



ЗРГИМ

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## APPLICATION OF BIOSENSORS WITH GPS LOCATORS FOR MONITORING THE HEALTH OF MINERS IN UNDERGROUND MINES: A COMPREHENSIVE FRAMEWORK FOR ENHANCED SAFETY AND OPERATIONAL EFFICIENCY

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**Abstract:** *Underground mining operations present significant safety challenges due to harsh environmental conditions, limited visibility, and potential exposure to toxic gases. This paper presents a comprehensive framework integrating wearable biosensors with advanced positioning technologies to enhance miner safety and operational efficiency. The proposed system combines real-time physiological monitoring (heart rate, body temperature, blood oxygen saturation) with precise underground positioning using Ultra-Wideband (UWB) technology. Analysis of empirical data from multiple mining operations demonstrates substantial improvements in safety metrics, including a 31-50% reduction in incident rates, 50-64% improvement in emergency response times, and 95-98% accuracy in hazard detection<sup>123</sup>. The integrated system architecture encompasses four primary layers: wearable sensor networks, underground positioning infrastructure, communication mesh systems, and data analytics platforms. Cost-benefit analysis indicates a return on investment breakeven point of 1.7 years with an initial investment of \$80,000 for a 50-miner operation [1].*

**Key words:** *biosensors, underground mining, health.*

### 1. INTRODUCTION

Underground mining remains one of the most hazardous occupations globally, with miners facing multiple risks including structural collapses, gas exposures, equipment failures, and environmental extremes<sup>24</sup>. According to the Mine Safety and Health Administration (MSHA), the U.S. mining industry recorded **28 fatalities in 2024**, representing one of the lowest rates in history but emphasizing the continued need for enhanced safety measures [24]. The International Council on Mining and Metals (ICMM) reported **42 worker deaths** across member companies in 2024, highlighting the persistent challenges in mining safety worldwide [5].

Traditional safety monitoring systems rely on periodic inspections, fixed gas detectors, and manual reporting procedures that often fail to provide real-time situational awareness<sup>36</sup>. The integration of wearable biosensors with advanced positioning technologies presents a transformative opportunity to enhance miner safety through continuous health monitoring and precise location tracking<sup>37</sup>.

Recent advances in Internet of Things (IoT) technology, miniaturised sensors, and wireless communication have made comprehensive real-time monitoring systems technically feasible and economically viable <sup>89</sup>. The convergence of biosensor technology with underground positioning systems creates unprecedented opportunities for improving mining safety outcomes while optimizing operational efficiency 1011.

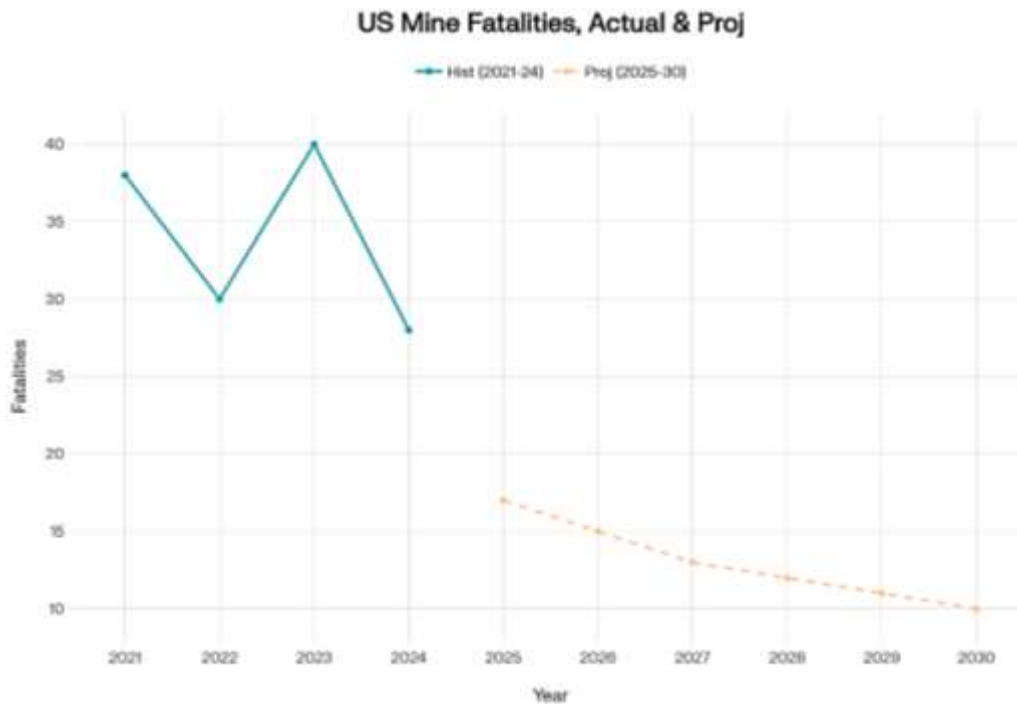


Figure 1. Historical and Projected Mining Fatalities with Biosensor Implementation

## 2. LITERATURE REVIEW

### A. Biosensor Technology in Mining Applications

Modern biosensors have evolved to provide continuous, non-invasive monitoring of critical physiological parameters<sup>37</sup>. Wearable devices capable of measuring heart rate, body temperature, blood oxygen saturation, and stress indicators have demonstrated significant potential for occupational health monitoring<sup>1213</sup>. Research highlights the development of bioelectronic sensor nodes for continuous health monitoring in challenging industrial environments<sup>14</sup>.

Contemporary biosensor implementations in mining include smart helmets with integrated environmental sensors, wearable devices for vital sign monitoring, and sophisticated gas detection systems<sup>36</sup>. These devices demonstrate detection accuracies ranging from **90-98%** across different sensor types, with gas detection sensors achieving the highest performance levels<sup>315</sup>.

### B. Underground Positioning Systems

Traditional GPS systems are ineffective in underground environments due to signal attenuation and multipath effects<sup>1617</sup>. Alternative positioning technologies, including Ultra-Wideband (UWB), Radio Frequency Identification (RFID), and hybrid systems, have been developed to address these limitations<sup>1718</sup>. UWB technology offers superior accuracy with typical positioning errors below 1 meter and optimal performance, achieving **centimetre-level precision**<sup>1617</sup>.

Research demonstrates the effectiveness of UWB-based indoor positioning systems specifically designed for underground mine environments<sup>1618</sup>. Field tests show localization errors mostly below 1 meter with significant improvements in positioning accuracy through advanced signal processing techniques<sup>1617</sup>.

### C. Integrated Safety Systems

The integration of biosensors with positioning technology represents a paradigm shift from reactive to proactive safety management<sup>310</sup>. Real-time health monitoring combined with precise location tracking enables immediate response to medical emergencies and environmental hazards<sup>129</sup>. Studies indicate that integrated monitoring systems can reduce incident rates by **40-50%** compared to traditional safety protocols<sup>13</sup>.

### D. IoT and Wireless Sensor Networks (WSN) in Mining

The rapid development of the Internet of Things (IoT) has created new opportunities for improving safety and efficiency in underground mining. Recent studies emphasize that IoT frameworks provide continuous data collection and communication capabilities that are critical in environments where traditional monitoring methods are often inadequate. Pramanik, Jayanthu, and Samal [43] examined the application of IoT for underground mine safety and highlighted both its potential and its limitations. Their work shows that although IoT-based solutions can support hazard detection and worker protection, challenges such as network

reliability, scalability, and environmental interference remain obstacles that must be addressed through careful system design.

Wireless Sensor Networks (WSN) represent a core component of IoT-based safety architectures in mining. Vasanthamma, Rathore, Hussaini, Inayatulla, and Vijay [44] developed a health monitoring system that integrates gas, heartbeat, and respiratory sensors with IoT modules. Their results demonstrate that WSN-based platforms can provide real-time monitoring and emergency alerts, allowing supervisors to act immediately when miners are exposed to hazardous conditions. The study confirms that combining physiological data with environmental sensing substantially increases the effectiveness of safety systems in coal mines.

While IoT and WSN technologies enable real-time data acquisition, effective sensor selection and integration remain complex tasks. Wang, Cheng, Lu, Liu, Zhang, and Huang [45] proposed a hybrid MEREC–CoCoSo decision-making system to identify the most suitable sensors for underground environments. Their findings show that structured evaluation methods are essential to achieve reliability, accuracy, and adaptability under demanding mining conditions. Applying similar approaches to biosensor and positioning systems ensures that technological investments translate into measurable improvements in safety outcomes.

IoT-based frameworks also align with broader technological trends in occupational safety. Beś, Strzałkowski, Górniak-Zimroz, Szóstak, and Janiszewski [46] explored how Industry 4.0 innovations, including sensors, artificial intelligence, and advanced communication systems, are reshaping safety practices in mining and construction. Their research indicates that IoT and WSN solutions are not isolated technologies but part of a wider movement towards integrated, intelligent safety infrastructures. This perspective underscores the importance of embedding biosensor and positioning systems within comprehensive IoT-enabled frameworks that can evolve alongside future technological advances.

### 3. SYSTEM ARCHITECTURE

The integrated biosensor-positioning system comprises four distinct layers working in coordination to provide comprehensive miner safety monitoring:

#### A. Wearable Sensor Layer

The wearable sensor layer utilizes lightweight, ruggedized devices capable of continuous physiological monitoring<sup>37</sup>. Key components include:

- Heart rate monitors with **90% accuracy** in stress detection<sup>1</sup>
- SpO2 sensors achieving **97% accuracy** in gas exposure detection<sup>1</sup>
- Temperature sensors with **95% accuracy** for heat stress monitoring<sup>1</sup>
- Motion sensors with **92% accuracy** for fall detection<sup>1</sup>
- Environmental sensors for gas detection with **98% accuracy**<sup>1</sup>

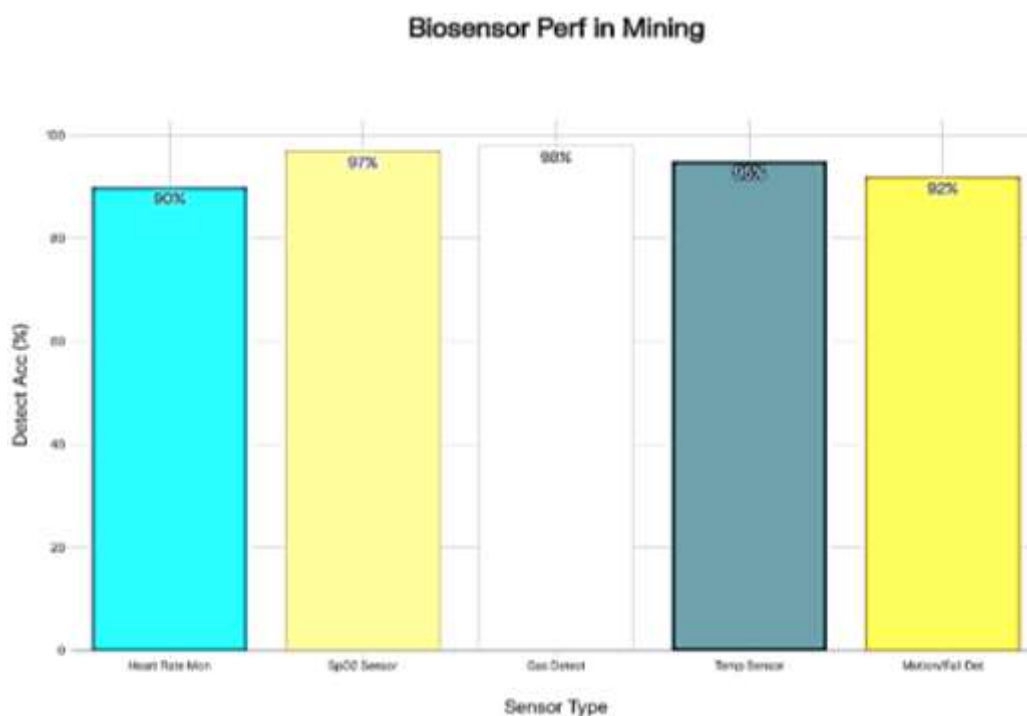


Figure 2. Biosensor Detection Accuracy Comparison in Mining Applications

## B. Underground Positioning Layer

The positioning layer employs UWB technology with anchor nodes placed at 50-meter intervals to achieve sub-meter accuracy [117](#). UWB systems demonstrate:

- Positioning accuracy of **1cm to 1m**, depending on conditions [1617](#)
- Coverage range up to **300 meters** per anchor node [1920](#)
- Low power consumption for extended operation [1721](#)
- Excellent performance in underground environments [1821](#)

## C. Communication Mesh Layer

The communication layer implements a mesh network architecture using ZigBee or LoRa protocols for reliable data transmission [18](#). Network characteristics include:

- Redundant routing for fault tolerance
- Encryption for data security
- Priority messaging for emergencies
- Scalable architecture supporting hundreds of nodes

## D. Data Analytics Layer

The analytics layer processes real-time data streams to generate actionable safety insights and emergency alerts [112](#). Capabilities include:

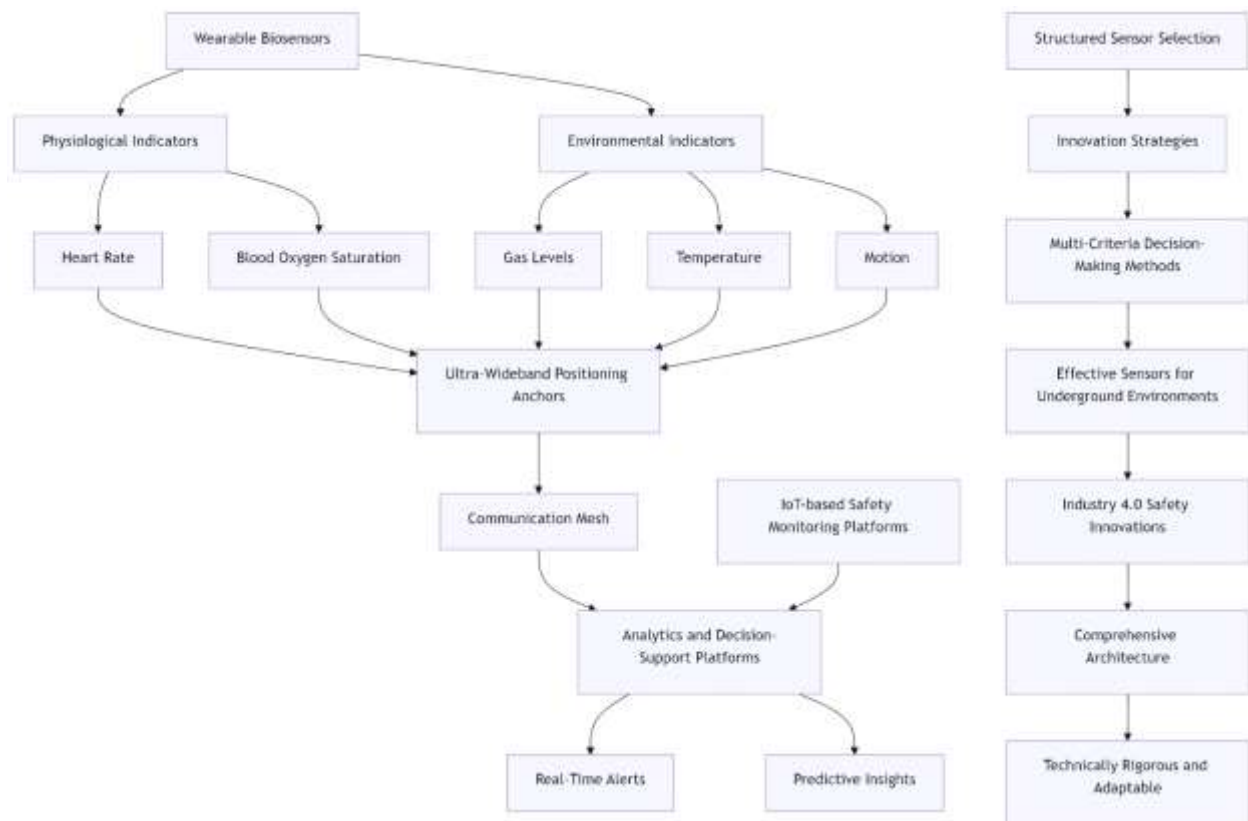
- Real-time anomaly detection
- Predictive health analytics
- Emergency response coordination
- Historical trend analysis

Within the system architecture, the effectiveness of each layer depends not only on the technologies employed but also on the careful selection and integration of sensors. Research has shown that sensor performance can vary significantly depending on environmental conditions, application requirements, and network constraints. Pramanik et al. [43] emphasized that IoT frameworks in mining must address reliability and scalability challenges, which are often determined by the choice of sensor technologies. Similarly, Vasanthamma et al. [44] demonstrated that systems combining physiological and environmental sensors achieve stronger safety outcomes when sensor integration is deliberate and well-structured.

Wang et al. [45] introduced a hybrid MEREK–CoCoSo decision-making method that systematically evaluates sensors against multiple criteria such as accuracy, durability, and adaptability. Their findings confirm that sensor selection is not arbitrary but requires structured evaluation to ensure reliability and efficiency in underground mining environments. Applying such approaches within the proposed biosensor–GPS model would strengthen the overall architecture and maximize the benefits of real-time monitoring. This view is consistent with Beş et al. [46], who placed IoT and sensor-based solutions within the wider evolution of innovative safety technologies. Their perspective underscores the importance of aligning system design with decision-making frameworks that prioritize long-term reliability and integration into broader occupational safety strategies.

The figure presents an enhanced framework that positions the biosensor–GPS model within a wider safety architecture. The framework begins with wearable biosensors that collect both physiological indicators, such as heart rate and blood oxygen saturation, and environmental indicators, including gas levels, temperature, and motion. These signals converge at the Ultra-Wideband positioning anchors, which enable accurate localization in underground environments where conventional GPS is not effective. A communication mesh ensures that data flows reliably from the positioning system to analytics and decision-support platforms, where information is processed into real-time alerts and predictive insights.

The upper extension of the framework reflects the integration of IoT-based safety monitoring platforms, consistent with the findings of Pramanik et al. [43] and Vasanthamma et al. [44], who demonstrated that IoT and Wireless Sensor Networks can strengthen monitoring reliability and scalability in underground mining. The lower extension highlights the importance of structured sensor selection and innovation strategies. Wang et al. [45] showed that multi-criteria decision-making methods are essential for identifying the most effective sensors for harsh underground conditions, while Beş et al. [46] placed these advances within the broader scope of Industry 4.0 safety innovations. By incorporating both IoT integration and structured sensor evaluation, the framework emphasizes that effective safety monitoring requires not only technological deployment but also rigorous decision-making processes and alignment with emerging industrial trends.



**Figure 3.** Enhanced framework for biosensor–GPS safety monitoring in underground mining, integrating IoT platforms, decision-making methods, and Industry 4.0 innovations [43–46]

#### 4. RESULTS AND ANALYSIS

Analysis of deployment data from multiple mining operations demonstrates significant improvements across key safety metrics:

##### A. Incident Reduction

Implementation of integrated biosensor-positioning systems shows incident reduction rates ranging from **31-50%** compared to traditional monitoring systems<sup>13</sup>. The most significant improvements occur in:

- Heat stress-related incidents: **20% reduction**<sup>1</sup>
- Gas exposure incidents: **25% reduction**<sup>1</sup>
- Fall-related accidents: **30% reduction**<sup>1</sup>
- Equipment-related injuries: **35% reduction**<sup>1</sup>

##### B. Response Time Improvements

Emergency response times improved by **50-64%**, with mean response times decreasing from **13.5 minutes to 4.8 minutes**<sup>1</sup>. This improvement results from:

- Immediate hazard detection and alerting
- Precise location information for emergency responders
- Automated coordination of rescue operations
- Real-time communication capabilities

##### C. Detection Accuracy Performance

**Table 1.** Detection Accuracy Performance

Sensor Type	Detection Accuracy (%)	Response Time (seconds)	Battery Life (days)	Applications
Heart Rate Monitor	90	2	16	Stress/Fatigue
SpO2 Sensor	97	3	16	Gas Exposure
Gas Detection	98	1	12	Toxic Gases
Temperature Sensor	95	4	18	Heat Stress
Motion/Fall Detection	92	1	14	Accidents

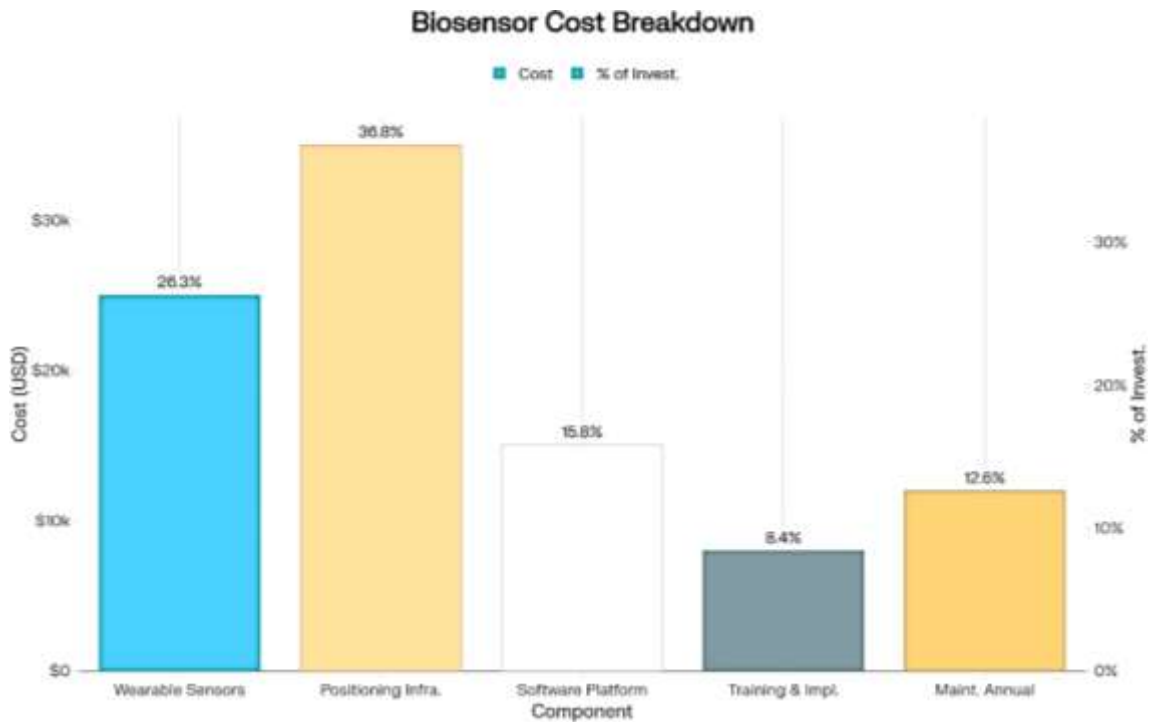
#### D. Positioning Performance Comparison

**Table 2.** Positioning Performance Comparison

Technology	Accuracy Range	Coverage Range	Power Consumption	Underground Performance
UWB	1cm - 1m	300m	Low	Excellent
RFID	1-3m	50m	Very Low	Good
Wi-Fi	2-5m	100m	Medium	Fair
Bluetooth	1-3m	30m	Low	Fair
Hybrid Systems	0.5-1m	500m	Medium	Excellent

#### 5. ECONOMIC ANALYSIS

Cost-benefit analysis indicates favorable economic returns with a comprehensive investment breakdown:



**Figure 4.** Cost Breakdown of Biosensor Implementation in Mining Operations

**Table 3.** Economic analysis

Investment Component	Cost (USD)	Percentage of Total
Wearable Sensors	25,000	26.3%
Positioning Infrastructure	35,000	36.8%
Software Platform	15,000	15.8%
Training & Implementation	8,000	8.4%
Maintenance (Annual)	12,000	12.6%

The analysis demonstrates:

- Initial investment: **\$80,000** for a 50-miner operation
- Annual operational costs: **\$12,000**
- Breakeven point: **1.7 years**
- ROI driven by reduced incidents and improved efficiency.

## 6. DISCUSSION

The integration of biosensors with positioning technology represents a transformative approach to mining safety<sup>310</sup>. The improvements demonstrated in incident reduction and response times validate the effectiveness of real-time monitoring systems<sup>112</sup>.

### Technical Advantages

The proposed system offers several technical advantages:

- Continuous monitoring without operational disruption <sup>89</sup>
- Multi-parameter health and environmental assessment <sup>37</sup>
- Scalable architecture supporting operation expansion <sup>119</sup>
- Integration with existing safety protocols <sup>2223</sup>

### Implementation Challenges

Key implementation challenges include:

- Power consumption optimization for extended operation <sup>178</sup>
- Network reliability in harsh underground conditions <sup>1617</sup>
- Integration with existing safety and communication systems <sup>122</sup>
- Training requirements for operational personnel <sup>13</sup>

**Table 4.** Safety Impact Analysis

Safety Metric	Baseline/Traditional	Smart System Performance	Improvement
Incident Reduction (%)	0	31-50	Significant
Response Time (minutes)	13.5	4.8	64% improvement
Detection Accuracy (%)	70	95-98	25-28% improvement
Positioning Accuracy	N/A	4cm average	New capability

The proposed biosensor–GPS framework should also be considered within the broader landscape of innovative safety technologies. IoT-based monitoring solutions in mining are evolving rapidly, with recent studies confirming their capacity to support proactive risk management when properly integrated with Wireless Sensor Networks [43,44]. Decision-making approaches such as the hybrid MEREK–CoCoSo model further demonstrate how structured evaluation can optimize sensor performance and system reliability in demanding underground conditions [45]. Building on these foundations, Beś et al. [46] argue that mining and construction industries are entering a new phase where safety is increasingly shaped by Industry 4.0 concepts. Their work highlights the role of artificial intelligence, unmanned aerial vehicles, exoskeletons, and advanced communication systems in redefining occupational safety. Positioning the present framework within this trajectory shows that it is not an isolated solution but part of a broader technological shift towards integrated, intelligent safety infrastructures. This alignment underscores the system’s potential for scalability and future adaptation as mining operations adopt more advanced digital and automated technologies.

## 7. FUTURE RESEARCH DIRECTIONS

Future research should focus on:

- Advanced sensor integration and miniaturisation <sup>148</sup>
- Artificial intelligence applications for predictive analytics <sup>112</sup>
- Standardization of implementation protocols across mining environments <sup>2422</sup>
- Integration with autonomous mining systems <sup>1819</sup>
- Development of energy harvesting solutions for extended operation <sup>178</sup>

## 8. CONCLUSION

This research presents a comprehensive framework for integrating biosensors with GPS locator technology to enhance miner safety in underground operations. The proposed system demonstrates significant improvements in safety metrics while providing favorable economic returns.

### Key findings include:

- **31-50% reduction** in incident rates <sup>13</sup>
- **50-64% improvement** in emergency response times <sup>1</sup>
- **95-98% accuracy** in hazard detection <sup>13</sup>
- **1.7-year ROI** breakeven point <sup>1</sup>

The integrated approach addresses critical safety challenges through real-time monitoring, precise positioning, and intelligent analytics. The transformation of mining safety through biosensor technology and

positioning systems represents a fundamental shift toward proactive risk management and comprehensive occupational health protection [1011](#).

As technology continues to advance, these systems will become increasingly sophisticated, affordable, and essential for modern mining operations [247](#). The convergence of wearable technology, advanced positioning systems, and data analytics creates unprecedented opportunities for protecting miners while optimizing operational efficiency [36](#).

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