IMPACT OF DIGITAL TECHNOLOGIES (IOT/AI) ON WORKPLACE SAFETY IN SAUDI INDUSTRIES

IMPACTO DAS TECNOLOGIAS DIGITAIS (IOT/IA) NA SEGURANÇA NO LOCAL DE TRABALHO NAS INDÚSTRIAS SAUDITAS

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Abstract

Background: The energy, petrochemical, construction, mining, and logistics industries in Saudi Arabia are considered high-hazard industries. The implementation of digital technology, such as the Internet of Things (IoT), computer vision, artificial intelligence (AI), and other digital technologies, presents a tremendous opportunity to change the paradigm in safety management from reactive to proactive. Objective: The purpose of this review is to synthesize the available literature on the implementation of IoT/AI-based technology, the impact on safety outcomes, the impact on the safety management process, the implementation framework, and guidelines on how the results should be reported and evaluated. Methodology: The methodology used in this review is based on the PRISMA protocol. The literature review focuses on published articles from 2020 to 2025 on the implementation of IoT, computer vision, AI, machine learning (ML), Safety 4.0, Industry 4.0, augmented/virtual reality, digital twin-based decision support systems (DSS), and their impact on the safety outcomes and the safety management process. Results: The results indicate that IoT/AI-based technology implementation has the potential to impact the safety outcomes as well as the safety management process. Real-time monitoring of the usage of personal protective equipment (PPE) by computer vision technology is considered useful. Industry 4.0/Safety 4.0 implementation has the potential to change the paradigm in the safety management process. The implementation

Resumo

Contexto: Os setores de energia, petroquímica, construção, mineração e logística na Arábia Saudita são considerados setores de alto risco. A implementação de tecnologias digitais, como a Internet das Coisas (IoT), visão computacional, inteligência artificial (IA) e outras tecnologias digitais, representa uma enorme oportunidade para mudar o paradigma da gestão da segurança de reativa para proativa. Objetivo: O objetivo desta revisão é sintetizar a literatura disponível sobre a implementação de tecnologia baseada em IoT/IA, o impacto nos resultados de segurança, o impacto no processo de gestão de segurança, a estrutura de implementação e as diretrizes sobre como os resultados devem ser relatados e avaliados. Metodologia: A metodologia utilizada nesta revisão é baseada no protocolo PRISMA. A revisão da literatura concentra-se em artigos publicados entre 2020 e 2025 sobre a implementação de IoT, visão computacional, IA, aprendizado de máquina (ML), Segurança 4.0, Indústria 4.0, realidade aumentada/virtual, sistemas de apoio à decisão (DSS) baseados em gêmeos digitais e seu impacto nos resultados de segurança e no processo de gestão da segurança. Resultados: Os resultados indicam que a implementação de tecnologia baseada em IoT/IA tem o potencial de impactar os resultados de segurança, bem como o processo de gestão de segurança. O monitoramento em tempo real do uso de equipamentos de proteção individual (EPI) por tecnologia de visão computacional é considerado útil. A implementação da Indústria

of wearable sensing technology is considered useful in the safety management process.

Keywords: Saudi Arabia. Workplace Safety. Occupational Health. Internet Of Things. Wearable Sensors. Computer Vision. Safety 4.0. Industry 4.0. Predictive Analytics. Governance.

4.0/Segurança 4.0 tem o potencial de mudar o paradigma no processo de gestão de segurança. A implementação de tecnologia de sensoriamento vestível é considerada útil no processo de gestão de segurança.

Palavras-chave: *Arábia Saudita. Segurança No Local De Trabalho. Saúde Ocupacional. Internet Das Coisas. Sensores Vestíveis. Visão Computacional. Segurança 4.0. Indústria 4.0. Análise Preditiva. Governança.*

1 INTRODUCTION

In Saudi Arabia, not only is the industrial sector growing, but its safety is becoming more central than ever. The more investments that come into the country in areas like energy, petrochemicals, construction, mining, and logistics, the more industrial accidents, falls, car crashes, confined space operations, heat stress, and fatigue errors we see. However, traditional safety management is too focused on injury rates and sporadic inspections, while disregarding the way risk is constantly changing in factory environments. Today, technology is changing safety by providing constant sensing, monitoring, and prevention. The Internet of Things (IoT) and Artificial Intelligence (AI) affect three areas: sensing, analytics, and workflows. However, making this a reality is not an easy task, as studies indicate that digitalization is likely to have both positive and negative effects on WS and OSH management, which may include mental overload, data protection concerns, and psychosocial risks, as well for cybersecurity threats and technology overdependence, respectively. There is also a gap that has not been filled when incorporating these new technologies into traditional safety management, which is discussed in the concept of Safety 4.0 and is an essential aspect of creating a blueprint and its workability in the industrial sector of Saudi Arabia.

2 AIM AND OBJECTIVES

2.1 Aim

This current study intends to synthesize and critically evaluate the literature published between 2020 and 2025 on the effects of the Internet of Things (IoT), artificial intelligence (AI), and other digital technologies on workforce safety (WS) and occupational safety and health (OSH) management in the Saudi Arabia industrial sector.

2.2 Objectives

1) Classify digital safety technologies in hazard domains and industry/sector.
2) Compare and contrast the methodologies used in evaluation and validation, human factors, and safety considerations.
3) Compare and contrast the challenges and hazards of applying digital safety technologies in OSH management in the Saudi Arabia industrial sector.
4) Formulate an actionable blueprint for Saudi Arabia for the specified period in line with the best practices in the thorough evaluation of DSSs.

3 CONCEPTUAL FOUNDATIONS

3.1 Safety 4.0 – a socio-technical system

It is defined as the application of Industry 4.0 concepts to OSH management in the prevention of work-related accidents and illnesses through the application of digital technologies and human factors. It is considered a socio-technical system in which the effectiveness of digital technologies and human factors is dependent upon the integration of human elements.

3.2 Evaluation and governance standards

Considering the significant influence of digital safety technologies on OSH management decisions in the Saudi Arabia industrial sector, it is imperative to evaluate the application of digital safety technologies in OSH management. The PRISMA 2020 guidelines are used to conduct transparent systematic reviews. The CONSORT-AI and SPIRIT-AI guidelines are used to report AI-related trials and systematic reviews, respectively. The DECIDE-AI guidelines are used to conduct early evaluation of DSSs in addressing all dimensions of human factors, safety, and human-technology interaction.

3.3 Digital transformation as an enabler for social performance

Digital transformation, including IoT and smart factories, is an enabler for digital transformation, and the meta-analysis indicates the considerable impact of digital transformation on economic, environmental, and social performance.

4 METHODS

4.1 Review design and scope

The review will be carried out following the PRISMA 2020 guidelines, with specific focus on the context of Saudi Arabia. The scope of the review will include industries where there is potential to improve through the application of digital technology to enhance safety and efficiency, such as construction, manufacturing, mining, utilities, energy, petrochemical, and logistics industries.

4.2 Search strategy and inclusion criteria

The keywords to be used in the search are as follows: (i) Occupational Safety and Health/Workplace Safety, (ii) Digital Technologies such as IoT, wearables, computer vision, artificial intelligence/machine learning, Safety 4.0, digital twins, and augmented reality/virtual reality for safety training, and (iii) Industry sectors relevant to Saudi

Arabia. The search period will be from 2020 to 2025. The outcomes will be based on quantitative measures such as performance metrics and safety management metrics.

4.3 Data extraction and synthesis

The focus of the data extraction will be on dimensions such as industry context, hazard domains, sensing modalities, analytics, integration, validation, and results. The aim of the synthesis will be to identify the technologies applied and their classification to establish a standardized pipeline.

4.4 Quality considerations

In terms of quality, the assessment of the data will cover aspects of provenance, validation, implementation, and human factors. In the pilot phase, the quality of the data will be assessed based on the guidelines for AI-based interventions and early decision support systems.

5 RESULTS

5.1 IoT sensing and connected worker wearables

In the case of wearables used by connected workers, these devices are used for collecting data on a wide range of physiological, biomechanical, and environmental parameters. A scoping review published in 2024 on the potential of wearables used in the connected workers' environment for improving safety highlighted the importance of data collection for improving safety through the adoption of data-driven risk management strategies. A systematic review confirms the contribution of wearables in the connected workers' environment, especially for ergonomics analysis and early detection of musculoskeletal hazards. In industries with a high risk of accidents, the main aim of risk exposure reduction can be achieved with the adoption of wearables, where thresholds are set, as highlighted in the systematic review on the adoption of digital technologies in the connected workers' environment.

5.2 Computer vision for safety compliance and hazard recognition

Computer vision is frequently utilized to track and detect the use of personal protective equipment, proximity to hazards, and other safety issues. A deep learning model with transfer learning for the detection of PPE at construction sites was successful, with the results obtained and documented in 2020 [12]. The formulation of a safety assurance system requires the integration of a variety of technologies with the objective of recognizing hazards within a complex environment. A review of the computer vision technology, with particular emphasis on the detection and monitoring of PPE, reveals that there is significant progress with regard to computer vision, although there is still a need to resolve issues with regard to environment, identity, and security. A critical analysis of the computer vision technology, with particular reference to the detection and monitoring of occupational safety and health, reveals that there is a limitation with regard to privacy and cost, which may impede the use of computer vision.

5.3 Safety analytics, prediction, and decision support

Moreover, the application of artificial intelligence and automated learning has been used for the identification and monitoring of safety issues, converting heterogeneous information into an actionable format for the identification and prediction of possible safety hazards. A systematic review of deep learning analytics for manufacturing safety points out the importance of deep learning analytics in the context of the manufacturing industry, while additionally identifying the challenges related to the security and privacy of the data, which need to be addressed by the industry. A methodological approach for the observation and supervision of complex industrial environments using machine learning, considering the top view, is applicable for industries with complex environments and large footprints. The development of safety management systems, such as Safety 4.0, involves the development of an integrated platform for risk identification, reporting, and prediction, while considering the security aspects during integration. The benefits of digitalization in the workplace are clear, while the psychosocial factors have created new risks in the work environment.

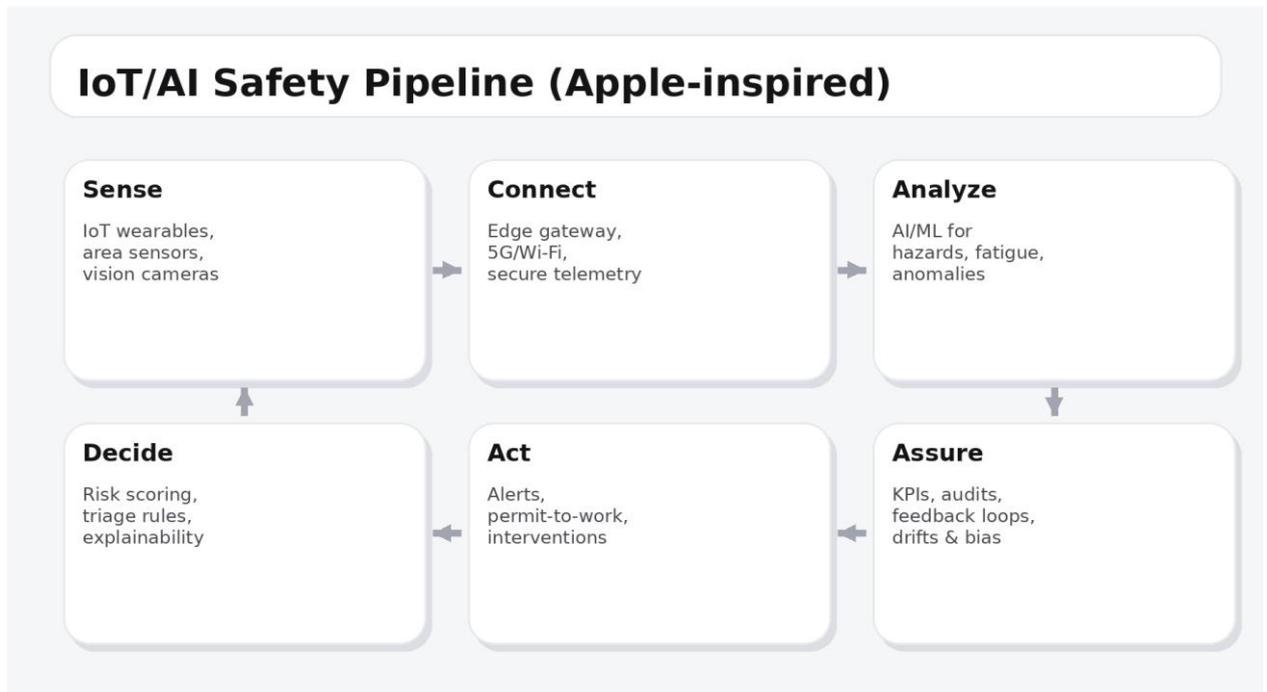**5.4 Immersive technologies for safety training**

Augmented reality and virtual reality technologies have become sufficiently sophisticated for the development of safety training tools. A systematic review and meta-analysis of augmented reality applications for safety training have concluded the potential benefits of augmented reality for safety training, while the development of safety training materials using augmented reality-based VR for construction hazard awareness has been found to be promising.

5.5 Digital twins and assurance

Digital twin technology has been found to have potential contributions to safety assurance in the context of the industry. A research study based on the survey method for the development of digital twins for occupational safety and health (OSH) has concluded the potential benefits for the development of digital twins for the field of OSH and related fields. Further research on the application of digital twin technology for safety assurance highlights the potential benefits for the development of safety assurance, while considering the human-robot collaborative manufacturing systems, along with the development of safety assurance using deep learning.

5.6 Summary of evidence applicable to saudi industries

For the Saudi Arabian industry, three applications are seen as likely to produce the most promising short-term evidence: connected worker wearables, computer vision, and integrated leading indicators. However, the most significant benefits are seen in high-hazard severity response situations, such as in the energy, petrochemical, or construction industries. To achieve these benefits, organizational readiness, security, and worker-centricity are critical factors, which are also seen in the digital transformation literature.

IoT/AI Safety Pipeline (Apple-inspired)

Sense	Connect	Analyze
IoT wearables, area sensors, vision cameras	Edge gateway, 5G/Wi-Fi, secure telemetry	AI/ML for hazards, fatigue, anomalies

Decide	Act	Assure
Risk scoring, triage rules, explainability	Alerts, permit-to-work, interventions	KPIs, audits, feedback loops, drifts & bias

Table 1

Evidence map of digital technologies and their safety impacts (2020–2025).

Technology	Typical data	Safety use case	Evidence level (2020–2025)	Key risks/constraints
Wearables & IoT sensors	Physiology, location, environment	Heat stress, fatigue, gas exposure, proximity	Strong (reviews + pilots) [16,17]	Privacy, comfort, battery, acceptance [10]
Computer vision	Video, images	PPE compliance, exclusion zones, unsafe acts	Strong (multiple studies + reviews) [12,11,15]	Occlusion, drift, identity/privacy, cyber [11]
AI/ML analytics	Multimodal streams, incident data	Risk scoring, anomaly detection, leading indicators	Moderate-to-strong (frameworks + reviews) [6,10]	Bias, calibration, false negatives
AR/VR training	Simulation interactions	Hazard awareness, procedural rehearsal	Moderate (SLR/meta-analysis) [18,19]	Content cost, cybersickness, transfer validity
Digital twins	Sensor + models	Scenario testing, HRC safety, reliability	Emerging (surveys + frameworks) [20,22]	Integration complexity, data quality

The evidence map above shows how "Safety 4.0" technologies are being used for workplace safety and the strength of the evidence for each technology (2020–2025), as well as the primary limitations of each technology that will affect its adoption and its

likelihood of being successful beyond the pilot stage. The overall picture shows that wearables/IoT and computer vision have the strongest evidence of real-world application of these technologies for workplace safety, AI/ML analytics has good evidence but with limitations related to data quality and accuracy, AR/VR has good evidence for training outcomes but limitations related to job transfer and cost considerations, and digital twins are showing good evidence but are still relatively early days for these technologies due to integration and data quantity considerations.

5.7 Wearables & IoT sensors (strong evidence)

Wearables and IoT sensors are best used for safety risks that are continuously measurable in the field. This includes heat stress, fatigue detection, gas exposure, and proximity hazards. The data collected by these sensors may include physiological sensors (heart rate, skin temperature), environmental sensors (temperature, humidity, gas), and proximity sensors (ULB, BLE, GPS depending on the environment). The strength of the evidence for these sensors reflects repeated reporting of feasible

The restrictions outlined in the table above are not minor roadblocks; they can be the difference between success and failure. Similarly, privacy and acceptance depend upon transparent policies, clear worker communication, and strict use restrictions, such as limited use for safety, identity, and retention. Comfort and battery life can affect the overall success of workers adopting and using the system. Devices that are uncomfortable, too heavy, or require frequent battery replacement do not perform well when the user base is expanded. Finally, for research and reporting, the wearable device reporting must address not only "data collected," but also how often the device was worn, false alarms, reaction time to the alarm, and results such as fewer heat-related incidents or near-misses.

5.8 Computer vision

Computer vision is a commonly used solution to monitor workers and enforce policies. Workers can be monitored for proper use of PPE, entering off-limit areas, detecting risky behavior, and enforcing high-risk behavior. The strong evidence for

computer vision, from 2020 to 2025, is based upon the advantage of improving an existing CCTV solution and the clear instances in which a visual cue is the best solution. The major problems with computer vision are based upon technical and privacy issues. Gradual degradation in accuracy, such as workers being hidden from the camera or camera drift, such as changes in the environment, can affect the overall accuracy. Similarly, the privacy and identity aspects can be major roadblocks. The best solution is privacy by design, which includes edge computing, blurring images, and avoiding facial recognition unless necessary and legal. Finally, cybersecurity is an important issue with cameras, which can be targeted if not properly secured. For accurate reporting, the study must address the conditions under which the data was collected, how the model performed over time, and the results, such as fewer instances of repeated PPE violations.

5.9 AR/VR training

AR/VR technology has its strongest applications where practice really matters, like procedures, hazards, and navigating through high-risk scenarios without actually being there. This area has shown positive results and learning outcomes in many studies and systematic reviews. This technology has been classified under the moderate evidence category. Besides practice, AR technology has been found to be useful for persons in the field with step-by-step instructions and connecting them to remote experts to help them stay safe and secure while performing hazardous tasks.

The challenges with AR/VR technology are mostly practical and include the expense of developing content, the expense of rolling out the equipment to the right place, cybersickness, and validating whether the training actually translates to better and safer procedures in the real world. The best way to roll out AR/VR technology would be to identify a few procedures that are considered to be of high risk and then build AR/VR technology for the same. Digital Twins (emerging evidence)

Digital twins combine data and modeling to test scenarios and make predictions to improve operations and reduce failures. In terms of safety, digital twins help to recreate hazardous conditions and test "what if" scenarios to reduce operational risks. This area has been classified under the emerging evidence category since it requires heavy integration with various systems and data to function properly and give the best results.

The challenges with digital twin technology are mostly related to integration complexities. The quality of the digital twin depends on the quality of the data architecture and the assumptions made during modeling. The practical value of digital twin technology would be best if it starts with a specific use case and then gradually expands to other areas.

In all the technologies, the evidence map shows the path from sensing and visibility, such as IoT and visual data, to decision intelligence, such as AI/ML analytics, and then to capability building, such as AR/VR, and finally to system-wide optimization, such as digital twins. The typical sequence of successful programs follows this pattern:

First, establish dependable data capture and safety signals; next, develop analytics to prioritize and predict; after that, develop training and simulation; and finally, integrate it all into a digital twin. If you wish to improve your paper in this section, note that there are three cross-cutting requirements that shape the outcomes of all the technologies:

1. Data governance and privacy, which entails the specifics of purpose limitation, consent, and communication, as well as the minimization of identity data, retention, and secure access controls;
2. Cybersecurity and resilience, which entails the specifics of hardening the entire chain, including secure device networks, camera endpoints, model pipelines, and integration APIs, especially where safety systems are involved in real-time;
3. Human factors and adoption, which entails the specifics of worker acceptance and ergonomics, including alarm fatigue and escalation.

6 DISCUSSION

6.1 The Meaning of "impact" in the context of workplace safety

The definite impact of digital technology on safety is achieved through intermediate or operational results. Intermediate results relate to the performance metrics of the detection system (precision, recall, F1, latency) as well as the ability to quantify. The operational results are achieved through lower exposure, fewer near-miss incidents, quicker hazard mitigation, quicker transfer of training, and quicker leading indicator improvements. In the context of the Saudi Arabian environment, a significant implication

is the a priori determination of the measurement model that relates digital technology to the results.

6.2 Saudi arabian deployment blueprint for digital technology

In the context of the preceding discussion, a six-step blueprint is proposed for the implementation of digital technology, as relevant to the Saudi Arabian environment, particularly in the context of the oil fields, as illustrated in Figure 1.

Step 1: Sense – Selection of hazard signals as well as validation of the feasibility of the sensors in the real world.

Step 2: Connect – Establishment of secure connections, device identifiers, data integrity, as well as offline capabilities.

Step 3: Analyze – Determination of interpretable baseline models, as well as the risk of false negatives.

Step 4: Decide – Determination of risk thresholds, as well as the explanations, in alignment with the decision processes of the supervisor.

Step 5: Act – Integration with permits, toolbox talks, as well as corrective actions, avoiding communication duplication.

Step 6: Assure – Monitor key performance indicators, periodic audits, and assessment of subgroup effects, such as job roles and shifts.

This blueprint for safety seeks to attain significant improvements in safety outcomes by addressing the limitations identified in the review of Safety 4.0 and Industry 4.0 OSH, as discussed in the references [6, 7, 9]. The recommendations made by the DECIDE-AI framework for assessing the outcome of the initial stage pilots, such as human-AI interaction, safety, and refinement, are to be followed to avoid the risks associated with automation bias and over-monitoring, as discussed in reference [4].

6.3 Governance, privacy, and cybersecurity

There are possibilities for safety data collected in an industrial environment to include personal information, leading to the violation of the workers' right to privacy and creating mistrust between the employees and the employers. A review of the use of data

collected in an industrial environment and the integration of technology in the field of OSH have concluded that the issue of privacy and security is a hindrance to the implementation of technology and technology-based OSH solutions in the workplace, as discussed in the review articles. The issue of privacy in the context of the OSH program in Saudi Arabia is to be addressed by the inclusion of data minimization, minimum data storage, restricted data access, and transparency regarding the collection and use of the data with the employees. Cybersecurity is an essential component of the OSH program, and the violation of the data stored in the devices by hackers can cause workers to make wrong decisions, leading to accidents, and therefore, the architectural considerations for the OSH program are to be made for the industrial environment.

6.4 Saudi operational evaluation plan: metrics, study designs, and assurance

One limitation of the literature from 2020 to 2025 is the disconnect between model outputs and safety improvements. The Saudi organizations will address the aforementioned constraint by developing an operational evaluation plan that integrates sensing and analytics into decision-making procedures and, eventually, into safety improvements. Part of the plan will be an evaluation model that incorporates the metrics to be used, the sensing process to be applied, and the expected outcome. For example, the vision sensor for personal protective equipment will incorporate the expected types pertaining to personal protective equipment to be detected (such as helmets, vests, and goggles), the context of individual protective equipment within the active work zone, and the conclusions to be drawn. In another example, the heat stress sensor will incorporate the physiological aspects of heat stress, the expected measurement rate, and the expected conclusions to be drawn. The aforementioned disconnect in the literature from 2020 to 2025 will hinder the assessment of the accuracy metrics to be used to measure the success of the program. The evaluation process will involve several stages. Stage A will involve bench testing to assess the accuracy of the sensors and the effectiveness of the labeling process in terms of exactness and recall. Stage B will involve silent-mode deployment to assess projected alert rates, false alarm rates, and population coverage. Stage C will involve limited intervention to assess the outcomes in terms of time to correction, hazard removal, and near-misses. Stage D will involve deploying the program across multiple

organizations to assess safety outcomes using a quasi-experimental design. The main requirement here is to incorporate calibration and threshold governance, which means providing classification exactness and the relationship of risk scores to sites in Saudi Arabia, followed by threshold determination based on net benefits and capacity constraints. Decision curve analysis should be applied to determine whether the alerting policy has more true hazard mitigations than false interruptions. Subgroup analyses should be conducted for different roles, such as contractors vs. employees and diurnal variations such as day vs. night shifts, because of differential sensor coverage. The programs should be developed to detect "alert fatigue indicators" such as changes within response times, dismissals, and repeated violations. Adaptation of interfaces ought to be preferred over adaptation of models. The phase of assurance is still important even after the go-live process. The monitoring dashboard should be extended to incorporate data quality indicators, such as data presence, sensor availability, and model drift indicators, such as feature shifts, video domain alterations, and cybersecurity events. The second requirement is to incorporate privacy aspects such as data limitation, data retention, worker communication, and using data for safety instead of punitive actions. By using these best practices, the Saudi Safety 4.0 programs will be able to show their effect while continuing to sustain trust. For ease of comparison between projects, the provision of information must be limited to key information such as site type, workforce size, hazard definition, sensor placement, labeling method, model version, and operating policy. The economic analysis must be simple yet clear, including device costs, maintenance costs, and time spent by the workers. The leading indicators must be able to be connected to the lagging indicators by standardized taxonomies of incidents, such that they are disseminated publicly, replicated in the clusters in Saudi Arabia, and useful to the government in determining the next stages of implementation. Implementation in Saudi Arabia's high-hazard industries would also be aided by the design of the proposed system being specifically informed by human factors considerations. Although existing studies have shown positive detection metrics, very little work has been done to investigate the underlying mechanisms of detection event generation, communication of detection events to supervisors and workers, and the utilization of detection events in the context of the monitoring task. A viable solution to these problems would be to conceptualize an "alert contract" for each of the application scenarios, specifying who to alert, what form the

alert takes, what action to take in response to the alert, and when the alert process is closed. Provisions for connectivity loss must also be considered, especially in the context of remote locations and underground mines. Rate limiting and bundling of similar alerts must also be considered to avoid dismissing repeated alerts during mitigation. The user interface must also focus on brevity and clear communication of hazard type, location, level of confidence, recommended course of action, and evidence to support recommendations (such as a brief video clip, sensor trace, and/or checklist when possible and appropriate). Training must also extend beyond device operation to boundaries in decision-making related to dismissal of automated recommendations and failure modes, including failure modes of PPE, PPE visibility (such as PPE being occluded from view), and sensor failure. Deployment-related factors are likely to have a larger impact on the performance of computer vision-based applications, and for applications deployed in Saudi Arabia, documentation of these factors would be required. A simple pre-deployment checklist for lens cleaning, time synchronization, buffering, and masking of privacy areas was shown to significantly reduce false alarm rates. Due to the varied PPE regulations in different geographies, a geo-fenced policy should be used instead of a global policy, as the same actions might be required in one area and not required in another area. In cases where facial recognition is not required for safety, privacy-preserving techniques such as blurring, on-device inference, and storage should be used to ensure safety and improve the acceptability of the application. In addition, consideration should be given to the methods used for model evaluation, as incorrect methods could lead to an overestimation of the improvement and mask safety-related issues that could have occurred. In addition, updates related to the model should include discrimination metrics, along with operational metrics such as rates, time, and mitigations.

7 CONCLUSION

Evidence from 2020-2025 suggests that the Internet of Things (IoT) and artificial intelligence (AI) can be used to augment worker safety in industries by increasing the visibility of hazards, ensuring better compliance, and providing better leading indicators for safety performance. The most mature applications include connected worker

wearables and computer vision for personal protective equipment and exclusion zone detection. With respect to Saudi industries, the impact would be based on the reliable integration of IoT and AI into their industries, which would include defining clear thresholds, ensuring the explainability of results, cybersecurity, and continuous performance assurance. A gradual deployment from pilot to scale-up, focusing on a narrow set of high-value hazards initially, would help address the problem of alert fatigue and ensure long-term adoption.

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Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.