technology-adoption theories centred on perceived usefulness, ease of use, and performance/effort expectancy.	[115]
TOE	Technology–Organization–Environment framework explaining organisational-level adoption as a function of technological, organisational and environmental factors.	[120, 122, 123]
DOI	Diffusion of Innovations theory, explaining adoption through relative advantage, compatibility, complexity, trialability and observability.	[90]
RII	Relative Importance Index – a survey-based weighting used in the cited barrier/enabler studies to rank factor importance (higher values indicate greater importance/severity).	Table 2 sources

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Appendix A - Search Strategy and Quality Appraisal

A.1 Databases and search window: Scopus (primary) and Google Scholar (supplementary), articles published January 2010 - April 2026.

A.2 Example Boolean search string: ("construction safety" OR "occupational safety" OR "site safety" OR "health and safety") AND ("digitalization" OR "BIM" OR "building information modelling" OR "artificial intelligence" OR "IoT" OR "internet of things" OR "wearable*" OR "computer vision" OR "virtual reality" OR "augmented reality" OR "drone*" OR "unmanned aerial" OR "sensor*")

A.3 Filters applied: document type (journal article / conference proceeding); language (English); subject area (engineering, construction management); publication years 2010–2026.

A.4 Quality appraisal: each full-text-reviewed study on four criteria - (1) clarity of research aim/question, (2) transparency and appropriateness of method, (3) adequacy of reporting of findings, (4) relevance to the TCCM dimensions.

Table A1. Summary of key papers

Study (Author, Year)	TCCM Focus	Technology/Theory	Key Finding	Ref. No.
Cheng and Teizer	Characteristics	RTLS / resource tracking	Real-time location tracking enables proactive safety monitoring.	[18]
Collinge et al.	Characteristics	BIM safety risk library	Deployed an industry-ready BIM-based safety risk library.	[21]
Zhang et al.	Characteristics	BIM fall-hazard identification	Established an influential BIM-based fall-hazard framework.	[127]
Lu and Deng	Theory	Extended TAM / intelligent surveillance	Perceived usefulness, perceived ease of use, cost savings, training, and technical support influence acceptance of intelligent surveillance systems.	[59]
Daniel et al.	Methodology	Systematic review	Research remains concentrated on digital technology applications, models and simulations, with limited implementation and safety-impact evidence.	[69]
Tezel et al.	Theory/Context	Lean construction, safety culture	Adoption–outcome link held only where safety culture and fidelity were strong.	[107]
Waqar et al.	Context	Developing-economy adoption	Institutional and resource constraints shape digital safety adoption in developing economies.	[117]
Paul et al.	Methodology	TCCM review methodology	Established the TCCM framework used for structuring literature reviews.	[83]
Venkatesh et al.	Theory	UTAUT	Unified individual-level technology-adoption theory.	[115]
Roger	Theory	Diffusion of Innovations	Foundational adoption/diffusion theory (relative advantage, compatibility, etc.).	[90]
Guo et al.	Characteristics	Computer-vision technical performance	Emphasises technical performance metrics over organisational mediators.	[47]
Zhang et al.	Theory/Context	Construction 4.0 / organizational mechanisms	Highlights organizational mechanisms for implementing Construction 4.0 technologies in construction organizations.	[128]