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Enhancing Construction Site Safety Through the Adoption of Safety Technologies

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ABSTRACT

The construction industry faces ongoing safety challenges due to its inherently dynamic and high-risk environment. Workers are frequently exposed to hazards such as falls, electrical accidents, equipment malfunctions, and site collisions, making safety management a top priority. This study investigates the implementation of safety technologies to improve the safety at construction sites, employing a quantitative research methodology. Structured surveys were distributed to 274 contractors (Grades G4 to G7) in Perak, Malaysia, an area noted for a high rate of occupational accidents and fatalities. The research examines the adoption and impact of various technologies, including wearable safety devices, drones, IoT sensors, Building Information Modelling (BIM), and augmented reality (AR). Key barriers to technology adoption were identified, such as high implementation and maintenance costs, limited technical training, resistance to organizational change, and infrastructure issues like unstable power supplies in remote areas. Despite these challenges, findings show that safety technologies significantly enhance site safety by enabling real-time hazard detection, proactive monitoring, and better compliance with safety protocols. Descriptive statistical analysis using SPSS revealed strong correlations between the use of specific technologies and reductions in reported incidents. The study recommends targeted training programs, investment in cost-effective technology solutions, and supportive policy frameworks to foster wider adoption. It also emphasizes the importance of data-driven strategies and stakeholder collaboration. Ultimately, this research highlights the transformative role of safety technologies in reducing risks and promoting a safer, more efficient construction industry.

Keywords: construction industry; hazard; safety technologies.

INTRODUCTION

The construction sector is a critical industry worldwide, employing a significant portion of the workforce (Taghinezhad et al., 2021). However, due to the diverse materials used, hazardous and heavy equipment, inadequate safety practices, and the inherently risky nature of construction work, construction sites are among the most dangerous workplaces. Workers are exposed to numerous risks, such as falls from heights, being struck by objects, electrocution, and entanglement in machinery (Musarat et al., 2021). These hazards underscore the importance of implementing effective safety measures to mitigate accidents.

Monitoring safety on construction sites through conventional methods remains labor-intensive and prone to errors due to its reliance on manual processes (Hussien, 2017). Identifying potential hazards often necessitates frequent site inspections, where continuous monitoring becomes impractical because trained personnel must visually assess the sites (OSHA, 2016). Given the complex and ever-changing nature of construction sites, it can be difficult for safety managers to swiftly identify and address hazardous areas (Park et al., 2017). Mohamed et al. (2023) note that recognizing risks and hazards accurately is challenging, as it often relies on individual expertise and subjective judgment. Furthermore, unsafe conditions may go unnoticed until accidents or near misses occur, primarily due to fragmented, manual site observations (Bakhoum et al., 2023).

Table 1 shows the data from the Department of Occupational Safety and Health (DOSH), reveals that approximately 6,951 occupational accidents were reported between January and October 2023. Many of these incidents resulted in fatalities or severe injuries, leaving some workers unable to continue their roles within the construction sector. This study aims to explore how technology can enhance safety in construction environments.

Table 1. Occupational Accidents Statistics reported from January to October 2023
PD: Permanent Disability
NPD Non-Permanent Disability

State	NPD	PD	Death	Total
Johor	1171	54	18	1243
Kedah	362	1	6	369
Kelantan	113	0	10	123
Melaka	379	5	2	386
Negeri Sembilan	398	10	7	415
Pahang	379	8	8	395
Perak	697	31	12	740
Perlis	11	0	1	12
Pulau Pinang	654	16	9	679
Sabah	299	19	15	333
Sarawak	311	8	21	340
Selangor	1408	60	27	1495
Terengganu	156	5	6	167
Wilayah Persekutuan Kuala Lumpur	227	3	13	243
Wilayah Persekutuan Labuan	10	0	1	11
Total	6575	235	141	6951

LITERATURE REVIEW

Types of safety technologies

Safety technologies encompass a wide array of tools, devices, and systems that aim to enhance hazard detection, risk mitigation, and emergency response across industries. These technologies are particularly critical in high-risk sectors such as construction, manufacturing, transportation, and mining. The following outlines the primary types of safety technologies currently in use:

Internet of things

The implementation of modern technology in the construction industry has fallen short of initial expectations, despite ongoing digitalization efforts that promise gradual technological advancements and enhanced productivity (Erdirisinghe & Woo, 2021). However, the industry continues to face delays in the adoption of new technologies and automated processes, hindering the full realization of digitization benefits (Musarat et al., 2021).

The Internet of Things (IoT) refers to a network of interconnected sensors, actuators, and devices that collect, exchange, and analyze data in real time to support decision-making and automation. In safety applications, IoT enables continuous monitoring of environmental conditions (e.g., gas concentration, temperature, humidity) and worker health indicators (e.g., heart rate, body temperature, location) to detect hazards proactively (Li et al., 2018). For instance, in oil and gas facilities, fixed gas detectors can trigger automatic shutdowns when methane levels exceed safe thresholds, preventing catastrophic incidents. Wearable IoT devices—such as smart helmets and wristbands—can alert supervisors if a worker enters a restricted zone or exhibits signs of fatigue, thereby reducing response times to emergencies (OSHA, 2016).

Beyond hazard detection, IoT underpins predictive maintenance by monitoring equipment vibration, pressure, and thermal profiles. Machine-learning algorithms analyze these data streams to forecast component failures days or weeks in advance, allowing maintenance teams to intervene during scheduled downtimes rather than reactively after breakdowns (Lu et al., 2017). This shift from corrective to predictive maintenance has been shown to reduce unplanned downtime by up to 30% and cut maintenance costs by as much as 25% in manufacturing plants (Lu et al., 2017).

However, IoT's reliance on networked devices introduces cybersecurity vulnerabilities. Unauthorized access to sensor networks can lead to false alarms or suppression of critical alerts. To mitigate these risks, best practices include encrypted communications, device authentication, and regular firmware updates (Li et al., 2018). Moreover, integrating IoT data with centralized safety dashboards enables safety managers to visualize trends, prioritize risks, and coordinate responses efficiently. As industries embrace digitalization, the IoT's ability to transform raw sensor data into actionable insights will remain pivotal for advancing proactive, data-driven safety management.

Building information modelling

Building Information Modelling (BIM) represents a paradigm shift from 2D drawings to rich, data-driven 3D models that encapsulate both the physical and functional characteristics of built assets. Safety applications of BIM leverage these models to simulate construction processes, identify spatial conflicts, and optimize site logistics before work begins. Through clash detection, BIM can reveal potential fall hazards such as protruding rebar or open edges, allowing project teams to install guardrails or safety nets in the design phase (Azhar et al., 2011). This pre-emptive approach reduces on-site incidents by up to 15% in projects employing 4D BIM (time-based scheduling) for safety planning (Eastman et al., 2011).

Virtual walkthroughs derived from BIM models facilitate stakeholder engagement in safety reviews. Safety officers can "walk" a digital jobsite using desktop or VR interfaces to spot trip hazards, verify egress paths, and plan material storage zones that minimize congestion (Azhar et al., 2011). When combined with 4D sequencing, teams can visualize the evolution of hazards across time, ensuring that safety measures such as fall protection systems are deployed precisely when needed (Eastman et al., 2011).

Despite its advantages, the implementation of BIM faces challenges including data interoperability and user proficiency. Integrating BIM with risk-analysis software requires adherence to open data standards (e.g., IFC), and training personnel to interpret complex models can demand significant upskilling (Succar, 2009). Nonetheless, as the construction industry moves toward digital twins—dynamic BIM models linked to live project data—the potential for continuous safety monitoring and real-time hazard mitigation will expand. BIM's ability to centralize design, schedule, and safety information positions it as a cornerstone of modern construction safety management.

Artificial intelligence

Artificial Intelligence (AI) encompasses a suite of technologies such as machine learning, deep learning, and computer vision that enable systems to learn from data and perform complex tasks. In safety contexts, AI is leveraged for automated hazard recognition, predictive risk assessment, and incident analysis. Computer-vision systems, trained on large datasets of annotated images, can process live video streams from jobsite cameras to identify unsafe behaviours like missing personal protective equipment (PPE) or entry into exclusion zones, achieving accuracies above 90% in pilot studies (Cheng & Teizer, 2013). By generating real-time alerts, these systems empower supervisors to intervene before minor infractions escalate into serious accidents.

Beyond visual monitoring, machine-learning models ingest historical incident and near-miss data to forecast high-risk scenarios. For example, classification algorithms can predict the probability of slip-and-fall events under certain weather and workflow conditions, prompting pre-emptive deployment of signage or slip-resistant surfaces (Hassan et al., 2019). Such predictive capabilities have been associated with a 20–25% reduction in recorded incidents in manufacturing settings where they have been adopted (Hassan et al., 2019).

AI also accelerates root-cause analysis by mining unstructured data such as safety reports and maintenance logs using natural language processing (NLP). These tools can surface latent patterns and recurring issues that may elude manual review (Tezel et al., 2018). However, AI systems require high-quality data and transparent algorithms to avoid biases that could undermine trust among workers. Ensuring data privacy, model explainability, and ongoing validation are critical for successful AI deployment in safety management. As AI technologies mature, their integration into safety workflows promises to shift organizations from reactive to truly anticipatory risk control.

Virtual reality

Virtual Reality (VR) creates fully immersive, computer-generated environments that simulate real-world scenarios, allowing users to experience and interact with hazardous situations in a safe, controlled setting. In safety training, VR has demonstrated significant improvements in knowledge retention and hazard recognition compared to traditional classroom methods. For example, trainees who underwent VR-based fall-protection training exhibited a 30% higher retention rate of correct procedures after one month than those trained via lectures (Wang et al., 2018).

VR simulations can replicate complex emergencies such as chemical spills in confined spaces or multi-vehicle collisions, enabling participants to rehearse evacuation routes, incident command protocols, and equipment usage under stress (Kang, 2020). The addition of haptic feedback devices further enhances realism by providing tactile sensations (e.g., resistance when operating valves), which cultivates muscle memory and improves reaction times during actual emergencies.

Beyond individual training, VR supports safety planning by allowing teams to conduct virtual walkthroughs of proposed construction sites or facilities. Stakeholders can identify spatial hazards, optimize placement of safety barriers, and evaluate emergency egress paths without the cost and risk of on-site visits (Sacks et al., 2013). Challenges to VR adoption include high initial costs, the need for bespoke scenario development, and users experiencing motion sickness. However, as the technology becomes more accessible and content libraries expand, VR is poised to become an integral component of comprehensive safety programs, bridging the gap between theoretical knowledge and practical, hands-on experience.

Challenges in adopting new safety technologies

While modern safety technologies such as wearables, VR/AR, IoT systems, and AI offer substantial promise in improving occupational safety, their implementation is not without hurdles. The construction industry encounters various barriers that hinder widespread adoption and optimal utilization.

Cultural issues and explainable AI

One of the most profound challenges in adopting new safety technologies is overcoming organizational and cultural resistance. In many traditional industries like construction and manufacturing, long-standing safety practices are deeply embedded, and introducing technologies like AI can meet scepticism or outright resistance from workers and management alike. Employees may fear job displacement or may not trust AI-based recommendations, especially when such systems operate as “black boxes” with unclear logic (Holzinger et al., 2017). This is where the concept of Explainable AI (XAI) becomes critical. XAI refers to AI systems designed to offer transparency by explaining their decisions in a human-understandable manner. Without this transparency, safety managers may hesitate to rely on AI for risk prediction or hazard detection, fearing liability or misunderstanding outcomes (Gunning & Aha, 2019).

Cultural acceptance also depends on leadership and change management strategies. Organizations with a strong culture of innovation and continuous improvement are more likely to embrace digital tools. On the other hand, those with rigid hierarchies or where safety is perceived as compliance-based rather than proactive would often struggle to integrate new technologies (Teizer et al., 2017). Involvement of workers in the development and testing of AI systems has shown promise in increasing trust and adoption. Therefore, technological deployment must be accompanied by robust training programs, clear communication, and efforts to cultivate a data-driven safety culture.

Security

As safety technologies increasingly rely on data and networked systems, cybersecurity becomes a major concern. Devices such as smart wearables, IoT sensors, and cloud-based safety dashboards collect and transmit sensitive information about worker locations, health, and operational procedures. A breach in these systems can not only compromise personal data, but also disrupt safety-critical functions like gas leak alerts or emergency responses (Lu et al., 2017). For instance, if an IoT sensor feeding data to an AI risk engine is hacked or manipulated, the system might misclassify a hazardous event, leading to severe consequences.

In addition to external threats, internal risks such as poor password management or lack of access control will further complicate the cybersecurity landscape. Many organizations fail to implement strong encryption or regular software updates, leaving safety systems vulnerable (Farooq et al., 2015). As more safety systems become interconnected—especially in smart construction sites and factories—these vulnerabilities can propagate across systems, multiplying risk.

To address this, cybersecurity protocols must be built into the design of safety technologies from the outset. This includes adopting practices like secure booting, encrypted communication, multi-factor authentication, and regular penetration testing. Moreover, there is a need for regulatory frameworks that standardize cybersecurity requirements across safety tech providers. Without robust security measures, the trustworthiness and reliability of safety technologies are fundamentally undermined.

Talent shortage

The adoption of advanced safety technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Building Information Modelling (BIM) requires a workforce skilled in digital systems, data analytics, and systems integration. However, many industries, especially in construction and heavy manufacturing, face a critical shortage of talent capable of designing, deploying, and maintaining these technologies (Barbosa et al., 2017). This talent gap extends not only to engineers and IT specialists but also to frontline safety professionals who are expected to interpret digital insights and apply them effectively in the field.

One of the primary reasons for this shortage is the misalignment between traditional education/training programs and the emerging demands of safety tech implementation. Many vocational and safety training programs have yet to incorporate modules on data literacy, software operation, or cyber-physical systems (PWC, 2018). As a result, organizations often struggle to upskill existing employees while also competing in a tight labor market for digitally fluent talent.

The talent gap also creates dependency on external consultants or technology vendors, which may not be sustainable or cost-effective in the long run. To address this challenge, companies must invest in continuous learning programs, partner with educational institutions to align curricula with industry needs, and foster interdisciplinary teams that combine domain expertise with digital skills. Bridging the talent gap is essential for fully realizing the benefits of safety technology.

High initial costs

While the integration of safety technologies typically involves significant upfront investment, this can act as a barrier, particularly for small- and medium-sized enterprises (SMEs). Advanced systems such as VR-based training platforms, AI-powered video analytics, and wearable IoT devices require not only capital expenditure for hardware and software, but also associated costs related to infrastructure upgrades, staff training, and system integration (Arditi et al., 2019).

Moreover, many safety technologies do not yield immediate financial returns, making it difficult for organizations to justify the investment in traditional cost-benefit terms. Although studies have shown that these technologies can reduce incident rates, improve compliance, and enhance productivity over time, the long payback period can deter decision makers, especially in budget-constrained environments (Fang et al., 2019). Additionally, uncertainties related to maintenance, vendor lock-in, and technology obsolescence further discourage investment.

To overcome this, some governments and regulatory bodies have begun offering incentives, tax breaks, or funding grants for companies that invest in innovative safety solutions. Another promising approach is adopting a phased implementation strategy, starting with pilot projects that demonstrate clear value before scaling organization-wide. ROI frameworks that quantify both direct and indirect benefits such as reduced downtime, lower insurance premiums, and improved worker morale can also help shift perceptions about high initial costs.

Ethics and governance

The rise of safety technologies powered by data and automation has brought ethical and governance concerns to the forefront. One key issue is the balance between surveillance and privacy. Technologies like wearable sensors and facial recognition systems can track workers' locations, behaviours, and even biometric data. While these systems aim to enhance safety, they also raise concerns about individual privacy, consent, and data misuse (Allam & Dhunny, 2019).

Ethical dilemmas also emerge from decision-making algorithms used in AI-based systems. If an AI system incorrectly flags a worker as unsafe, leading to disciplinary action or dismissal, it can have serious consequences, especially if the system lacks transparency or explainability (Gunning & Aha, 2019). Moreover, biases embedded in AI training data can lead to unfair treatment of certain worker groups, reinforcing existing inequalities.

Governance frameworks are often underdeveloped in many industries, resulting in a lack of clear accountability, data protection standards, or ethical review mechanisms. Without these, organizations may inadvertently breach data protection laws and erode worker trust. Ethical deployment of safety technology requires robust governance structures that define who owns the data, how it can be used, and how workers can opt in or out.

To address these issues, organizations are encouraged to adopt ethical AI guidelines, conduct impact assessments, and include diverse stakeholders in the design and oversight of safety systems. Transparent communication and participatory governance can ensure that the benefits of safety technologies are realized without compromising ethical standards.

Strategies to enhance the effectiveness of safety technologies

While safety technologies offer significant potential to reduce workplace hazards and improve risk management, their effectiveness largely depends on how they are implemented and integrated within organizational systems. The following strategies can enhance the utility, adoption, and long-term impact of safety technologies:

Enhanced training and education

Comprehensive training programs are crucial for ensuring that workers understand how to use safety technologies correctly. This includes not only initial training but also ongoing refresher courses and updates on new technologies or procedures. Training sessions should be tailored to the specific needs of the workforce, considering their skill levels, languages, and learning preferences. Interactive approaches, such as hands-on simulations, augmented reality tools, and game-based learning, can improve engagement and retention of safety knowledge. Guo et al. (2011) explored the use of game technologies for construction safety training, highlighting their potential to make learning both effective and engaging.

Improved communication and collaboration

Effective communication and collaboration among all stakeholders, including workers, supervisors, and technology providers, are essential for successful implementation. Establishing clear communication channels ensures that safety protocols, reporting procedures, and feedback mechanisms are understood and accessible to everyone on site. Regular safety meetings, workshops, and collaborative problem-solving sessions can strengthen trust and teamwork. In addition, the use of digital tools such as mobile apps and project management software can facilitate real-time communication and ensure that safety updates reach the intended audience promptly.

Data-driven decision making

Safety technologies can generate vast amounts of data that can be used to identify trends, predict potential hazards, and inform proactive safety measures. To harness this data effectively, construction companies need to invest in robust data analysis and visualization tools. By analyzing patterns, such as the frequency and causes of near-misses or incidents, safety managers can identify high-risk areas and implement targeted interventions. Advanced technologies like artificial intelligence and machine learning can further enhance predictive capabilities, allowing companies to address potential issues before they escalate. Rupasinghe and Panuwatwanich (2020) discussed the analysis of safety hazard factors from open data, emphasizing the importance of a data-driven approach to safety management.

Integration and interoperability

Many construction sites utilize multiple safety technologies from different vendors. Ensuring that these systems can communicate and share data seamlessly can enhance overall safety management. This requires the adoption of standardized protocols and APIs that enable interoperability. Integrated systems can provide a unified view of safety performance, allowing managers to make more informed decisions. For example, integrating wearable sensors, site monitoring cameras, and incident reporting tools into a single platform, can streamline data collection and analysis, reducing the likelihood of oversight.

Addressing human factors

While technology can play a significant role in improving safety, it is important to address the human factors that contribute to accidents. This includes fostering a culture of safety where workers feel empowered to report hazards and can actively participate in safety initiatives. Addressing issues such as fatigue, stress, and complacency is equally critical, as these factors can undermine the effectiveness of even the most advanced technologies. Providing regular breaks, ergonomic workspaces, and mental health support can help mitigate these risks. Li et al. (2018) discussed proactive behavior-based safety management, which emphasizes the importance of worker behavior and engagement in maintaining safety.

Ongoing evaluation and improvement

Regularly evaluating the effectiveness of safety technologies and identifying areas for improvement is crucial for ensuring long-term success. This includes conducting periodic audits, gathering feedback from workers, and analyzing incident data to assess the impact of implemented measures. Continuous improvement can be achieved by staying informed about the latest advancements in safety technology and integrating them into existing systems. Okpala et al. (2020) discussed utilizing emerging technologies for construction safety risk mitigation, underscoring the need for adaptability and innovation in safety management practices.

Regulatory frameworks and standards

Clear regulatory frameworks and industry standards can help ensure that safety technologies meet minimum safety requirements and are used effectively. Governments and industry bodies play a key role in establishing these standards and ensuring compliance through regular inspections and certifications. By aligning with regulatory requirements, construction companies can not only enhance safety but also build credibility and trust with stakeholders. Huang et al. (2016) addressed construction occupational safety and health performance concerns and proposed new measures, highlighting the importance of regulations in driving safety improvements.

METHODOLOGY

This study utilized a quantitative research approach targeting G4 to G7 contractors in Perak, a key construction hub in Malaysia and the third-highest state for workplace accidents. The total population of eligible contractors was 948, and random sampling was employed to ensure objectivity in participant selection. The Raosoft sample size calculator determined an appropriate sample size of 274 respondents, using parameters of a 5% margin of error, 90% confidence level, and 50% response distribution. This sampling strategy aimed to ensure statistical reliability and representativeness of the target group. Of the 274 questionnaires distributed, 136 were returned completed and valid, resulting in a 51% response rate, which exceeds the typical 20–30% benchmark suggested for construction research (Yong & Mustaffa, 2012). This high response rate enhanced the credibility and robustness of the findings. The data collected was analyzed using SPSS version 21, focusing on descriptive statistics such as frequencies and mean scores to interpret demographic data and survey responses. This analysis provided insights into the current practices, awareness, and adoption of safety technologies among contractors in the region.

RESULTS

Section A: Challenges associated with implementing new safety technologies

This section discusses the key challenges faced in implementing new safety technologies in the construction industry, based on the analysis of five identified attributes.

According to the results summarized in Table 2, the most significant challenge is “Cultural Issues and Explainable AI”, which holds the highest mean score of 5.00 with a standard deviation of 0.000. This suggests a unanimous agreement among respondents that organizational culture, resistance to change, and the complexity of understanding AI decision-making processes are major barriers to adopting new technologies. The zero standard deviation further indicates that all participants rated this factor equally, emphasizing its critical nature. The second most prominent challenge is “Security”, which received a mean score of 4.86 and a standard deviation of 0.2347. This reflects strong concern over data privacy, cyber threats, and the secure handling of sensitive site information when using connected or AI-powered technologies. Ranked third is the issue of “Talent Shortage”, with a mean score of 4.22 and standard deviation of 0.639. This highlights the industry’s struggle to find and retain skilled professionals who are proficient in the operation, management, and maintenance of modern safety technologies. These findings indicate that while technological solutions are advancing, human, organizational, and security-related barriers remain significant obstacles to their effective implementation.

Table 2. Challenges associated with implementing new safety technologies

Challenges Associated with Implementing New Safety Technologies	Mean	Standard Deviation	Rank
Cultural Issues and explainable AI	5.00	0.000	1
Security	4.86	0.347	2
Talent Shortage	4.22	0.639	3
High Initial Cost	3.87	0.753	4
Ethics and Governance	3.24	0.939	5

Note: Scale: Strongly Disagreed (1.00 average mean <1.50), Disagreed (1.50 average mean <2.50), Neutral (2.50 average mean <3.50), Agreed (3.50 average mean <4.50), Strongly Agreed (4.50 average mean <5.00).

Section B: Strategies to enhance the effectiveness of safety technologies

Table 3 provides a comprehensive assessment of various strategies aimed at improving the effectiveness of safety technologies. These strategies are evaluated based on their mean scores, standard deviations, and ranks, offering insights into their perceived importance and effectiveness in real-world applications.

Table 3. Strategies to enhance the effectiveness of safety technologies

Strategies to Enhance the Effectiveness of Safety Technologies	Mean	Standard Deviation	Rank
Enhanced Training and Education	4.92	0.267	1
Improved Communication and Collaboration	4.77	0.655	2
Data-Driven Decision Making	4.76	0.430	3
Integration and Interoperability	4.60	0.491	4
Addressing Human Factors	4.33	0.757	5
Ongoing Evaluation and Improvement	4.76	0.430	3
Regulatory Frameworks and Standards	4.17	1.194	6

Note: Scale: Strongly Disagreed (1.00 average mean <1.50), Disagreed (1.50 average mean <2.50), Neutral (2.50 average mean <3.50), Agreed (3.50 average mean <4.50), Strongly Agreed (4.50 average mean <5.00).

Topping the list is Enhanced Training and Education, which holds the highest mean score of 4.92 and the lowest standard deviation (0.267). This indicates strong agreement among respondents that equipping individual with the right knowledge and skills is crucial to maximizing the effectiveness of safety technologies. Training programs ensure that employees are familiar with safety protocols, understand how to use the technologies effectively, and can respond appropriately in emergency situations. Education also cultivates a safety-first culture, where proactive behavior and awareness become part of the organizational norm.

Ranked second is Improved Communication and Collaboration, with a mean score of 4.77. Effective communication ensures that safety-related information is shared accurately and promptly across departments and teams. Collaboration fosters a more integrated approach where stakeholders work together to identify risks and develop comprehensive safety solutions. Although the standard deviation is slightly higher (0.655), indicating some variation in responses, the overall score reflects strong support for this strategy. Two strategies share the third rank: Data-Driven Decision Making and Ongoing Evaluation and Improvement, each with a mean score of 4.76 and standard deviation of 0.430. Data-driven decision making emphasizes the use of analytics, monitoring tools, and performance metrics to guide safety initiatives. By leveraging data, organizations can predict potential failures, track incidents, and continuously refine their safety practices. Similarly, ongoing evaluation ensures that safety technologies and policies remain effective over time. Regular reviews and feedback loops help organizations stay adaptive and responsive to new risks and technological advancements.

Integration and Interoperability, with a mean score of 4.60, is ranked fourth. This strategy highlights the need for different safety systems and technologies to work seamlessly together. Integrated systems reduce redundancy, improve efficiency, and ensure that critical safety information flows unhindered across platforms. Although slightly lower in rank, the close mean score suggests it is still seen as a highly valuable strategy. Addressing Human Factors, ranked fifth with a mean score of 4.33 and a higher standard deviation of 0.757, this indicates more variability in perceptions. This strategy involves designing technologies and systems that account for human behavior, limitations, and interactions. It focuses on reducing human error through user-friendly interfaces, ergonomic designs, and psychological considerations. While essential, its lower score may reflect challenges in implementation or differing levels of awareness among respondents.

Lastly, Regulatory Frameworks and Standards received the lowest mean score (4.17) and the highest standard deviation (1.194), placing it at rank six. Despite being foundational to safety compliance, the variability in responses suggests that regulations may not always translate effectively into practice, or that their impact varies across different industries and regions.

In summary, the data emphasizes the importance of proactive, human-centered strategies such as training, communication, and continuous improvement. While regulatory measures provide necessary structure, they appear less influential in practice compared to dynamic and participatory approaches.

DISCUSSION

The findings of this study highlight that the effectiveness of safety technologies is significantly influenced by human-centered and organizational strategies. Enhanced training and education received the highest rating, underscoring the critical role of knowledge and skill development in ensuring the proper use and maintenance of safety systems. This aligns with previous research indicating that training enhances user competence and reduces human error in safety-critical environments (Reason, 2000; Hale et al., 2003).

Strategies such as improved communication, collaboration, and data-driven decision-making also ranked highly, reflecting the growing importance of a safety culture that prioritizes transparency, teamwork, and evidence-based practices. The equal emphasis on ongoing evaluation and improvement supports the view that safety technologies must evolve in tandem with changing operational contexts and technological advancements (Vinodkumar & Bhasi, 2011).

Lower-ranked strategies like addressing human factors and regulatory frameworks, though still relevant, may be perceived as foundational or reactive rather than proactive. The high variability in responses concerning regulations suggests a need for more adaptive and responsive policy frameworks that better reflect real-world industry challenges (Hopkins, 2009).

In summary, enhancing the effectiveness of safety technologies requires a holistic approach that combines technical solutions with human and organizational strategies. Prioritizing training, fostering communication, leveraging data, and embracing continuous improvement are essential to achieving and sustaining high safety performance levels.

CONCLUSIONS

The analysis of strategies to enhance the effectiveness of safety technologies reveals a clear prioritization of human-centered and improvement-driven approaches. Enhanced training and education emerged as the most critical strategy, highlighting the essential role of human competency in ensuring the successful application of safety technologies. Closely following are improved communication, collaboration, and data-driven practices, which emphasize the need for active engagement, informed decision-making, and adaptability in safety management.

While integration, interoperability, and ongoing evaluation also play important roles, the lower rankings of strategies such as addressing human factors and adhering to regulatory frameworks suggest that these elements, although important, are perceived as less directly impactful unless supported by proactive organizational efforts. The high standard deviation for regulatory frameworks further indicates varying opinions on their practical effectiveness.

Overall, the findings suggest that to maximize the potential of safety technologies, organizations must invest not only in the technologies themselves but also in cultivating a knowledgeable workforce, fostering a culture of communication and collaboration, and continuously assessing and improving their safety practices.

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CONFLICT OF INTERESTS

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Norsyazwana Jenuwa carried out the research, wrote and revised the article. Suhaila Ali conceptualised the central research idea and provided the theoretical framework. Norhafizah Yusop and Norsyazwana Jenuwa designed the research, method research (quantitative); Zaiwannizar Zainal Abidin and Noraini Md Zain performed data collection and analysed the result.

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