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Empowering Artisanal Miners through Innovative Wearable Technology: A Smart Helmet Approach

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Abstract

This research project aims to empower artisanal miners by developing a wearable technology: a smart helmet designed to improve their safety and overall mining experience. In a quantitative study approach involving 400 artisan miners, a survey questionnaire was conducted to gather data on their experiences and perceptions regarding current mining practices and the potential utility of smart helmets. The survey responses offered valuable insights into these miners' specific needs and challenges. The collected data was analysed using the IBM Statistical Package for the Social Sciences (SPSS) to provide descriptive and inferential statistics. By applying the principles of design science methodology, the survey findings informed the design and development of a smart helmet tailored to the artisanal mining context. The resulting smart helmet integrates features such as real-time location tracking, environmental monitoring, health tracking and communication capabilities. This study showcases the potential of combining user-centric design with advanced technology to address the unique requirements of artisanal miners, ultimately leading to safer and more efficient mining operations. The proposed smart helmet represents a significant advancement in leveraging technology to enhance the well-being and productivity of artisanal miners.

Keywords
Smart Helmets, Artisanal Mining, Internet of Things, Long Range Wide Area Network (LoRa WAN), Wearable Technology.

1. Introduction
Artisanal mining in Zimbabwe focuses on conventional mining techniques that employ simple equipment. Individuals or groups engage in such practices to extract minerals from the earth's surface (Mutemeri and Ponnan 2024). In 2022, research found that 35% of artisanal miners in Zimbabwe experience accidents, while 25% suffer injuries, with major incidents including mine collapses and underground trappings (Singo et al. 2022). One recent accident was the Redwing mine disaster, where 15 artisanal miners were trapped when a mine shaft collapsed (The Herald 2024). These incidents support the necessity of attempts at improving miner safety.

The Internet of Things (IoT) is an emerging technology that enables widespread, everyday devices to connect to the Internet (Mutunhu 2022). Wearable technology, which refers to anything worn on the user's body for extended periods to provide significant enhancement to the user, integrates with IoT to deliver real-time data from sensors (Collier and Randolph 2015). In recent years, wearable technologies have rapidly advanced globally (Worlanyo et al. 2023). Wearable smart helmets with sensors and communication capabilities designed for artisanal miners have the potential to transform the artisanal mining industry (Kamble et al. 2023). Traditional mining practices often expose workers to significant risks, including toxic gases, physical injuries and poor environmental conditions (Mwandiringana and Ye

2023). Implementing smart helmets can mitigate these risks by providing real-time monitoring and alerts, thus preventing accidents and improving miners' overall well-being. However, adoption of these technologies in artisanal mining remains limited, primarily due to factors such as cost, usability and awareness (Ediriweera and Wiewiora 2021). This research bridges this gap by developing a smart helmet customised to meet the specific needs of artisanal miners and investigate the factors affecting its adoption. By employing a quantitative research approach, data on miners' experiences, perceptions and the barriers they face in adopting smart helmets are gathered through a questionnaire. This data will be used to inform the design and implementation of a user centered smart helmet system that addresses the identified needs and challenges.

Earlier studies have highlighted the potential of technology in transforming mining operations (Rogers et al. 2019). However, the available literature on this topic with regards to the artisanal mining sector is limited. This study seeks to contribute to this gap by providing empirical evidence on these factors and develop a practical solution, which is the smart helmet to enhance the safety and productivity of artisanal miners. The smart helmet represents a significant step toward leveraging technology to empower artisanal miners, thereby contributing to safer and more efficient artisanal mining practices.

1.1 Objectives

- To investigate the factors influencing artisanal miners' adoption of smart helmets.
- To design a wearable IoT smart helmet informed by these factors.

2. Literature Review

Artisanal mining is crucial to the livelihoods of millions in developing countries, contributing to poverty alleviation and economic development (Mawowa 2013). However, it is often characterised by informal practices, poor working conditions and lack of access to technology, leading to severe health and safety risks for miners (Hentschel et al. 2002; Siegel and Veiga 2009). Miners face numerous challenges, including exposure to hazardous substances, inadequate safety measures and limited access to healthcare (Hinton et al 2003; Heemskerk 2005). These conditions often result in accidents, respiratory diseases and other occupational health issues (Stewart 2020; Veiga et al. 2006)

Adoption of Smart Helmets in Mining

One of the primary challenges in implementing IoT-based Smart Helmets in the mining industry is their adoption and integration into current workflows and processes (Kartik 2020). The Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) offer frameworks for understanding the factors influencing technology adoption. Perceived usefulness, ease of use, social influence and facilitating conditions are fundamental determinants (Thompson 2019; Venkatesh et al., 2003). These models have been utilised in various contexts, including health and safety technologies in mining (Hsiao and Tang 2015; Rodrigues et al. 2016). Despite the potential advantages, the implementation of smart technologies in mining is limited (Gruenhagen and Parker 2020). Factors such as cost, usability, lack of awareness and resistance to change have been recognised as significant obstacles (Turner 2007; Venkatesh and Bala 2008). Research suggests that miners are often hesitant to embrace new technologies due to financial constraints and the complexity of the devices (Hoque and Sorwar 2017).

Technological Interventions in Mining

The mining industry has seen significant advancements through the integration of smart technologies. Wearable devices, particularly smart helmets, have been developed to enhance safety and operational efficiency (Wang et al., 2016; Gupta et al., 2016). Smart helmets can provide real-time environmental monitoring, health tracking and improved communication, thereby reducing risks and improving miners' well-being (Kanase et al. 2023; Patel et al. 2023; Vishwakarma et al. 2023). Smart helmets are equipped with sensors that monitor environmental conditions such as gas levels, temperature and humidity (Priyanka1 et al. 2022). They also include health monitoring features like heart rate and body temperature sensors and communication systems for emergency alerts (Dhanalakshmi 2017; Sabeenian et al. 2023). These features can significantly mitigate the risks associated with artisanal mining (Minhajul et al. 2021; Chowdhury et al. 2021). Previous Studies on Wearable Technology in Mining have explored the application of wearable technology in mining. For instance, Shashidhar et al. (2022) designed a smart helmet for coal miners, using an Arduino Uno as a microcontroller, demonstrating its effectiveness in enhancing safety. Similarly, Kishore et al. (2013) examined the use of IoT-based smart helmets for coal miners using Zigbee technology. Furthermore Shabina (2014) developed a smart helmet that uses a wireless sensor network based on radio frequency technology, their overall design comprised a helmet, localiser and control room module.

Thus, the novelty of the present research lies on using a Wazidev microcontroller which transmits data up to 7Km using the RFM95W LoRa module. An IoT gateway device was built using open-source technology from Waziup called Wazigate. This gateway serves as a bridge between the smart helmet and the internet, allowing data from the gas, heartrate and temperature and humidity sensors to be transmitted to the cloud (WaziLab 2024). Prior smart helmet architectures have used Zigbee and Radio Frequency technologies which have several limitations. Zigbee though cheaper has constraint of shorter transmission range of 10-100 meters and require heavy network of nodes to cover large area of mining which leads to architecture complexity and cost (Alhmiedat and Samara 2017). While generic radio frequency solutions can be cheaper they are inferior in terms of range and reliability suitable for underground environments (Bandyopadhyay et al. 2007).

On the contrary, due to the application of LoRa technology, which is especially effective in long-range communication, the range of up to 7 kilometers allows the use of the hardware in extreme conditions of underground mining. This drastically diminishes the number of nodes needed thus cuts down on infrastructure and maintenance requirements. Moreover, we place a LoRaWAN gateway near the mine entrance and integrate it with mobile network through a Wi-Fi hotspot, thus guaranteeing long distance communication regardless of infrastructure constraints that are still rampant in Zimbabwean context. Additionally, the presence of a heart rate sensor will provide data on whether a trapped miner underground is still alive. Furthermore, the use of the Wazidev microcontroller will provide location tracking showing the exact location of a miner in a mineshaft which usually stretches several kilometers in non-uniform directions found in artisanal mines. This will make rescuing trapped miners easier in the case of a mineshaft collapse (Fahrurrasyid et al. 2022).

Supporting this, in the design of our helmet, we have incorporated needs from the questionnaire responses to maximise miners' needs and comfort. This approach guarantees that the helmet does not only boost safety and working effectiveness by monitoring the surrounding environment and tracking workers' health conditions in real-time but also complies with the typical practical requirements and usability concerns that individual miners experience. Therefore, the research work contributes a solution using enhanced technology and human-focused design in protecting miners and enhancing their occupational health and safety.

3. Methods

The methodology was carried out in two phases:

3.1 Quantitative Study

To understand the experiences of artisanal miners and their perceptions of smart helmets, a survey questionnaire was designed and physically administered to 400 miners from various artisanal mines across Zimbabwe. The survey was conducted using the Unified Theory of Acceptance and Use of Technology (UTAUT) framework, encompassing four key constructs: performance expectancy, effort expectancy, social influence, and facilitating conditions (Akhter and Hossain 2022;Venkatesh et al., 2003). The questionnaire aimed to capture data on miners' working conditions, safety concerns, awareness and perceptions of wearable technology and potential barriers to adopting smart helmets. These constructs were used to develop questions that assess miners' perceptions and potential adoption factors of smart helmets. The questionnaire consisted of the sections shown in Table 1. Data collected was subsequently analysed in SPSS version 25, correlations and significant factors influencing the adoption of smart helmets. Descriptive statistics, correlation and regression analysis were employed to analyse the data.

Table 1. Survey Questionnaire Sections

Section	Description
A	Demographics (age, gender, years of mining experience, etc.)
B	Working conditions (safety measures, frequency of accidents, health issues)
C	Awareness and perceptions of smart helmets
D	Barriers to adoption (cost, usability, cultural factors, etc.)
E	Willingness to adopt and use smart helmets

3.2 Design of the Smart Helmet System

Informed by findings from the quantitative study, the smart helmet system was designed and developed tailored to the needs and conditions of Zimbabwean artisanal miners. The system architecture included an Arduino IDE and Wazidev board with LoRa WAN capabilities, a Raspberry Pi 4 gateway and various sensors for environmental and health monitoring.

Based on insights from the quantitative study, the smart helmet system was designed to meet the specific needs and conditions of Zimbabwean artisanal miners. The smart helmet was built using the Arduino IDE and the Wazidev board, an Arduino-based platform with LoRa WAN capabilities. The system architecture is shown if Figure 1 below.

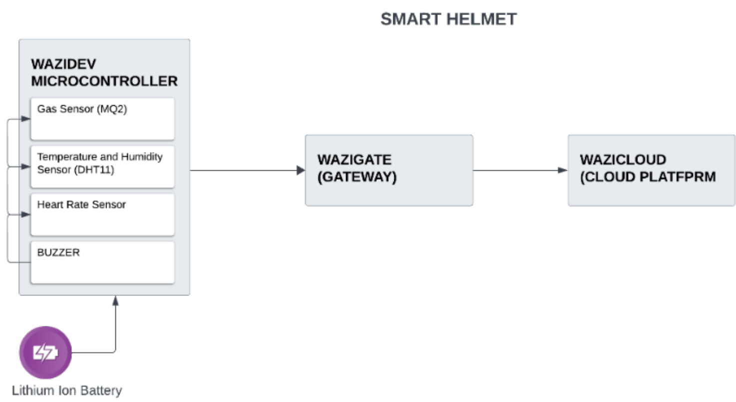

Figure 1. Architecture of the Smart Helmet

a. Wazidev (Microcontroller): this is the central processing unit in the helmet that gathers data from all the connected sensors and manages the buzzer. It is an Arduino-based sensing and actuation development board designed for use in IoT applications. It can transmit data up to 7 km using the RFM95W LoRa module with an embedded LoRa antenna (Waziup, 2024).
b. **Gas Sensor (MQ2):** detects the presence of harmful gases such as methane and carbon dioxide and sends data to the Cloud.
c. **Temperature and Humidity Sensor (DHT11):** Measures the environmental temperature and humidity
d. **Heart Rate Sensor (MAX30105):** Monitors the miner's heart rate and sends the readings to the Wazidev.
e. **Buzzer:** Acts as an alert system triggered by the Wazidev based on a set condition from sensor data.
f. **Wazigate (Gateway):** A gateway shown in Figure 2 was set up using a Raspberry Pi 4 Model B, equipped with a LoRa HAT and antenna, to send sensor data over the network. The Raspberry Pi gateway aggregated sensor data and transmitted it to a remote server for monitoring.
g. **Wazicloud (Cloud Platform):** A remote server where the data from the Wazigate is stored, processed and analysed. It enables real-time monitoring and alerts.
h. **Power Supply**: The system is powered by a Li-ion battery to ensure long-lasting and reliable operation in remote mining areas.
i. **Communication Module:** LoRa WAN technology was used for long-range, low-power communication between the helmet and the gateway.

Figure 2. Gateway built using Raspberry Pi and LoRa hat.

3.3 Software Development

The software for the smart helmet system was developed using C++ programming language in the Arduino IDE. The code was designed to continuously read sensor data and trigger alerts if defined thresholds are met. Data from the sensors is subsequently sent to the cloud platform via the LoRa WAN gateway. Fig shows a snippet of the code developed for the smart helmet system. The snippet in Figure 3 is part of a program written for the LoRaWAN smart helmet using several libraries. It begins by including the necessary libraries and defining keys and addresses used for securing LoRaWAN transmissions. Furthermore, it configures the device address, application and network session keys. The setup function initialises the serial communication at a baud rate of 38400 and configures the LoRaWAN settings using the wazidev object of the WaziDev class, which is provided with the device address and the session keys This setup is essential for preparing the microcontroller and its embedded sensors in the helmet to communicate securely over a LoRaWAN network.

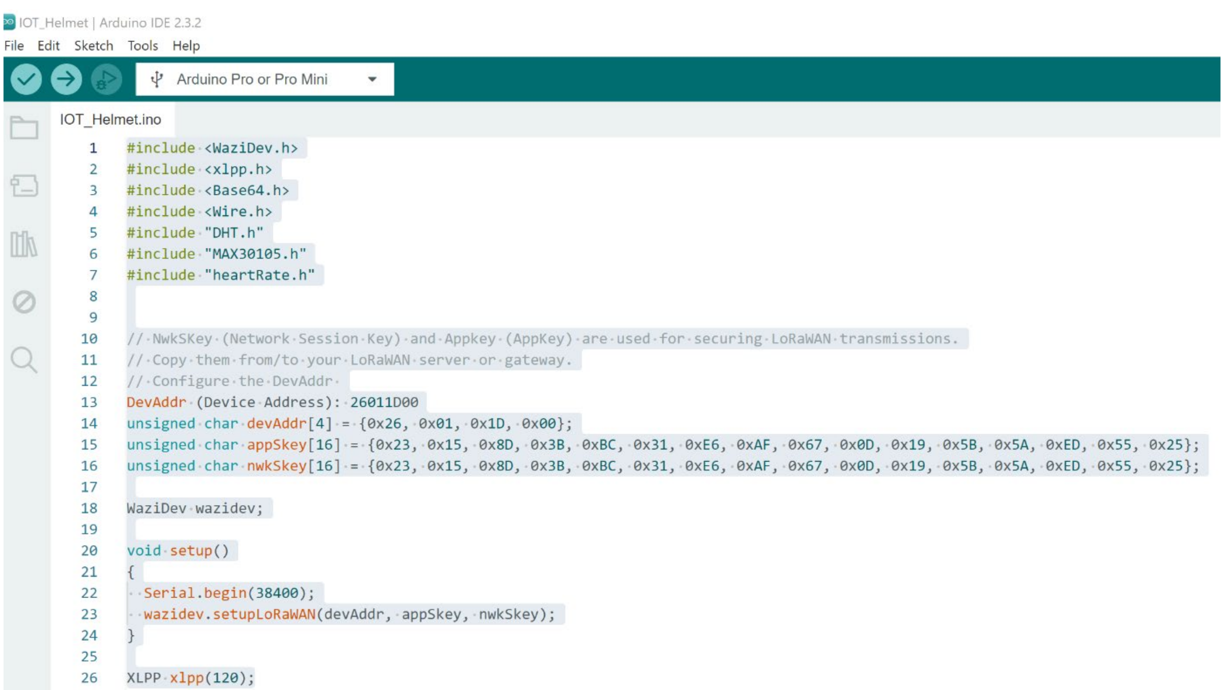

Figure 3. Code snippet for the Lora WAN smart helmet.

3.4 Wiring and programming sensors

The MQ2 gas sensor, DHT11 temperature and humidity sensor and heart rate sensor are each connected to the Wazidev microcontroller, utilizing its digital and analogue input pins. For secure and reliable connections, soldering is employed to attach the sensor leads to the microcontroller's corresponding pins, ensuring firm electrical contacts. The buzzer is similarly connected to a digital output pin on the Wazidev. Power connections are made to the Li-ion battery, with appropriate voltage regulation to protect the components. Housing for all these components was also 3D printed, the heart rate sensor was left out of the housing so that it is in immediate contact with the head to sense the heartbeat of a miner wearing the helmet while in use. Figure 4 below shows how this was achieved.

Figure 4. Smart Helmet showing WaziDev and the MQ2, DHT11 and MAX30105 sensors.

4. Data Collection

The quantitative study's data collection process included using a structured survey questionnaire as shown in Table 2. This questionnaire was administered to 400 artisanal miners from various mining sites across Zimbabwe. A stratified random sampling method was used to ensure a diverse and representative sample, covering different regions and types of artisanal mining operations. The survey was administered in person to ensure a high response rate and accurate data collection. The researcher outlined the study's purpose, assured confidentiality and assisted respondents in understanding and completing the questionnaire. This approach helped to overcome literacy barriers and ensured that participants fully comprehended the questions. Once the surveys were completed, the responses were entered into SPSS for analysis. The data was cleaned to check for inconsistencies, missing values and outliers. Any ambiguous or incomplete responses were reviewed and clarified with the respondents where possible. This ensured the reliability and accuracy of the collected data. The survey data were analysed using statistical software. Inferential statistics, including correlation and regression analyses, were employed to identify significant factors influencing the adoption of smart helmets. The UTAUT framework guided the interpretation of these factors, focusing on performance expectancy, effort expectancy, social influence and facilitating conditions(Gumasing et al. 2024; Lan et al. 2020). In parallel with the survey, field tests were conducted at selected mining sites. Miners were observed while using the helmet in their daily operations. These field tests were crucial for identifying practical issues and making necessary adjustments to ensure the helmet met the miners' needs and preferences. Sensor data was observed from a central workstation.

Table 2. Survey Questions

Question Number	Question	Response Type
A1	What is your gender?	Open-ended
A2	How old are you?	Multiple Choice
A3	How many years have you been involved in artisanal mining?	Open-ended
B1	What safety measures are currently in place at your mining site?	Open-ended
B2	How often do accidents or health issues occur during your mining operations?	Multiple Choice
C1	Are you aware of smart helmets and their features?	Yes/No
C2	How do you perceive the potential benefits of using a smart helmet?	Likert Scale (1-5)
D1	What might hinder the adoption of smart helmets in your mining activities?	Open-ended
D2	How important is the cost of the smart helmet to your decision to adopt it?	Likert Scale (1-5)
D3	How important is the user-friendliness of the smart helmet in your decision to adopt it?	Likert Scale (1-5)
E1	Would you be willing to use a smart helmet if it were provided at an affordable cost?	Yes/No
E2	What additional features would you like to see in a smart helmet?	Open-ended

5. Results and Discussion

The survey results revealed several key factors influencing the adoption of smart helmets among artisanal miners:

a) Performance Expectancy

- Miners believed that smart helmets could significantly enhance their safety and operational efficiency.
- This belief was supported by a positive correlation between performance expectancy and willingness to adopt smart helmets ($r = 0.62$, $p < 0.01$).

b) Effort Expectancy

- Ease of use was a critical factor, with miners expressing concerns about the complexity of operating smart helmets.
- There was a moderate negative correlation between perceived complexity and willingness to adopt ($r = -0.45$, $p < 0.05$).

c) Facilitating Conditions

- The availability of support and training positively influenced miners' readiness to use smart helmets.
- This was evidenced by a positive correlation ($r = 0.58$, $p < 0.01$).

d) Price

- The cost was a significant consideration, with many miners indicating that high prices could deter adoption.
- There was a strong negative correlation between price and willingness to adopt smart helmets ($r = -0.67$, $p < 0.01$).

The regression analysis further highlighted that performance expectancy and facilitating conditions were the primary predictors of adoption, accounting for 70.8% of the variance in willingness to adopt smart helmets. This is shown by the results of the ANOVA test in Figure 5 below.

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	70.807	5	14.161	9.174	.000[b]
	Residual	608.193	394	1.544		
	Total	679.000	399			

a. Dependent Variable: Initial Perception of Smart Helmets
b. Predictors: (Constant), Importance of Battery Life, Importance of Comfort and Fit, Importance of Location Tracking, Importance of Communication System, Importance of Safety Sensors

Figure 5. ANOVA test results from SPSS

User Interface and System Testing
The user interface for monitoring the smart helmet system was an open-source cloud platform called the WaziCloud. The dashboard displays real-time sensor data, including temperature, heart rate and the miner's location as shown in Figure 6 below. The UI shows real-time data of miners, including temperature readings and heart rate. Alerts are generated for abnormal readings and the exact location of the miner is mapped using the Wazidev board.

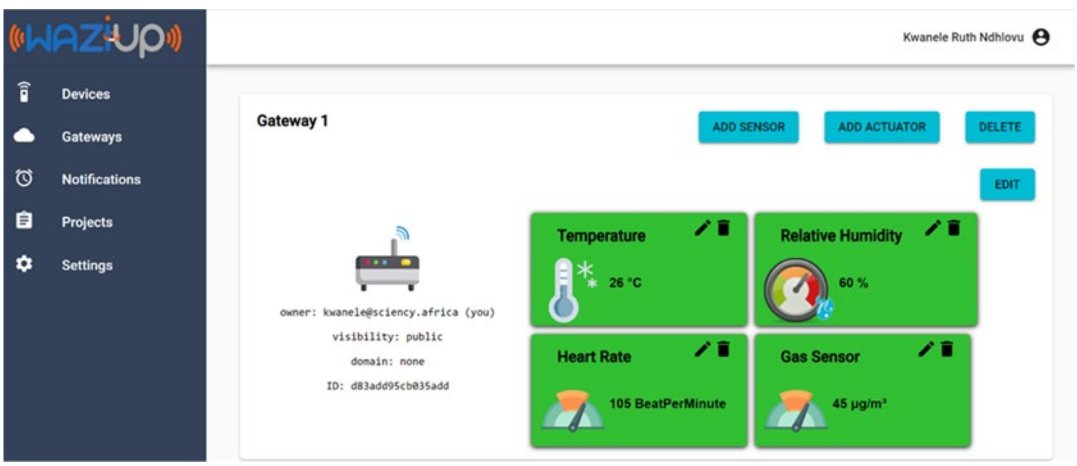

Figure 6. Sensor readings dashboard on the WaziCloud

Field Testing
The smart helmet was tested in several artisanal mining sites. Miners wore the helmet during their daily operations and the system's performance was monitored from a central workstation. During this period, it was observed by the researcher that the miners did not face any challenges in wearing and using the smart helmet. The feedback from miners was overwhelmingly positive, particularly appreciating the safety alerts and real-time monitoring features (Figure 7).

Figure 7. Artisan Miner wearing the helmet just before going into a mineshaft

5.1 Discussion

This study discovered that knowledge about smart helmets and their functions significantly influenced miners' willingness to adopt this technology. This finding supports existing literature, which consistently emphasises the importance of awareness in adopting new technologies. For example, previous literature underscores that awareness and understanding of the benefits of technology are critical in shaping user attitudes and acceptance (Davis 1989; Venkatesh et al. 2003). Similarly, Mathieson et al. (2001) noted that individuals are more likely to adopt a technology if they comprehend its potential benefits and relevance to their tasks. The positive link between performance expectations and the willingness to adopt smart helmets aligns with previous research findings. Venkatesh et al. (2003) identified performance expectations as a strong predictor of technology acceptance, indicating that users are more likely to embrace technology if they believe it will enhance their performance. In our study, miners expressed that smart helmets would significantly improve their safety and operational efficiency, supporting the importance of this factor. Interestingly, our study identified price as a significant factor affecting the adoption of smart helmets, whereas existing literature does not consistently highlight this factor. This difference may be attributed to the unique socioeconomic context of Zimbabwean artisanal miners. Many miners operate on limited budgets and are highly sensitive to the cost of new technologies. This research also highlighted several unique challenges Zimbabwean artisanal miners face, such as frequent power cuts and limited access to reliable internet connectivity, especially in remote areas where artisanal mines are usually found. This context-specific finding underscores the need for tailored technology solutions that address users' specific constraints and needs in different regions.

5.2 Limitations

Due to time and budget constraints, only 400 artisanal miners from 10 artisanal mines were used in testing and validating the smart helmet system. This limited sample size can influence the generalisability of the outcome, as the results may not fully represent the diverse conditions and challenges encountered in different mining environments. The Lithium-ion battery offers lightweight and high energy however, artisanal miners in Zimbabwe usually spend long periods in mineshafts where there is no power to recharge the battery. This limitation could impact the overall effectiveness and reliability of the smart helmet in a mining environment. Another limitation of this research is its specific focus on the Zimbabwean context, which may impact the applicability of the outcome to other regions or mining environments. The unique socioeconomic, infrastructural and regulatory conditions in Zimbabwe present distinct challenges and opportunities that shaped the design and development of the smart helmet.

5.3 Recommendations for future

Future research should expand the sample size and diversity of miners to enhance the generalisability of findings and conduct longitudinal studies for long-term effectiveness. Exploring alternative energy sources and advanced battery technologies will higher longevity could address battery limitations. Contextualising the study of artisanal miners' experiences globally could ensure adaptability to various contexts because infrastructure and policies are different in each country. Focusing on cost-effective solutions, infrastructure development and user-centered design, along with providing comprehensive training and support, will improve usability and adoption. Collaborative efforts with multidisciplinary experts and mining companies will facilitate larger-scale trials and secure funding for further research and development. Furthermore, employing deep learning algorithms on collected sensor data could be leveraged to predict hazards such as methane gas build-up which result in explosions and mineshaft collapses.

6. Conclusion

This research achieved its objectives of investigating the factors influencing the adoption of smart helmets among artisanal miners and implementing a smart helmet equipped with IoT sensors. Our primary goal was to gather contextual insights necessary for the development of a helmet tailored specifically for use in the Zimbabwean artisanal mining context. Through a quantitative survey and the development of a prototype smart helmet system, we identified critical factors such as awareness, performance expectancy, effort expectancy, social influence and economic considerations, including price sensitivity. These findings provide essential guidance for designing technology solutions that effectively address the unique challenges faced by Zimbabwean artisanal miners, such as unreliable power supply and limited internet connectivity. By integrating theoretical insights with practical application, this study contributes to advancing wearable technology in artisanal mining, aiming to enhance safety and operational efficiency in resource-constrained environments.

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