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INTEGRATED SAFETY PROTOCOLS FOR UNDERGROUND DRILLING: A SYSTEMATIC REVIEW AND CONCEPTUAL FRAMEWORK LINKING AUTOMATION, REAL-TIME MONITORING, AND HUMAN FACTORS

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ABSTRACT

Underground drilling operations remain among the most hazardous industrial activities due to the combined risks of gas leakage, dust explosions, rock mass instability, and human error. As mining operations extend to greater depths and technical complexity increases, conventional safety management approaches based on static procedures and reactive interventions have proven increasingly inadequate. This systematic review synthesises evidence from 204 peer-reviewed studies to critically examine the transition from traditional reactive safety protocols toward proactive, data-driven safety systems in underground drilling environments. The analysis identifies three interdependent pillars that currently define the state of the art: real-time multi-sensor monitoring and early-warning systems, intelligent automation technologies (including automated blowout prevention and drill-pipe handling), and human-factors integration through established frameworks such as the Human Factors Analysis and Classification System (HFACS). Building on this synthesis, the paper proposes the Integrated Underground Drilling Safety System (IUDSS), a novel conceptual framework that systematically couples multi-source data fusion, dynamic risk assessment, and human-centred design within a closed-loop architecture. Despite notable technological progress, significant research gaps persist in underground communication infrastructure, adaptive artificial intelligence, human-machine interface optimisation, and long-term equipment integrity under highly corrosive and abrasive conditions. The IUDSS framework offers researchers and industry practitioners a coherent and structured pathway for advancing toward zero-incident underground drilling operations.

Keywords: Underground drilling safety; Intelligent automation; Real-time monitoring; Human factors; Risk assessment; Digital twin; Mining 4.0

1 INTRODUCTION

Underground drilling operations remain among the most hazardous activities in the mining and geotechnical sectors. Personnel and equipment are continuously exposed to high concentrations of flammable and toxic gases, dust accumulation, unstable rock masses, confined working spaces, and the risk of sudden mechanical or geological failure [1,12,15]. Despite progressive regulatory frameworks and technological improvements, fatal accidents persist, as evidenced by the death-toll trends recorded in major mining countries between 2000 and 2013 (Fig. 1). These enduring

losses underscore the inherent limitations of conventional safety management systems that rely predominantly on static procedures, periodic inspections, and reactive interventions [4,7].

The increasing depth and technical complexity of modern underground operations have further exposed the inadequacies of traditional approaches. In parallel, the advent of Mining 4.0 has accelerated the development of intelligent technologies capable of supporting a shift from reactive to proactive safety management [22,26]. Advances in wireless sensor networks, multi-source data fusion, automated blowout prevention systems, hydraulic pipe-handling devices, digital twins, and human-factors analysis frameworks such as the Human Factors Analysis and Classification System (HFACS) have created new opportunities to enhance situation awareness and reduce human exposure to high-risk zones [3,6,9,19,28,29,36].

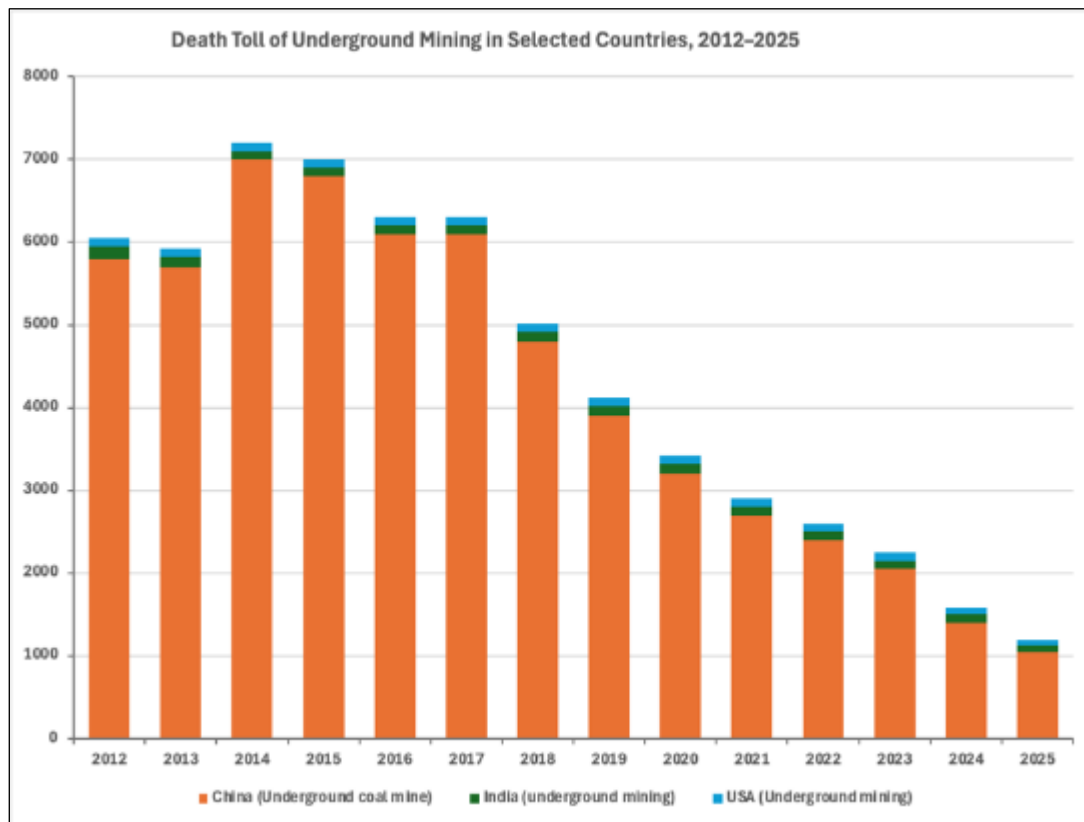


Figure 1: Death toll of underground mining in selected countries between 2012 and 2025

Nevertheless, the existing literature remains fragmented. The majority of studies examine isolated technological solutions, such as gas monitoring systems, automation of specific drilling processes, or human-error classification, without systematically integrating these elements into a cohesive safety architecture [2,10,23,30]. Furthermore, evidence derived specifically from underground drill-rig environments is frequently conflated with findings from surface mining, offshore drilling, or general mining contexts. This lack of contextual differentiation obscures the extent to which solutions are transferable and which are constrained by the distinctive conditions of underground operations, including intrinsic safety requirements, limited communication bandwidth, confined geometries, and highly corrosive atmospheres [16,33,35].

This systematic review addresses these deficiencies by synthesising evidence from 204 peer-reviewed studies. Through a structured thematic analysis, the paper maps the current state of real-time monitoring, intelligent automation, and human-centric risk management in underground drilling. Building on this synthesis, it develops the Integrated Underground Drilling Safety System (IUDSS), a conceptual framework that explicitly couples multi-source data fusion, dynamic risk assessment, and human-centred design. By distinguishing between context-specific and transferable knowledge, the review provides both a critical assessment of existing approaches and a coherent foundation for advancing toward zero-incident underground drilling operations.

2 METHODS

This review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [36]. The review protocol was developed using the PICOS framework (Population,

Intervention, Comparison, Outcome, Study design) to define the scope and minimize selection bias, with a primary focus on integrated Safety Protocols for Underground Drilling

2.1 Literature Search Strategy

A systematic literature search was conducted across major databases to identify peer-reviewed studies addressing safety protocols in underground drilling operations. The search was performed across Web of Science, SciSpace, PubMed, Scopus, Science Core Collection, Embase, and Google Scholar, covering publications up to 2026. Three complementary query clusters were developed to ensure comprehensive coverage:

- Cluster 1 focused on integrated safety protocols and underground drilling hazards, targeting catastrophic failure modes such as gas outbursts, blowouts, and rock instability.
- Cluster 2 addressed automation, monitoring, and equipment safety, with emphasis on real-time telemetry, blowout prevention systems, automated pipe handling, and digital-twin applications.
- Cluster 3 examined human factors, operator safety, and risk management, including HFACS-based analyses, organisational influences, and dynamic risk assessment methods.

The initial search retrieved 638 records. Search strings combined controlled vocabulary and free-text terms related to “underground drilling”, “drill rig safety”, “blowout prevention”, “real-time monitoring”, “human factors”, and “risk assessment”, adapted to the syntax of each database.

2.2 Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they met the following criteria: (i) peer-reviewed journal articles, conference papers, or technical reports; (ii) explicit focus on safety technologies, risk assessment methods, or human-factor interventions relevant to drilling operations; and (iii) provision of empirical, analytical, or conceptual insights applicable to underground or transferable drilling contexts.

Exclusion criteria were: (i) studies limited exclusively to surface mining or non-drilling underground activities; (ii) purely economic, environmental, or production-optimisation analyses without a safety component; (iii) laboratory-scale experiments lacking operational relevance; and (iv) non-English publications and non-peer-reviewed sources (e.g., pure patents without accompanying scientific analysis).

2.3 Study Selection and Evidence Categorisation

Following the removal of duplicates, titles and abstracts were screened for relevance. Full-text assessment of the remaining records resulted in a final corpus of 204 unique studies. The selection process will be illustrated using a PRISMA flow diagram.

To enhance analytical clarity, the included studies were categorised according to contextual specificity. Evidence derived from underground drill-rig environments (including gas drainage, raise boring, and coal-mine drilling) was distinguished from transferable evidence originating in offshore drilling, surface mining, or general oil-and-gas operations. This dual categorisation enabled a systematic evaluation of the extent to which technological and organisational solutions are constrained by the distinctive conditions of underground environments, such as intrinsic safety requirements, limited communication bandwidth, confined geometries, and corrosive atmospheres, versus those that can be adapted across domains.

The final set of studies underwent thematic synthesis organised around three interdependent domains: real-time monitoring and early-warning systems, intelligent automation and remote operation, and human-factors analysis combined with dynamic risk assessment. This structured approach provided the empirical foundation for the critical comparison and the subsequent development of the Integrated Underground Drilling Safety System (IUDSS) framework.

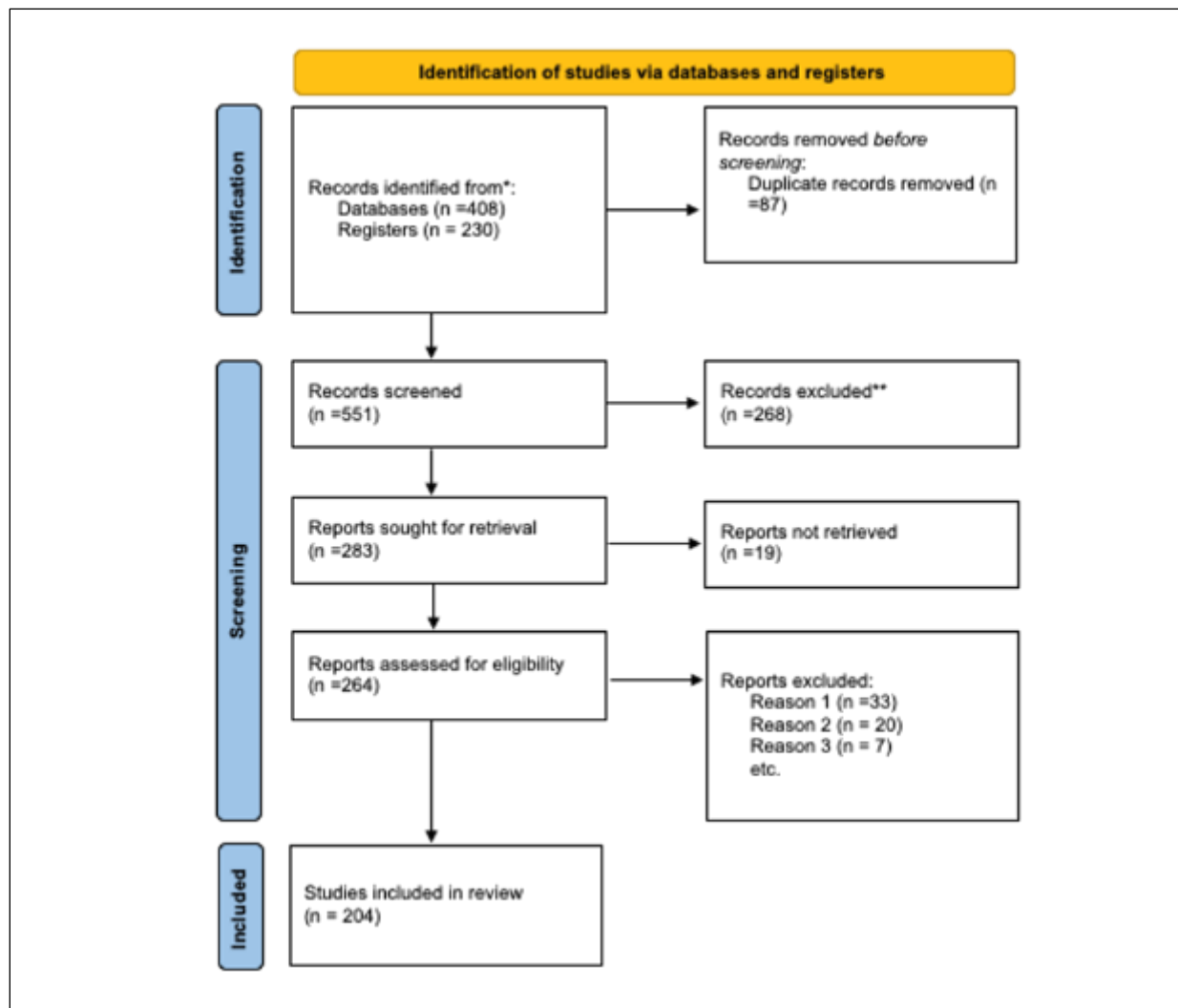


Figure 2: PRISMA 2020 flow diagram of the study selection process. A total of 204 studies met the inclusion criteria and were included in the qualitative synthesis.

3 THEMATIC SYNTHESIS OF INTEGRATED SAFETY PROTOCOLS

3.1 Real-Time Monitoring and Early Warning Systems

Real-time monitoring constitutes the sensory foundation of modern underground drilling safety systems. In underground coal mines, dust concentration sensors are increasingly deployed to automatically regulate water-spraying systems, thereby simultaneously reducing explosion risk and preventing secondary water-related hazards [1,18]. For gas drilling operations, integrated systems that combine engineering parameter monitoring with continuous gas-component analysis have demonstrated effectiveness in preventing drill-pipe jamming and providing early warnings of dangerous gas accumulations [11,21].

A significant advancement in recent years has been the shift toward multi-source data fusion. Contemporary approaches integrate surrounding rock deformation, gas concentration, and rig vibration data into multi-factor time-series models (e.g., ARIMAX) to generate real-time early warnings, particularly during emergency rescue drilling [10]. Wireless sensor networks and field-bus technologies further enable continuous monitoring of flammable, explosive, and toxic gases, supporting both operational safety and geological interpretation [33].

Fig. 2 illustrates exemplary real-time graphs of key working parameters, including hammer pressure, drill pressure, feeder pressure, engine speed, and drilling depth, recorded on an underground mining rig. Such continuous telemetry forms the essential data layer for predictive algorithms and digital-twin synchronisation [22,29].

Despite these advances, most current monitoring systems remain largely reactive or rule-based. The full potential of real-time data for predictive and adaptive control has yet to be realised in deep underground environments, where communication constraints and sensor reliability under harsh conditions continue to pose challenges [35].

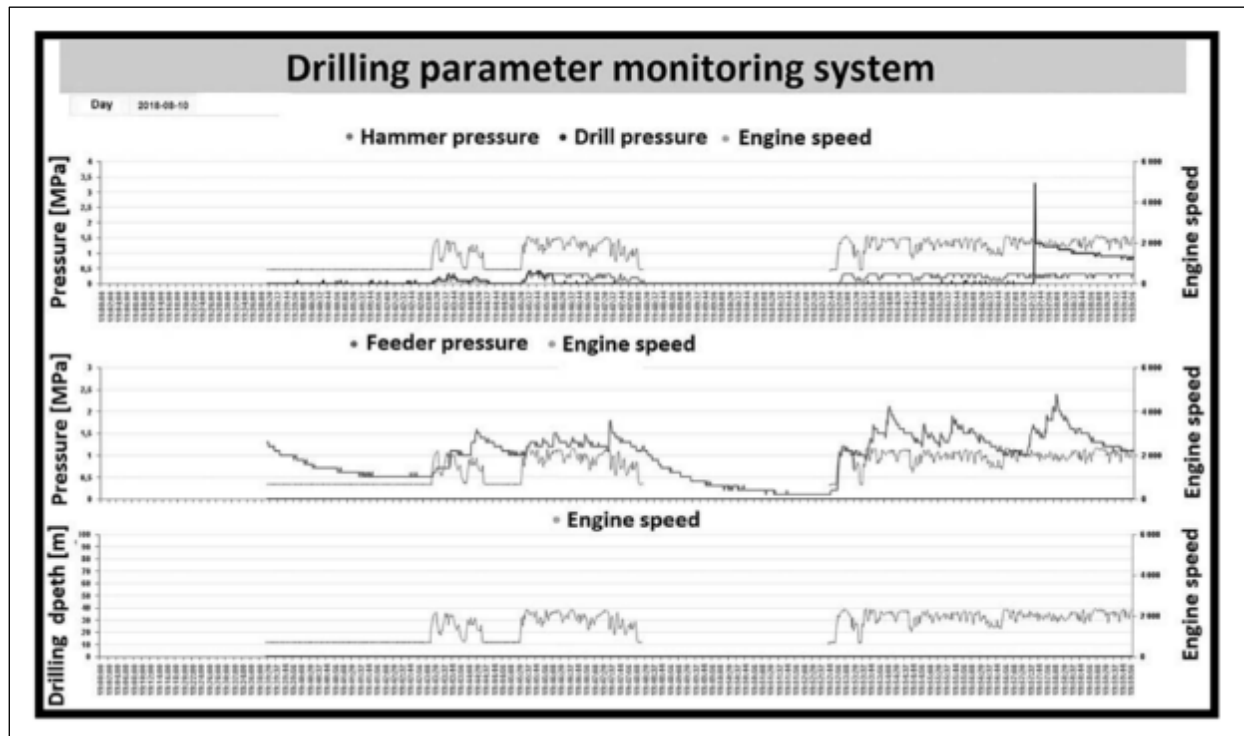


Figure 3: Exemplary graphs of measured working parameters of an underground mining rig (hammer pressure, drill pressure, feeder pressure, engine speed, and drilling depth).

3.2 Intelligent Automation and Remote Operation

Intelligent automation reduces safety risk primarily by removing personnel from high-hazard zones, particularly the drill floor and areas surrounding rotating machinery. Several technological developments have proven especially relevant to underground drilling.

Normally closed blowout prevention (BOP) systems designed for underground coal-mine construction enable automatic pressure relief closure, significantly reducing both gas leakage risk and the need for manual intervention [3]. Full-hydraulic automatic drill-pipe handling devices have reduced pipe-addition cycle times to approximately 35 seconds while markedly improving operator safety during one of the most hazardous routine tasks [6]. Integrated drilling and bolting systems, such as the Feeder Guiding System (FGS), allow operators to perform blast-hole drilling and rock bolting from remote, protected locations, away from high gas concentrations and potential rock-burst zones [9].

Digital-twin technologies are also gaining traction. By creating a real-time digital replica of the physical drilling system, these platforms process hydraulic and dynamic models to deliver early diagnostic alerts for potential failures [25,29,40]. Although originally developed in the oil-and-gas sector, Managed Pressure Drilling (MPD) techniques offer transferable principles for precise bottom-hole pressure control and are increasingly considered for adaptation to underground conditions (Fig. 3) [20].

Collectively, these automation technologies demonstrate clear safety benefits. However, the majority of current systems remain rule-based rather than adaptive. The development of automation capable of autonomously adjusting drilling parameters in response to real-time geological feedback remains an important frontier [23,26].

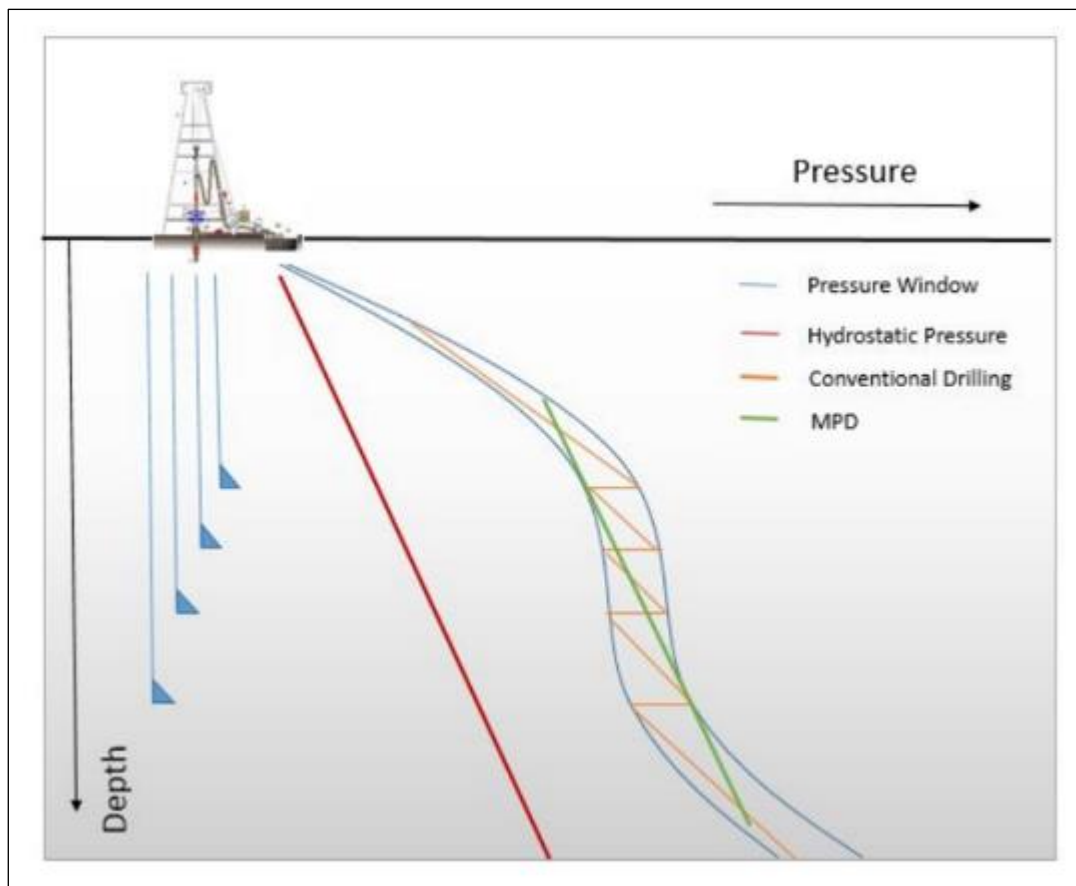


Figure 4: Schematic illustration of Managed Pressure Drilling (MPD) using the constant bottom-hole pressure technique, showing the pressure window relative to hydrostatic and conventional drilling profiles.

3.3 Human Factors and Risk Assessment

Technological solutions alone are insufficient. Human error continues to feature prominently in underground drilling incidents. Applications of the Human Factors Analysis and Classification System (HFACS) have consistently identified “preconditions for unsafe acts”, including inadequate supervision, poor crew resource management, and environmental stressors, as critical intervention points [19,28,36].

Risk assessment methodologies have evolved in parallel. Traditional static approaches, such as the Analytical Hierarchy Process (AHP) and Work Breakdown Structure–Risk Breakdown Structure (WBS–RBS) matrices, remain widely used for classifying risks associated with specialised equipment such as raise-boring rigs [2]. More recent work has shifted toward dynamic and uncertainty-tolerant methods, including Fuzzy TOPSIS and Risk Factor Fuzzy Evaluation Models (RFEM), which better accommodate the high levels of uncertainty inherent in underground environments [30,32]. Ontology-based decision-support systems are also emerging, enabling more systematic recognition and prevention of abnormal drilling conditions [23].

Despite this progress, the integration of human-factors insights with real-time monitoring and automation remains limited. Most existing risk models operate independently of live sensor data and automated control systems, reducing their operational utility [37].

4 CRITICAL COMPARISON OF SAFETY APPROACHES

A critical examination of the literature reveals important distinctions between safety solutions developed specifically for underground drill-rig environments and those originating in offshore, surface, or general drilling contexts. While many technologies are conceptually transferable, the unique physical, regulatory, and operational constraints of underground settings, particularly the requirement for intrinsic safety (IS) circuit design to eliminate ignition sources, limit direct application [16]. Table 1 summarises these differences across four core domains.

Table 1: Comparison of safety approaches in underground drill-rig contexts versus transferable/general drilling contexts.

Protocol Category	Underground Drill-Rig Context (Specific)	Transferable / General Drilling Context
Monitoring	Intrinsically safe dust and gas sensors; rock stability radar [33,34]	Mud-pit level monitoring; seismic geophones for geothermal wells [18]
Automation	Automatic gas drainage rigs; bolting robots; normally closed BOP systems [3,6,9]	Managed Pressure Drilling (MPD); offshore autonomous casing running [20,46]
Human Factors	Simulation-based training for jumbo operators; worker-centric crew station design [31,50]	Drill-Well-on-Paper (DWOP) reviews; offshore safety culture assessments [37,43]
Risk Assessment	WBS–RBS for raise-boring rigs; dynamic site safety models for emergency rescue [2,10]	Quantitative Risk Assessment (QRA) software; HFACS applications in oil and gas [19,42]

The comparison highlights that underground-specific solutions are strongly shaped by the need to operate in explosive atmospheres and confined spaces. Intrinsically safe sensors and normally closed blowout prevention systems, for example, are direct responses to the high risk of gas ignition [3,16]. In contrast, many transferable technologies, such as Managed Pressure Drilling and advanced digital twins, originated in environments where space, communication bandwidth, and ignition risk are less constrained [20,25,29].

Human-factors approaches also differ in emphasis. Underground studies tend to focus on equipment interface design and simulation training for operators working in close proximity to machinery [31,50], whereas offshore and general drilling literature places greater weight on organisational safety culture and procedural reviews [37,43]. Risk assessment methods show a similar divergence: underground applications frequently employ structured hierarchical techniques (e.g., WBS–RBS) suited to discrete equipment systems [2], while broader drilling contexts increasingly favour quantitative and dynamic models [30,42].

Overall, the evidence suggests that successful safety improvement in underground drilling requires selective adaptation rather than wholesale transfer of technologies. Solutions must be re-engineered to satisfy intrinsic safety standards, function under limited communication infrastructure, and accommodate the spatial and environmental constraints of the underground workplace. This contextual differentiation provides the analytical foundation for the integrated framework proposed in the following section.

5 INTEGRATED CONCEPTUAL FRAMEWORK (IUDSS)

Despite notable advances in monitoring technologies, automation systems, and human-factors analysis, existing approaches to underground drilling safety remain largely fragmented. Most solutions address only one dimension of the problem, either sensing, machine automation, or human performance, without establishing systematic linkages between them [10,23,29]. This fragmentation limits the potential for proactive, system-level risk reduction. To address this limitation, we propose the Integrated Underground Drilling Safety System (IUDSS), a conceptual framework that unifies multi-source data fusion, intelligent automation, and human-centred design into a single, closed-loop safety architecture specifically adapted to the constraints of underground drill-rig operations.

The IUDSS comprises three interdependent modules, as summarised in Table 2. These modules are designed to function synergistically rather than as standalone components, enabling continuous interaction between physical safeguards, predictive analytics, and human decision-making.

The Hardware Integrity Module forms the physical foundation of the framework. It integrates normally closed blowout prevention systems capable of automatic activation, full-hydraulic pipe-handling equipment that minimises manual intervention, and optical safety curtains that immediately halt machinery upon detection of unauthorised access [3,6,14]. By prioritising engineered safeguards, this module directly reduces the frequency and duration of human presence in high-risk zones.

The Digital Twin Monitoring Module **constitutes** the predictive and analytical core of the IUDSS. It continuously aggregates data from gas sensors, vibration monitors, rock-deformation instruments, and operational parameters, applying multi-factor time-series and machine-learning models to detect early signs of instability or equipment degradation [10,29,33]. Digital-twin representations of the drilling system further allow operators and algorithms to simulate potential failure trajectories under varying geological and operational conditions [25,40]. This capability shifts safety management from reactive response toward anticipatory control.

Table 2: Core modules and primary functions of the Integrated Underground Drilling Safety System (IUDSS).

Module	Primary Functions	Key Enabling Technologies	Safety Contribution
Hardware Integrity Module	Automatic isolation of hazardous energy; prevention of unplanned machine motion; physical safeguarding of personnel	Normally closed BOP systems, hydraulic pipe-handling devices, optical safety curtains [3,6,14]	Reduces direct human exposure to mechanical and pressure-related hazards
Digital Twin Monitoring Module	Real-time multi-source data acquisition and fusion; predictive detection of failure precursors; generation of early warnings	Wireless sensor networks, ARIMAX and machine-learning models, digital twins [10,22,25,29,33]	Enables timely, data-driven intervention before incidents escalate
Human-Centred Management Module	Structured analysis of human error precursors; remote operation and decision support; maintenance of operator situation awareness	HFACS frameworks, advanced human-machine interfaces, simulation-based training [19,28,31,36,37]	Mitigates human error and prevents automation-induced complacency

The Human-Centred Management Module ensures that technological sophistication does not come at the expense of human performance. Drawing on the Human Factors Analysis and Classification System (HFACS), the module supports systematic identification of latent organisational and supervisory failures that create preconditions for unsafe acts [19,36]. At the same time, carefully designed remote-operation interfaces and simulation-based training programmes help preserve operator situation awareness and reduce the risk of automation complacency [31,37].

A defining feature of the IUDSS is its closed-loop architecture. Real-time insights generated by the Digital Twin Monitoring Module simultaneously trigger automated protective actions within the Hardware Integrity Module and inform decision-support tools in the Human-Centred Management Module. This continuous feedback cycle distinguishes the IUDSS from earlier fragmented approaches and provides a coherent foundation for progressive movement toward zero-incident underground drilling operations.

6 PRACTICAL AND THEORETICAL IMPLICATIONS

6.1 Practical Implications

From an operational perspective, the evidence indicates that substantial safety gains are most likely to be achieved through the prioritisation of technologies that demonstrably reduce direct human exposure to high-risk tasks. Normally closed blowout prevention systems and automated drill-pipe handling devices have already shown measurable reductions in both labour intensity and the frequency of personnel entering hazardous zones [3,6]. Equally critical is the deployment of multi-source, real-time monitoring platforms capable of fusing gas concentration, equipment vibration, and rock-mass deformation data to support early intervention [10,29,33].

Mining organisations that continue to rely predominantly on static procedures, periodic inspections, and reactive emergency response are unlikely to realise further significant reductions in incident rates. Instead, a phased implementation strategy is recommended. Initial efforts should focus on strengthening hardware integrity and establishing reliable real-time monitoring infrastructure. Subsequent phases can then introduce higher levels of remote operation and decision-support systems. Throughout this process, structured operator training remains essential to preserve situation awareness and to mitigate the risk of automation-induced complacency [37]. The IUDSS framework offers a coherent reference architecture for sequencing these investments and for evaluating their combined effectiveness.

6.2 Theoretical Implications

Theoretically, this review advances the application of Safety-II principles within the domain of underground drilling. Traditional safety management in mining has largely been grounded in a Safety-I paradigm, which emphasises the prevention of adverse events through compliance, standardisation, and the elimination of human error. While this approach has delivered important improvements, it has proven insufficient in the face of increasing system complexity and operational variability.

The body of evidence examined here supports a complementary Safety-II orientation—one that focuses on understanding and actively reinforcing the conditions under which complex socio-technical systems succeed despite uncertainty and disturbance. The proposed IUDSS framework contributes to this theoretical shift by integrating

predictive digital-twin monitoring, engineered safeguards, and human-centred design into a closed-loop architecture. In doing so, it moves beyond post-hoc incident analysis toward continuous anticipation, adaptation, and system resilience [24].

Furthermore, the framework helps bridge two traditionally separate streams of safety research: engineering-based risk assessment models and human-factors theory. By explicitly linking multi-source data fusion with HFACS-informed organisational analysis, the IUDSS provides a more holistic conceptual foundation for studying safety performance in underground drilling environments. This integrated perspective offers a basis for future empirical work examining how technological, organisational, and human elements interact to produce (or undermine) safe operational outcomes.

7 RESEARCH GAPS AND FUTURE AGENDA

Despite meaningful advances in real-time monitoring, intelligent automation, and human-factors analysis, several critical research gaps continue to constrain progress toward fully proactive and resilient safety systems for underground drilling. These gaps are summarised in Table 3 and elaborated below.

Table 3: Key research gaps and corresponding future research directions.

Research Gap	Current Limitation	Recommended Future Research Directions
Underground communication systems	Limited reliability and high latency of high-bandwidth networks (including 5G) in deep underground environments [35]	Development of hybrid communication architectures (5G combined with leaky-feeder or through-the-earth systems) and edge-computing solutions for real-time control
Adaptive and autonomous intelligence	Most existing automation systems remain rule-based and cannot adjust to rapidly changing geological conditions [23,26]	Design and validation of AI-based controllers capable of autonomously optimising drilling parameters (torque, vibration, feed rate) in real time
Human–Machine Interface (HMI) design	Risk of reduced situation awareness and automation complacency during remote operation [37]	Development and empirical testing of human-centred HMIs that actively support supervisory control and maintain operator engagement
Long-term equipment integrity	Insufficient research on predictive maintenance under highly corrosive and abrasive underground conditions [15,24]	Creation of physics-informed machine-learning models and sensor-based degradation monitoring specifically calibrated for underground drilling equipment
Integrated system validation	Very few studies evaluate monitoring, automation, and human-factors interventions as a unified system	Large-scale field trials and digital-twin-enabled virtual commissioning of integrated architectures such as the IUDSS

One of the most significant technical barriers is the performance of communication systems underground. Although 5G technology offers low latency and high bandwidth, signal attenuation in deep and geometrically complex mine environments remains a major obstacle [35]. Future work should therefore focus on hybrid communication solutions and edge-computing architectures that can sustain closed-loop control even under intermittent connectivity.

A second critical gap concerns the level of intelligence embedded in current automation systems. While automated pipe handling, blowout prevention, and bolting technologies have improved safety, the majority still operate on pre-defined rules and lack the capacity to adapt autonomously to changing geological conditions [23,26]. Research into adaptive, learning-based control systems is urgently needed.

Human-factors challenges also persist. As operations become increasingly remote and automated, new risks emerge, particularly the potential loss of operator situation awareness and over-reliance on automated systems [37]. Systematic research is required to design and validate human–machine interfaces that support effective supervisory control rather than passive monitoring.

In addition, long-term equipment reliability under the severe corrosive and abrasive conditions characteristic of underground environments has received limited attention [15,24]. Predictive maintenance approaches specifically developed for these conditions are essential if the safety benefits of automation are to be sustained over the full equipment lifecycle.

Finally, there is a notable absence of studies that evaluate monitoring, automation, and human-factors interventions as an integrated system. Future research should prioritise full-scale field trials and digital-twin-supported virtual commissioning of comprehensive frameworks such as the IUDSS. Addressing these gaps in a coordinated manner will be essential if the conceptual advances proposed in this review are to be translated into measurable improvements in underground drilling safety.

8 CONCLUSION

Underground drilling operations continue to present some of the most severe safety challenges in the mining and geotechnical sectors. This systematic review of 204 peer-reviewed studies has examined the progressive shift from conventional, reactive safety practices toward integrated, data-driven approaches that combine real-time monitoring, intelligent automation, and human-centred risk management.

The synthesis demonstrates that meaningful safety improvement depends on the coordinated application of three interdependent elements: continuous multi-source monitoring capable of generating early warnings, automation technologies that reduce direct human exposure to hazardous tasks, and human-factors frameworks that address the organisational and cognitive precursors of error. Building on this evidence, the review has proposed the Integrated Underground Drilling Safety System (IUDSS), a conceptual framework that explicitly links hardware integrity, digital-twin-based prediction, and human-centred management within a closed-loop architecture.

While substantial technological progress has been achieved, critical gaps remain—particularly in underground communication systems, adaptive artificial intelligence, human-machine interface design, and long-term equipment integrity under harsh operating conditions. Addressing these gaps through coordinated research and industrial collaboration will be essential if the transition toward zero-incident underground drilling is to be realised.

Ultimately, the safety of underground drill-rig operations will be determined not by the performance of isolated technologies, but by the extent to which monitoring, automation, and human capability are deliberately integrated into coherent socio-technical systems. The IUDSS framework offers one structured pathway for advancing this integration.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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