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Blockchain-driven sustainable business model for artisanal and small-scale mining operators in Zambia

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Abstract

This study investigates blockchain adoption barriers among artisanal and small-scale mining operators in Zambia's Ndola Rural Emerald Restricted Area (NRERA) and proposes a Blockchain-enabled Sustainable Business Model (BSBM) to enhance sustainability and profitability. Using a convergent parallel mixed-methods design, quantitative surveys ($n = 11$) and qualitative interviews ($n = 9$) highlight that 72.7 % of ASM operators have basic education, 81.8 % rely on predatory informal loans, and 90.9 % face infrastructural deficits like unreliable electricity and poor internet. None have adopted blockchain technology due to financial, structural, and technological barriers. Exploitative intermediaries capture most mineral value, perpetuating low investment cycles and limiting technological progress. The BSBM addresses these challenges by leveraging mining associations to automate compliance via smart contracts, establishing traceability for premium pricing, and offering tiered financing alongside mobile blockchain interfaces to overcome literacy and connectivity issues. Early implementations suggest transaction cost reductions of 30–50 % and premium markets adding 15–30 % margins. This study underscores the need for integrated interventions that combine financial inclusion, policy collaboration, and tailored technology to enable sustainable ASM sector development. These findings provide actionable policy insights and contribute to the emerging discourse on the role of blockchain in resource-constrained mining contexts.

1. Introduction

Blockchain technology has transformative potential in various sectors, including mining. Artisanal and small-scale mining (ASM) is a vital employment source in sub-Saharan Africa (Hilson & Hu, 2022; Ofosu & Sarpong, 2022). Despite ASM's association with environmental degradation and negative social issues, this mining sector contributes significantly to global mineral production, accounting for 25 % of diamonds, 20 % of gold, 80 % of colored stones, and 30 % of cobalt in renewable energy batteries (Archuleta, 2016). However, operators often rely on exploitative intermediaries, leading to unethical practices and a lack of transparency (Atal, Trapnell, & Zinnbauer, 2022; Siwale & Siwale, 2017a). Governments are urging the ASM sector to adopt sustainable production practices in response to illegal operations and environmental damage (OECD, 2016). To meet consumer demand for responsibly sourced materials, ASM operators must enhance the transparency and visibility of their supply chains (Cartier, Ali, & Krzemnicki, 2018; Mullen, 2018). Blockchain technology can facilitate this by improving transparency, reducing trade financing risks, promoting fair trade, and providing accurate market data (Jeppsson & Olsson, 2017). Blockchain also combats mineral fraud through immutable records, supporting sustainable business models aligned with the sharing economy (T. M. Tan et al., 2024). For successful blockchain adoption, ASM operators must embrace innovative business models that integrate economic, social, and environmental goals (Evans et al., 2017). A blockchain-enabled sustainable business model (BSBM) enhances transparency and accountability, ensuring adherence to sustainability standards and improving access to credit and investment opportunities (Choi, 2019; Gozman, Liebenau, & Mangan, 2018; Sze, Salo, & Tan, 2024). Most studies focus on general supply chain applications, often neglecting

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specific industries such as ASM, where the sustainability benefits of blockchain remain largely unexplored. In Zambia, the level blockchain technology adoption in the ASM sector is unknown. Although blockchain has significant potential advantages in ASM, substantial research gaps persist. One area of particular interest is the empirical impact of blockchain on sustainable business models or its integration as a sustainable business model (Tiscini, Testarmata, Ciaburri, & Ferrari, 2020). These knowledge gaps can be addressed by demonstrating the actual effects of blockchain on sustainable business models in this sector. This will in turn maximize the benefits of blockchain to promote sustainable practices in ASM. Existing studies frequently overlook critical barriers to blockchain adoption, including organizational and regulatory challenges (Singh, Kumar, Irfan, Mohandes, & Awan, 2023). Furthermore, the innovative nature of blockchain technology suggests that many of its implications, especially those related to sustainability, are still evolving and not yet fully understood (Kwok & Treiblmaier, 2024). This study addresses these gaps by providing a thorough empirical investigation that elucidates the essential components of blockchain-based sustainable business models and their connection to sustainability within the ASM sector, thereby underscoring the importance of this research. In this study, the following research questions (RQs) were adopted:

- RQ1: What is the current level of blockchain adoption among ASM operators in Zambia?
- RQ2: What are the barriers to blockchain adoption?
- RQ3: How can blockchain be integrated into sustainable business models for ASM?

This pilot study on technology adoption in Zambia's ASM sector employs a mixed-method approach to explore the integration of blockchain technology. This study assessed the impact of technology on operational efficiency and sustainability by combining quantitative surveys and qualitative interviews.

2. Literature review

2.1. Sustainable business model innovation

Businesses today face significant challenges, including climate change, population growth, resource depletion, social inequalities, and environmental degradation, necessitating a shift towards sustainable practices (Lüdeke-Freund, 2013). Traditional business models often overlook social and environmental impacts; however, a Sustainable Business Model (SBM) framework is emerging. This approach emphasizes broader business objectives beyond financial gain. The SBM framework adopts a triple bottom line approach that considers environmental, social, and financial performance (Konietzko, Das, & Bocken, 2023). SBMs recognize the needs of all stakeholders, including nature, and advocate for changes in taxation to penalize environmentally harmful practices while promoting local capital reinvestment (Lüdeke-Freund, 2013). Business model innovation, defined as the intentional alteration of a company's fundamental elements, is crucial for creating substantial positive impacts on society and the environment. This innovation can involve technological, social, or organizational changes, allowing companies to combine various SBM archetypes to enhance sustainability and competitiveness in their operations (Annesi, Battaglia, & Sganzetta, 2023; Bocken et al., 2014a; Stubbs & Cocklin, 2008).

The characteristics of blockchain technology, such as decentralization, transparency, security, and immutability, make it well-suited for enabling sustainable business models (Tiscini et al., 2020). Blockchain-enabled Sustainable Business Models (BSBMs) leverage these features to enhance traceability, reduce costs, and promote transparency in supply chains (Jeppsson & Olsson, 2017; Y. Tan, 2024). By providing immutable records of transactions and activities, blockchain helps combat fraud and ensures adherence to sustainability standards, quality, and mineral authenticity (Choi, 2019; Sze et al., 2024). This transparency fosters trust among stakeholders and encourages responsible sourcing and sustainable investments (Gozman et al., 2018). Moreover, blockchain can mitigate environmental impacts by promoting controlled alternatives and aligning with the Sustainable Development Goals (SDGs) (Menta Simonsen Nico, Henrique Xavier Araujo, Goldemberg, & de Tomi, 2024; Tomassi, 2024). Despite the potential of blockchain technology to enable sustainable business models, research gaps remain, particularly regarding empirical evidence and comprehensive frameworks for implementation (Tiscini et al., 2020; Vern, Panghal, Mor, & Kamble, 2024).

2.2. Sustainable business model innovation in the ASM sector

The ASM industry faces significant challenges due to intensifying competition and counterfeits, as well as criticism for its unfair labor practices and use of environmentally and socially harmful practices (Calik, Karaca, Yasar, & Ulugergerli, 2019; Hentschel et al., 2002; Limsuwan, 2019; Ofosu & Sarpong, 2022). An emergent viable approach to address these sustainability challenges in the minerals sector (especially the ASM) is the implementation of supply chain traceability (Calvão & Archer, 2021; Choi, 2019). While the literature on innovation has traditionally focused on high-tech businesses, there is a growing interest in studying traditional industries such as ASM, as an organization's profitability is closely tied to its ability to innovate (Caiazza & Volpe, 2017). However, researchers have not devoted much attention to the innovation of business models aimed at achieving sustainability in industries such as ASM (Barth, Ulvenblad, & Ulvenblad, 2017). Blockchain technology has garnered significant attention in other sectors such as Fintech and Big Pharma, exemplifying BSBM innovation and providing clear societal advantages, such as enhanced data openness, integrity, and security in the mineral supply chain (Javaid, Haleem, Singh, Suman, & Khan, 2022; Jha, Young, & Sattarvand, 2023; Zakari et al., 2022). Additionally, it contributes to environmental conservation by minimizing resource and energy wastage (Iansiti & Lakhani, 2017; Tripoli & Schmidhuber, 2018).

In Zambia, ASM operators face challenges in accessing legal mineral markets, leading to unsustainable production of gemstones and the participation of unethical intermediaries (Siwale & Siwale, 2017b). The Zambian government has implemented policies and regulations to formalize the ASM sector and raise sustainability standards. This includes interventions such as the GRZ mineral certification scheme which is part of the broader regional International Conference on the Great Lakes Region (ICGLR) Regional Certification Mechanism (RCM) (IGF, 2018). However, this scheme lacked awareness and understanding of the ASM sector's dynamics, limiting its ability to target and engage the appropriate value chain actors (McQuilken, 2018). The integration of blockchain technology into the ASM sector presents a transformative opportunity to address many of the challenges currently faced by the industry. By enhancing supply chain traceability, blockchain can provide a transparent and immutable record of transactions, which is essential for combating counterfeiting and ensuring ethical labor practices (Cartier et al., 2018; Choi, 2019). This technology facilitates the verification of the origin of minerals, thereby fostering accountability among stakeholders and promoting responsible sourcing of materials (Jha et al., 2023). Furthermore, blockchain's ability to streamline operations and reduce inefficiencies can significantly improve the ASM operators' access to legal markets, mitigating the influence of unethical intermediaries (Javaid et al., 2022). As the Zambian government seeks to strengthen the formalization of the ASM sector through policies and certification schemes, blockchain can serve as a critical tool for enhancing compliance with sustainability standards and reinforcing the integrity of the supply chain (World Bank, 2019, 2020). By leveraging blockchain technology, the ASM industry can not only improve its operational practices but also align itself with global sustainability goals, ultimately contributing to the sector's long-term viability and success.

2.2.1. Advancements in minerals traceability and authentication

The global gemstone industry has undergone significant transformation in recent years, driven by advances in traceability and authentication technologies. These developments aim to address critical challenges, such as fraud, ethical sourcing, and supply chain transparency, particularly in high-value sectors, such as diamonds and colored gemstones. This subsection examines key initiatives that leverage cutting-edge technologies, including blockchain, artificial intelligence (AI), and gemological fingerprinting, to enhance the integrity of the gemstone supply chain.

2.2.2. Blockchain-driven traceability systems

Blockchain technology has emerged as a cornerstone for ensuring immutable provenance records across the gemstone industry. De Beers' Tracr platform, launched in 2017, exemplifies this approach by utilizing blockchain, AI, and the IoT to track diamonds from extraction to retail (Smits & Hulstijn, 2020). The platform creates a decentralized ledger that secures transaction histories and ownership transfers, mitigating risks of counterfeiting and fraud. By enabling stakeholders to verify a diamond's journey in real time, Tracr fosters trust and compliance with ethical standards (Maione, 2024).

Similarly, IBM's Trustchain initiative focuses on diamonds, gold, and jewelry, employing blockchain to automate compliance through smart contracts and reduce human error in supply chain management (Kshetri, 2022). These platforms highlight blockchain's dual role in enhancing transparency and operational efficiency, though challenges such as interoperability and scalability persist (Cartier et al., 2018).

Another notable blockchain-based initiative is Everledger's Diamond Time-Lapse Protocol, which monitors the lifecycle of diamonds on a permissioned private blockchain. This protocol ensures traceability, transparency, and security by allowing only authorized stakeholders to access and update transaction histories. By automating processes through smart contracts, the protocol enhances efficiency and reduces costs while providing verifiable information about a diamond's provenance (Cartier et al., 2018; Holm & Goduscheit, 2020).

2.2.3. Gemmological fingerprinting and origin determination

Gemmological science remains critical to traceability, particularly for colored gemstones. The Emerald Paternity Test, introduced by Gübelin Gem Lab in 2017, represents a groundbreaking advancement in origin determination. This technique embeds nanoparticles within emeralds during their formation, creating unique identifiers that act as a "birth certificate" for tracking their geographic origin (Cartier et al., 2018). Unlike traditional chemical and spectroscopic analyses, which can be less definitive because of overlapping characteristics among emeralds from different regions, the Emerald Paternity Test provides a precise and tamper-proof method for verifying provenance. This innovation is particularly significant given the historical and cultural value associated with certain origins, such as Zambian emeralds, and the increasing complexity of global emerald mining (Groat et al., 2019).

Similarly, the Swiss Gemmological Institute (SSEF) introduced GemTrack in 2019, a service that links cut gemstones to their rough counterparts using crystallographic, chemical, and microscopic analyses. By creating unique "fingerprints" for rough stones, GemTrack validates provenance claims and combats misrepresentation—a significant issue in markets where origin directly influences value (e.g., Colombian emeralds or Burmese rubies) (Groat et al., 2019; Hügi & Krzemnicki, 2019).

2.2.4. Collaborative industry initiatives

Partnerships between gemological institutions and technology firms have further advanced traceability. The Provenance Proof initiative, developed by Gübelin Gem Lab in collaboration with Everledger, combines blockchain with gemmological data to create tamper-proof records for colored gemstones. This system not only tracks a stone's journey but also integrates scientific verification of origin, addressing consumer demands for ethical sourcing (Cartier et al., 2018).

The Mine to Market (M2M) program launched by the Gemmological Institute of America (GIA), is another comprehensive initiative that tracks diamonds from their rough state to their final cut. The M2M program emphasizes ethical sourcing and supports female operators in the colored stone sector through collaborations with actors such as Pact, an active NGO. The program enhances supply chain transparency through certification systems and emerging technologies such as blockchain, reflecting a commitment to corporate social responsibility and sustainable practices (Vertriest & Saeseaw, 2019).

2.2.5. The role of standardization, alignment, and collaborative initiatives

Despite these advancements, several challenges remain to be addressed. The fragmented nature of artisanal mining complicates traceability efforts, particularly in regions such as Africa where supply chains are less centralized. Additionally, smaller enterprises often lack the financial or technical capacity to implement advanced systems such as blockchain or nanoparticle-based authentication.

Moreover, the integration of these technologies across global markets requires active stakeholder participation and regulatory alignment. For instance, while blockchain offers a decentralized and tamper-proof ledger, its scalability and interoperability with existing systems remain areas of concern. Similarly, the financial implications of adopting technologies like the emerald paternity test or AI-driven authentication systems may pose barriers for smaller entities within the industry.

Future success will depend on industry-wide standardization, regulatory alignment, and education to bridge gaps between technological potential and practical application. Collaborative efforts, such as those seen in the Provenance Proof and M2M initiatives, demonstrate the importance of merging technological innovation with gemmological expertise to build scalable and interoperable solutions.

3. Methodology

This study employed a convergent parallel mixed-methods design (Creswell & Creswell, 2018) to investigate technology adoption among ASM operators within Zambia's Ndola Rural Emerald Restricted Area (NRERA), with a particular focus on the barriers to blockchain implementation. The NRERA, a government-regulated ASM zone in Zambia's Copperbelt Province, presents a unique context for this research because of its formalization efforts and ongoing sustainability challenges (World Bank, 2020). This setting provided a critical opportunity to evaluate the alignment between policy intentions and practical realities. While prioritizing qualitative insights to explore complex issues, this study integrated quantitative data to provide context and support the exploratory nature of this pilot research. The intent was to triangulate the findings from both approaches, leading to a more comprehensive understanding of the barriers and opportunities related to technology adoption in this sector.

3.1. Quantitative approach: Establishing a baseline

The study commenced with a quantitative approach to establish a baseline understanding of technology usage and the demographic characteristics of ASM operators within the NRERA. A hybrid questionnaire, incorporating both closed-ended and open-ended questions, was administered to a convenience sample of eleven licensed ASM operators. While convenience sampling presents limitations in terms of generalizability, this sample represented approximately 55 % of the estimated 20 active licensed operators within the NRERA. Moreover, the sample was carefully selected to reflect the demographic diversity of the operator population in terms of gender, age, and education levels (as detailed in Table 2.). (See Fig. 1.) (See Table 1.)

The questionnaire instrument incorporated both closed- and open-

Table 2
Survey respondents' profile.

Particulars		*n* = 11	Percentage (%)
Gender	Male	8	72.7
	Female	3	27.3
Age Group	18–35 years	1	9.1
	36–45 years	5	45.5
	46–55 years	2	18.2
	56–65 years	2	18.2
	Above 65 years	1	9.1
Highest Education Level	Basic Education (Secondary school)	8	72.7
	Diploma	1	9.1
	Degree	2	18.2

Table 3
Technology application in routine business tasks.

Business Task	Tech Used Often/ Always (%)	Tech Rarely/ Never Used (%)	Process Not Done (%)
Document Preparation	45.5%	36.4 %	0%
Geoscience	27.3 %	18.2 %	45.5 %
Production Planning	27.3 %	18.2 %	45.5 %
Financial Statement Preparation	27.3 %	18.2 %	45.5 %
Link to Clients Electronically	18.2 %	18.2 %	45.5 %
Environmental Monitoring	18.2 %	27.3 %	45.5%
Sales Analysis	9.1 %	9.1 %	54.5%
Order Entry	9.1 %	36.4 %	45.5%
Site Surveys	9.1 %	27.3 %	45.5%
Progressive Site Remediation	0%	27.3 %	54.5%
Logistics	0%	36.4 %	54.5%
Payroll Processing	0%	18.2 %	72.7 %
Blasting	0%	45.5%	45.5 %

ended questions to gather comprehensive data. Closed-ended questions were designed to capture quantifiable demographic data, such as age, education level, and gender, and to quantify the frequency with which operators applied various technologies in their operational activities, including tasks related to geoscience, environmental monitoring, sales analysis, and logistics. Specifically, operators were asked to indicate the extent to which they utilized technology for each task, using a Likert-type scale ranging from "No technology used" to "Process done only by technology." Open-ended questions were strategically included to capture operators' perceptions of sustainability certifications and the financial challenges they encountered, allowing for richer, contextualized responses that could inform the subsequent qualitative data collection and analysis.

All eleven participants completed the questionnaire, resulting in a 100 % response rate. Given the limited sample size, the quantitative data were analyzed using descriptive statistics. Specifically, frequencies and percentages were calculated to summarize the prevalence of technology use across different business tasks and to characterize the demographic profile of the respondents. These quantitative findings served primarily to contextualize the qualitative findings and to illustrate broader trends, with the results synthesized narratively rather than through the application of inferential statistical analyses. Key findings were presented consicely in the text; for example, "most operators (45.5%) reported using technology for general admisistrative processes," rather than relying on traditional tabular presentations. This narrative approach allowed for the efficient communication of relevant quantitative data without overstating its generalizability given the small sample.

Table 5
BSBM vs. current model.

Aspect	BSBM	Current Model
Stakeholder Trust	Transparency in operations enhances public trust.	Opaque practices fuel mistrust
Revenue Streams	Premium pricing for traceable, ethical minerals (+15–30 % margins).	Price suppression by intermediaries.
Compliance Costs	Smart contracts reduce administrative overhead by 40 %	Manual processes incur high monitoring costs.

3.2. Qualitative approach: Exploring the nuances of technology adoption

Building upon the quantitative findings, the study adopted a qualitative approach to delve deeper into the nuanced and often complex dynamics of technology adoption within the ASM sector. The study recognized that technology adoption is not simply a matter of access but is also shaped by a complex interplay of many issues. These include social, economic, and institutional factors. The qualitative component of this study sought to uncover the underlying reasons for the observed patterns of technology use and the specific barriers that hindered the adoption of more advanced technologies, such as blockchain. Qualitative data were collected over a six-month period (May–October 2022) through semi-structured interviews and on-site visits with detailed observations.

3.2.1. Semi-structured interviews

Semi-structured interviews were conducted with nine ASM operators, including two females and seven males. The deliberate decision to employ semi-structured interviews stemmed from the recognition that this approach provided the optimal balance between structure and flexibility. While a pre-determined interview guide was used to ensure that key research areas were covered consistently across all interviews, the semi-structured format allowed for open-ended questioning and the exploration of emergent themes and unexpected insights that might not have been anticipated a priori.

The interviews focused on several critical areas deemed relevant to understanding technology adoption within the NRERA context. Specifically, the interview protocol explored:

Technology usage patterns, with a particular emphasis on the specific tools and technologies used for geoscience and environmental monitoring activities; The specific barriers encountered when

Table 4
Matrix coding for thematic analysis.

Participants	Age	Gender	Education level	Experience (years)	Economic Barriers	Other Tech	Structural Challenges	Technology Gaps
P1	55	Male	degree	24	7	0	1	3
P2	65	Male	secondary	30	0	0	4	5
P3	40	Male	diploma	12	0	1	3	5
P4	51	Female	secondary	20	5	0	2	2
P5	46	Male	degree	16	6	1	0	3
P6	42	Female	secondary	10	1	1	1	1
P7	32	Male	secondary	8	5	0	0	5
P8	58	Male	secondary	28	1	1	1	0
P9	57	Male	secondary	16	5	0	2	0

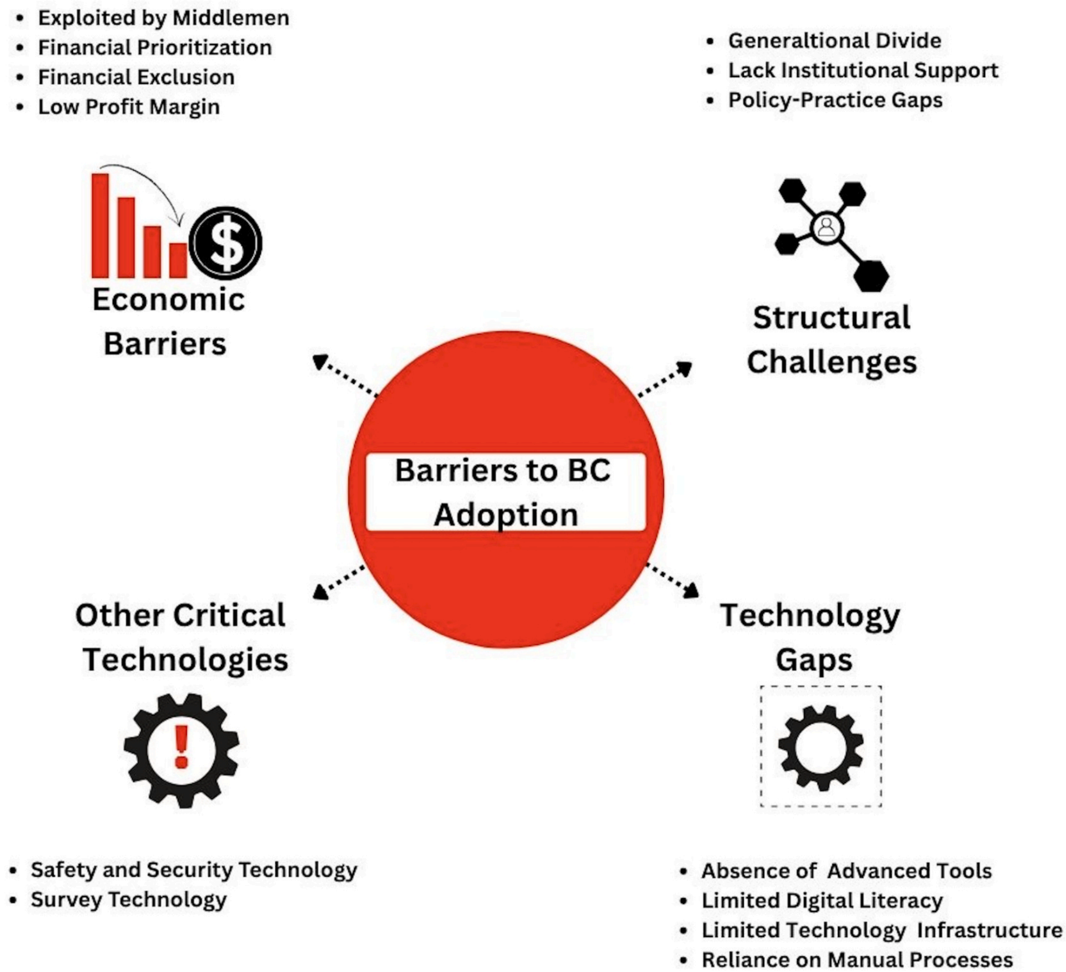

Fig. 1. Barriers to blockchain adoption framework.

attempting to adopt advanced systems such as blockchain technology, including both technical challenges and perceived risks; and the pervasive financial constraints that impact operational and market dynamics, including access to credit, relationships with intermediaries, and profitability.

Each interview lasted between 45 and 60 min and was conducted in English to ensure clarity and consistency. All interviews were audio-recorded to ensure accuracy, and the recordings were subsequently transcribed verbatim to facilitate rigorous analysis.

3.2.2. *Site visits and observations*

Site visits were conducted at nine mining operations to document workflows, environmental practices, and technology utilization. Field notes captured details on manual versus mechanized processes, while photographic evidence documented tools employed, such as handheld GPS devices and spreadsheets.

3.3. *Integrated data analysis: A convergent approach*

To ensure a robust and comprehensive analysis, this research followed a convergent parallel mixed-methods design, where quantitative and qualitative data were analyzed separately before being integrated to address the research questions holistically.

3.3.1. *Quantitative data analysis*

As previously described, quantitative data from the questionnaires were analyzed using descriptive statistics, focusing on frequencies and percentages to summarize demographic characteristics and technology usage patterns using SPSS 27. These analyses provided a broad overview of technology adoption within the NRERA and served as a context for interpreting the more nuanced qualitative findings.

3.3.2. *Qualitative data analysis: Reflexive thematic analysis*

Research question (RQ2) specifically investigates the specific barriers that hinder blockchain technology adoption among the ASM operators. Reflexive thematic analysis (RTA) was utilized to analyze the qualitative data in order to answer RQ2. RTA is a flexible yet rigorous method for identifying, analyzing, and interpreting patterns of meaning (themes) within qualitative data (Braun & Clarke, 2021). Its reflexive nature, which acknowledges the researcher's active role in the knowledge construction process, was particularly well-suited for exploring the complex and subjective experiences of ASM operators regarding technology adoption. Thematic analysis enabled a nuanced understanding of how social, economic, and structural factors interact to influence technology access and utilization within the NRERA's ASM sector. Data collected during site visits provided crucial contextual details, illuminating the realities of technology use on-site, while policy documents and government reports were analyzed to enhance the understanding of the broader regulatory and policy environment.

The data analysis followed a systematic and iterative process, guided by the six phases of RTA (Braun & Clarke, 2006, 2021):

1. Familiarization: The researchers immersed themselves in the data by repeatedly reading and rereading the interview transcripts and meticulously reviewing field notes. Accuracy was rigorously ensured through a detailed verification process that involved comparing the transcripts against the original audio recordings. This thorough

Table 1
Innovative traceability and provenance solutions in the mining sector.

Application	Description	Key Features	Source
Emerald Paternity Test	Developed by the Gubelin Gem Lab in 2017, this tool independently verifies the origin of emeralds. It uses nanoparticles embedded in emeralds to validate the provenance claims.	- Builds trust among miners, governments, and buyers - Protects emerald identity and chain of custody	(Cartier et al., 2018)
Mine to Market (M2M) Program	Initiated by the Gemmological Institute of America (GIA), it tracks diamonds from rough to cut forms, ensuring that buyers can observe the diamond's journey. Collaborates with Pact to focus on colored stones and female operators.	- GIA certification for each stone - Monitors diamond flow from suppliers to retailers	(Bastian et al., 2022)
Tracr	A De Beers project that utilizes blockchain, AI, and IoT to track the provenance and authenticity of diamonds from the mine to the consumer is also an example.	- Enables data management while preserving privacy - Verifies traceability of diamonds - Tracks inventory throughout manufacturing	(Smits & Hulstijn, 2020)
Diamond Time-Lapse Protocol	Developed by Everledger, this protocol involves various stakeholders to track a diamond's life cycle on a permissioned private blockchain, encrypting its provenance.	- Includes production touchpoints and certificates	(Cartier et al., 2018; Holm & Goduscheit, 2020)
Provenance Proof	An initiative by the Gubelin Gem Lab and Everledger that tracks gems and jewelry from mines to consumers using blockchain technology.	- Focuses on colored stones - Ensures traceability from mine to finger	(Cartier et al., 2018)
Trustchain	Owned by IBM, this initiative focuses on transparency in the diamond, gold, and jewelry supply chains. Participants document physical movements and meet audit requirements, ensuring authenticity from mine to merchant.	- Provides supply chain visibility - Utilizes IBM's blockchain technology for authentication	(Kshetri, 2022)

familiarization process was essential for developing a deep understanding of the data and identifying potential patterns and themes.

2. Initial Coding: Using NVivo 15, a qualitative data analysis software package, line-by-line coding was performed to systematically identify and label relevant segments of text. The codes captured key ideas, concepts, and phrases related to the research questions (Byrne, 2022). Examples of codes included "lack of financing," "buyer exploitation," "limited digital literacy," and "inadequate infrastructure." This process facilitated the organization and categorization of the data in a structured and meaningful way.

3. Theme Development: The coded data were then carefully analyzed to identify broader, overarching themes that represented recurring patterns of meaning within the data. This involved an iterative process of grouping related codes together and examining the relationships between them.

4. Theme Review: The identified themes were rigorously reviewed to ensure internal consistency and coherence. This involved assessing the extent to which the data within each theme were meaningfully related and whether the themes accurately reflected the overall patterns in the data. Themes that lacked sufficient support or that were poorly defined were refined or discarded.

5. Definition and Naming: The final themes were clearly defined and named, providing a concise and informative description of the core meaning of each theme. The themes were supported by illustrative quotes from the interview transcripts, providing concrete examples of the experiences and perspectives of the ASM operators (Braun & Clarke, 2021).

6. Reporting: The final step involved contextualizing the findings within the existing body of literature on ASM sustainability, technology adoption, and related issues. This allowed for a broader interpretation of the data and the identification of potential implications for policy and practice.

3.4. Data integration and triangulation

The final stage of the research involved the integration of findings to provide a more comprehensive and nuanced understanding of technology adoption among ASM operators in the NRERA. This was done after the separate analyses of the quantitative and qualitative data. This data integration process focused on identifying areas of convergence, divergence, and complementarity between the quantitative and qualitative results. For example, quantitative data on the prevalence of technology use for basic administrative processes were compared with qualitative data on the reasons why operators chose to use or not use technology for this task. Similarly, quantitative data on the demographic characteristics of technology adopters were compared with qualitative data on the social and economic factors that shaped technology access and utilization.

This integration of data was guided by the principle of triangulation, which seeks to strengthen the validity and reliability of research findings by examining the extent to which different data sources and methods converge on similar conclusions. In cases where quantitative and qualitative findings diverged, these discrepancies were carefully examined to identify potential explanations, such as sampling bias, measurement error, or the influence of contextual factors not captured by either the quantitative or qualitative data.

The study aimed to provide a holistic and evidence-based understanding of the complex dynamics of technology adoption within the ASM sector through this rigorous and iterative process of data integration and triangulation. The findings of this approach offer valuable insights for policymakers, industry stakeholders, and researchers seeking to promote sustainable and equitable development in this important industry.

3.5. Ethical considerations

Ethical considerations were crucial to this study. Participants provided written informed consent after reviewing study objectives, potential risks involved in participation, and confidentiality measures implemented to protect their identities and sensitive information.

3.6. Methodological limitations

Several limitations are acknowledged in this study's methodology:

Sample Size: The small convenience sample limits generalizability but offers depth suitable for exploratory research.

Researcher Bias: Regular peer debriefing sessions among co-authors helped minimize interpretive bias.

Context Specificity: Findings are reflective of NRERA's unique regulatory context; thus replication in other regions is advisable.

4. Results

The results of this study are presented in two sections. First, the quantitative findings are outlined, providing a statistical overview of the data. This is followed by the qualitative results, which offer deeper insights into the experiences and perspectives of participants. Together, these findings address the research questions and lay the groundwork for the subsequent discussion section.

4.1. Quantitative approach -technology Spectrum used by ASM operators

The key responses concerning the application of technologies within sampled mines revealed the use (and lack of use) of basic and advanced technologies, and are shown in Table 4. "Technology" in the data collection instruments was defined as use of Information Systems (IS), artificial intelligence (AI), Internet of things (IoT), blockchain and associated technologies.

Despite the diverse applications of technology, it is noteworthy that none of the ASM operators reported utilizing blockchain technology in their operations. This absence is particularly striking given the increasing demand for transparency and sustainability in mining practices. While many participants employed technology for administrative tasks—such as document preparation and payroll processing—this reliance did not extend to more advanced technologies like blockchain that could enhance operational efficiency and accountability. Technology integration varies significantly across different business tasks in ASM operations. Document preparation shows the highest level of technology adoption, with almost half the respondents frequently utilizing technology. Processes like geoscience, production planning, and financial statement preparation have moderate technology adoption levels. However, critical tasks such as progressive site remediation, logistics, and blasting exhibit very limited technology integration, with a large percentage of operators either rarely using technology or not performing these tasks at all. Payroll processing and sales analysis are largely outsourced as this has a higher percentage of "not done" activities, meaning that it is either outsourced or the operators don't do it. This suggests that technology adoption in ASM is selective and heavily dependent on the nature of the task and the specific needs and resources of the operators. There is a clear opportunity to promote technology use in areas where it's currently lacking, particularly in areas like logistics, environmental monitoring, and progressive site remediation, which are crucial for sustainable mining practices. This also shows that technology adoption is minimal in key mining activities and is focused on office work and adminstration.

The results of this study reveal a nuanced landscape of technology usage among ASM operators, particularly in the context of blockchain technology. A broad spectrum of technology adoption was observed, with some operators exhibiting a complete absence of technological tools while others relied on various technologies for specific tasks. This variation highlights differing levels of integration within their mining operations. Activities typically may include document preparation, sales analysis, geoscientific analysis for mineral prospecting, production planning, financial statement preparation, client communication, and environmental monitoring. The decision scores for technology usage across different aspects of ASM operations varied from low to high, reflecting inconsistent levels of integration and highlighting areas ripe for improvement. For instance, while technology is extensively used in document preparation and payroll processing, which reduces manual errors and expedites administrative tasks, its application in critical areas such as geoscience and site surveys remains limited. This suggests a significant opportunity for growth; enhancing technological integration in these domains could lead to more precise data collection and better-informed operational planning. Moreover, the limited use of technology in environmental monitoring and logistics indicates that current practices may not adequately address the sustainability challenges faced by ASM operators. Technological usage in these areas could be increased and may assist operators to improver their management of environmental impacts and increase the optimization of logistical processes. These relatively small incremental wins ultimately contribute to more sustainable mining practices. The analysis of the demographic data in Table 3 reveals several key insights regarding the participants in the study. The sample consists predominantly of males, with 72.7 % identifying as male compared to 27.3 % as female. This gender disparity suggests a male-dominated environment within the ASM sector, which may influence operational dynamics and decision-making processes. The age distribution indicates that a significant portion of participants, 45.5 %, falls within the 36–45 years age bracket. This is followed by two age groups 46–55 years and 56–65 years each comprising 18.2 %. The younger demographic (18–35 years) accounts for only 9.1 %, as does the group above 65 years. This concentration in middle age may reflect both experience and stability, potentially impacting the adoption of new technologies. The educational background of participants reveals that a substantial majority, 72.7 %, have only completed basic education (secondary school). A smaller percentage holds higher qualifications: 9.1 % has a diploma, and 18.2 % possess degrees. This educational profile may present challenges for adopting advanced technologies, as lower educational attainment could correlate with limited exposure to innovative practices. These factors could significantly influence the adoption of innovations like BSBM in the ASM sector, highlighting the need for targeted training and support to enhance operational efficiency and sustainability.

4.2. Qualitative approach – Thematic analysis

This study elucidates four interconnected barriers impeding the adoption of blockchain technology within the ASM sector; they are Economic barriers, other perceived influential technologies, structural challenges and technology gaps among the operators. The subsequent presentation of findings is structured thematically, outlining each barrier alongside the codes and specific phrases employed during the code generation process to enhance transparency and rigor.

4.2.1. Economic barriers to technology adoption

The Economic barrier theme refers to financial constraints, resource limitations, and systemic inequities that prevent individuals, organizations, or communities from acquiring, implementing, or sustaining new technologies (Fuentes & Mies, 2021). These barriers arise when the costs, risks, or financial structures associated with technology adoption outweigh perceived or actual benefits, disproportionately affecting marginalized groups and resource-constrained sectors.

4.2.1.1. Exploitation by middlemen. This sub-theme captures instances where intermediaries (middlemen) in supply chains, distribution networks, or service provision exacerbate economic challenges for the ASM adopters of technology. It includes practices such as price manipulation, inflated fees, monopolistic control, or unfair profit extraction that disproportionately increase the cost of accessing, maintaining, or upgrading technology. This code highlights how middlemen exploit their position to create financial dependencies, limit transparency, or restrict equitable access to technological solutions, thereby reinforcing economic inequalities (Randall, 2013). *(*e.g*., P1 "We end up working with middlemen who fund some of our activities", P4 "The middlemen pay us pennies for our stones and then sell them for ten times more. We have no power to negotiate. It's a real mess", P9 "Many operators are in the chokehold of the middlemen. No power to negotiate, its inhuman", P4 "We sell our emeralds for next to nothing, maybe 10% of their real market value").*

Intermediaries in mineral supply chains exacerbate financial burdens for ASM operators. Middlemen manipulate prices during mineral sales and inflate costs for essential tools (e.g., compressors, crushers), forcing miners into dependency. For example, P4 reported selling emerald to brokers at 60–90 % below market rates due to limited direct market access. This exploitation reduces capital available for technological upgrades.

4.2.1.2. Financial prioritization. Financial prioritization identifies instances where operators face difficult trade-offs in the allocation of limited financial resources to technology adoption in the face of other pressing needs. It captures decision-making processes where technology is deprioritized due to competing financial obligations (e.g., operations, education, basic subsistence) or perceived risks of investing in technology with uncertain returns. The sub-theme emphasizes how financial constraints force adopters to defer, reduce, or abandon technology investments, even when they recognize its potential benefits. *(*e.g.*, P1 "how do we invest in technology when the basics cant be met?", P5 "The question is how do we afford it when the basics are lacking?")*

ASM operators face acute trade-offs between immediate survival needs and long-term technology investments, suggesting therefore that miners frequently prioritize basic need e.g., wages, safety gear, or community obligations over purchasing technological equipment.

4.2.1.3. Financial exclusion. This sub-theme identifies systemic and institutional barriers that prevent ASM operators from accessing financial services or tools necessary to adopt, sustain, or benefit from technology. It encompasses exclusion from formal banking systems, credit, loans, insurance, or digital payment platforms, which limits the ability to purchase, upgrade, or integrate technologies into daily practices. *(*e.g.*, P1 "the biggest challenge we have as Emerald miners is getting funding to run our mines", P4 "The banks see us as too risky, so we can't get loans for new machines or even software", P5 "We have to rely on friends and relatives or even foreign middlemen").*

Financial exclusion reinforces cycles of poverty and inequality by denying marginalized groups (e.g., low-income populations, rural communities, unbanked individuals) the means to invest in technology that could improve productivity, connectivity, or quality of life.

Systemic exclusion from formal financial services limits access to credit for technology (Okunade, Olawumi, Adeyemi, & Olayemi, 2023). Without insurance or microloans, miners rely on high-interest informal lenders, perpetuating cycles of underinvestment as evident in the case under review.

4.2.1.4. Low profit margins. This code captures scenarios where ASMs operate with minimal financial returns, leaving insufficient capital to invest in technology adoption, maintenance, or upgrades. *(*e.g.*, P4 "How can we afford something like blockchain when we barely make a profit?", P7 "We can't invest in anything new because we're barely breaking even", P9 "How do you introduce technology when everyone barely makes anything in terms of return on investment?").*

It reflects how thin profit margins—common in sectors like informal economies—force stakeholders to prioritize short-term survival over long-term technological investments. Low profitability restricts access to credit, discourages risk-taking, and perpetuates reliance on outdated or inefficient methods, creating a cycle of stagnation that hinders competitiveness and innovation.Low margins also discourage partnerships with tech suppliers offering pay-later models (Aleke, 2024).

4.2.2. Other perceived critical (influencial) technologies

This theme highlights instances where participants suggest alternative, affordable, or contextually suitable technologies to overcome economic barriers to mainstream technology adoption (Alabdali, Pileggi, & Cetindamar, 2023). It reveals grassroots strategies for addressing affordability and accessibility and challenges assumptions about "ideal" technological solutions. The findings encourage investment in inclusive, adaptable, or hybrid technologies that better align with users' financial realities and help bridge economic and technological divides.

4.2.2.1. Safety and security technologies. This sub-theme captures instances where participants suggest or reference alternative tools, systems, or devices designed to protect individuals and communities from harm or threats. These technologies may include alternative or hybrid models tailored to local needs, prioritizing safety and security while managing economic constraints. *(*e.g.*, P5 "Some of the young men we hire to do the manual work come back to the mines at night and retrieve emerald that they had hidden. It's difficult to make it, and that's where technology would be beneficial").*

4.2.2.2. Survey technologies. This sub-theme reflects situations in which participants propose contextually appropriate survey technologies as a means to overcome financial barriers to adopting standard or preferred technologies. It demonstrates how stakeholders identify or develop survey tools and methods that fit within their economic limitations. The emphasis is on adaptive solutions that address technological needs for surveying while mitigating economic challenges (Alabdali et al., 2023). *(Eg., P3 "I wish I could have access to drones to help me to survey my piece of land for minerals.", P6 "The only technology I would really be interested in is drone-borne survey equipment that could help us know exactly where the minerals are within our mines.", P8 "We need technology. I would be interested in drone-borne survey technology that could help me pinpoint where the minerals are in my mine and their quantities to help me prepare the right estimates and costs involved, reducing the inherent risks that this venture exposes one to.").* This theme reveals how economic limitations drive creativity and resourcefulness in technology adoption. It underscores the mismatch between available technologies and the financial capacities of users, often exposing gaps in market offerings (e.g., lack of affordable, scalable solutions). The theme also highlights systemic issues such as centralized Research and Development (R&D) processes that neglect low-income users' needs, or market structures that prioritize high-margin technologies over inclusive designs (Boot, 2022).

4.2.3. Structural challenges

The theme encompasses systemic obstacles rooted in the organization and governance of institutions, policies, and social systems. These challenges impede the equitable access to and effective utilization of technology, thereby hindering the potential for sustainable development within the sector (Attiany et al., 2023). Unlike economic barriers, which primarily concern financial constraints, structural challenges are embedded in the fabric of organizations and societies.

4.2.3.1. Generational divide. Generational divide identifies systemic disparities in access to resources, adoption of technologies, or engagement with societal systems that arise from differences between age groups. These divides are rooted in structural factors such as policies, cultural norms, or institutional practices that disproportionately advantage or disadvantage specific generations (e.g., youth, working-age adults, elderly populations). *(*e.g.*, P2 "The younger miners, they want to use apps and new technology, but the elders like me, we stick to what we know", P3 "Young miners like my son is quite open to use technology and apps to make operations easy, but I would rather stick to the known paths of old").* Age-based disparities shape technology access (Suntai & Beltran, 2023).

4.2.3.2. Lack of institutional support. This sub-theme captures systemic failures of organizations, governments, or other formal entities to provide the resources, policies, or frameworks necessary to enable equitable access to opportunities, technologies, or services. *(*e.g.*, P1 "Our association tries to support us but it is struggling too", P4 "NGOs will make promises to come here but we hardly ever see them, it is hard to get any support here", P9 "The association for emerald miners exists, but like the operators, it is just a projection of the bad financial status").* These gaps reflect structural weaknesses in institutional commitment, coordination, or capacity, often exacerbating inequities and hindering progress (Indrasti, Rawung, Roufiq, & Sudolar, 2021; Zhao et al., 2020).

4.2.3.3. Policy-implementation gaps. This sub-theme identifies systemic disconnects between formal policies, regulations, or strategic frameworks and their real-world implementation. These gaps arise from structural inefficiencies, institutional inertia, or misalignment between policy design and the needs of affected stakeholders, undermining equity, effectiveness, and progress (Berardi et al., 2024). *(*e.g., *P2 "The government has these certifications for the minerals, but they don't really teach us how to comply", P3 "The government has requirements that we struggle to meet to be allowed to legaly operate from the NRERA. But they don't train us in any way to help us", P9 "The government agencies also that are supposed to aid the operators are ill funded as well and not effective. It is a matter of everyone for themselves and God for us all").*

4.2.4. *Technology gaps*

Technology gaps refer to deficiencies in the resources, skills, and infrastructure required to effectively acquire, integrate, and utilize new technologies. These gaps represent a multi-faceted barrier stemming from a confluence of factors outlined below:

4.2.4.1. Inadequate advanced tools and equipment. This sub-theme identifies instances where individuals, organizations, or communities lack access to modern, specialized, or up-to-date tools and equipment necessary to effectively adopt or utilize technology. This gap creates barriers to innovation, efficiency, and competitiveness, particularly in sectors where advanced tools are critical. The absence may stem from financial constraints, infrastructural limitations, or insufficient technical capacity to acquire, maintain, or operate such tools.

Most ASM sites rely on rudimentary tools (e.g., picks, shovels) due to the high cost of advanced equipment like excavators (Hooper, Jalilian, & Hull, 2024). (e.g., P1 *"We basically use notebooks and smart phones"*, P4 *"We record our sales in notebooks"*).

4.2.4.2. Limited digital literacy. This sub-theme captures instances where individuals or groups lack the skills, knowledge, or confidence to effectively use digital technologies, tools, or platforms, creating barriers to technology adoption and participation in digital ecosystems. This gap often intersects with socioeconomic, educational, or generational disparities and can perpetuate exclusion in increasingly digitized environments.

Limited proficiency in digital tools impeded adoption of mine-planning software or blockchain-based traceability systems (Csiszár, 2023). (e.g., P1 *"No one has approched me with information on technology and how it can make my operations efficient"*, P2 *"I can't use spreadsheets"*, P3 *"I have not heard of anyone using blockchain, I don't even know what it is and how it can help my operations"*, P4 *"computers are for offices, not mines"*, P6 *"We don't really need advanced technology. We know the rock formation and using the tools that are no sophisticated, basically what we need are resources to hire the right kind of equipment"*).

4.2.4.3. Limited technological infrastructure. This sub-theme identifies instances where foundational physical and organizational systems necessary for supporting technology adoption are inadequate, unreliable, or absent. These infrastructure gaps create systemic barriers to accessing, deploying, or sustaining technologies, particularly in under-resourced or remote areas. The absence of robust infrastructure often stems from underinvestment, geographic challenges, or prioritization failures, and it disproportionately affects marginalized communities *(*Anderson & Toshmatova, 2024*;* Csiszár, 2023*). (*e.g., *P1 "no computers in the mines as there is no power most of the time", P2 "We don't even have reliable Wi-Fi in the mines", P3 "We don't even have reliable network in the mines").*

4.2.4.4. Reliance on manual processes. This sub-theme identifies situations where individuals, organizations, or communities depend on non-automated, labor-intensive methods to complete tasks that could be streamlined or improved through technology. This reliance often reflects gaps in access, awareness, or capacity to adopt technological solutions, perpetuating inefficiencies, errors, or scalability challenges.

Manual processes dominated ore extraction and processing, despite known inefficiencies (Sarilo-Kankaanranta & Frank, 2024). (e.g., P2 *"Well, it's tough. We rely on the old ways here, manual labor mostly"*, P3 *"We basically are still very manual in our operations"*, P5 *"We have to resort to manual labor which is slow and inefficient"*, P7 *"We're stuck using manual processes. Everything is done by hand, which is slow and inefficient"*).

The ASM sector's technology adoption barriers are deeply interlinked. Economic exploitation and low margins restrict capital, while structural gaps in governance and training perpetuate reliance on manual methods. Grassroots innovations emerge but require institutional support to scale. Findings underscore the need for integrated interventions addressing financial inclusion, policy enforcement, and context-specific technology design.

These themes highlight complex challenges facing ASM operations today—ranging from economic constraints through technological underutilization to structural issues within policy frameworks—and underscore areas where interventions could potentially improve sustainability outcomes within these sectors.

4.3. *Matrix coding*

Matrix coding was conducted using NVivo 15 to explore the relationship between participant demographics and the identified thematic barriers to blockchain adoption within the ASM sector. The matrix coding results, detailed in Table 4, provides a quantitative overview of how demographic factors correlate with the prevalence of specific barrier types reported by participants.

The matrix coding reveals several interesting patterns related to the interplay of demographics and perceived barriers:

4.3.1. *Education and technology gaps*

Participants with lower levels of formal education (secondary or diploma) tended to express greater concerns related to technology gaps. For instance, Participant 2 and Participant 3, with secondary and diploma education levels, respectively, reported higher frequencies of codes associated with technology gaps (both scored 5). This suggests that a lack of formal education may limit understanding of technology and digital tools, thereby creating a barrier to technology adoption.

4.3.2. *Experience and economic barriers*

While not definitive, there appears to be a trend suggesting that more experienced miners may have a more nuanced understanding of economic barriers. Highly experienced miners (e.g., P1, P2, and P8) show varying concerns regarding economic exploitation and they are all male. This trend indicates more factors could determine whether miners are aware of economic exploitation. One example of such a factor could be their level of power in the organization.

4.3.3. *Gender and barrier perception*

Gender dynamics may play a role, as female participants expressed concerns about technology gaps as well as economic constraints. These differences may reflect variations in access to resources, training, or support networks, which can disproportionately impact female miners.

4.3.4. *Older miners*

A few of the older miners had experience with all of the areas in the study and there were trends of older miners lacking technological expertise. It is important to acknowledge that these observations are based on a relatively small sample size, which may limit their generalizability to the broader ASM population. This limitation is largely due to the significant challenges encountered in accessing participants, as it is not easy to reach the mines or the miners to collect this data in Zambia. Despite these difficulties, the findings provide valuable preliminary insights. However, future research with larger, more representative samples is necessary to validate these results and to better understand the complex interplay of demographic factors and technology adoption barriers in greater depth.

4.4. Synthesis and integration

Quantitative findings reveal a predominantly male (72.7 %) and middle-aged cohort (45.5 % aged 36–45 years), with 72.7 % of participants possessing only basic education—a factor likely to impede engagement with advanced technologies like blockchain. These demographic constraints intersect with qualitative insights underscoring systemic barriers to technology adoption. Participants emphasized low emerald prices, exploitative intermediaries extracting disproportionate profits, and high production costs as critical economic challenges. One operator lamented, *"Middlemen pay us pennies for stones they sell at tenfold prices. How can we afford new tools when profits vanish before reaching us?"* These dynamics deter investments in technologies perceived as financially risky, particularly in a sector already strained by thin profit margins (mean annual earnings: $1200–$2500). Operators reported limited access to institutional financing, with 81.8 % relying on informal lenders charging exorbitant interest rates (25–40 %). This situation compounds these economic barriers. Risk averse banks and non governmental organizations (NGOs) were criticized for neglecting ASM needs, leaving operators unable to fund technological upgrades. *"Banks see us as too risky,"* noted one participant, *"so we borrow from middlemen, trapping us in cycles of dependency."* This financial exclusion perpetuates reliance on outdated practices, despite growing buyer demands for sustainability certifications (e.g., proof of ethical sourcing). Notably, demographic factors such as age and gender played a role in shaping perceptions of these barriers. Female participants expressed concerns about both economic constraints and technology gaps more frequently than their male counterparts. Additionally, younger operators tended to be more open to adopting new technologies but faced training barriers that hindered effective integration into operations. Fig. 2 visually represents the cyclical and reinforcing nature of barriers hindering blockchain adoption within the Zambian ASM sector. This diagram illustrates how economic exploitation, facilitated by intermediaries who extract a disproportionate share of profits from ASM operators, leads to low profit margins. These constrained margins, in turn, limit operators' access to capital and financial resources, resulting in financial exclusion from formal lending institutions. Consequently, ASM operators often rely on manual methods and lack the capacity to invest in technology upgrades or sustainable practices. These constraints further perpetuate policy gaps, which reduce any incentive to use blockchain to improve. This interconnected cycle highlights the need for integrated interventions targeting multiple barriers simultaneously to promote sustainable technology adoption effectively. The analysis underscores the urgent need for a BSBM tailored to ASM contexts. Current operational frameworks lack transparency, enabling intermediary exploitation and hindering compliance with sustainability standards. A BSBM could mitigate these issues by enhancing traceability, automating contracts, and reducing administrative costs. For instance, blockchain's immutable ledger could empower operators to verify emerald origins directly, bypassing intermediaries and securing premium prices. However, adoption hinges on addressing structural gaps: 63.6 % of operators lacked awareness of blockchain's functionalities, while 90.9 % cited unreliable electricity and internet as implementation barriers. To operationalize a BSBM, targeted interventions are critical. First, foundational programs must bridge digital literacy gaps through hands-on training in blockchain applications. Second, partnerships with fintech platforms could offer microloans or pay-as-you-go models to finance technology adoption. Third, integrating renewable energy solutions (e.g., solar-powered blockchain nodes) would address infrastructural deficits. As one operator argued, *"If we had training and stable power, tools like blockchain could transform how we run our mines."* By aligning technological solutions with ASM realities, a BSBM could enhance market access, stabilize incomes, and align the sector with global sustainability benchmarks—transforming artisanal mining from a site of exploitation to one of innovation.

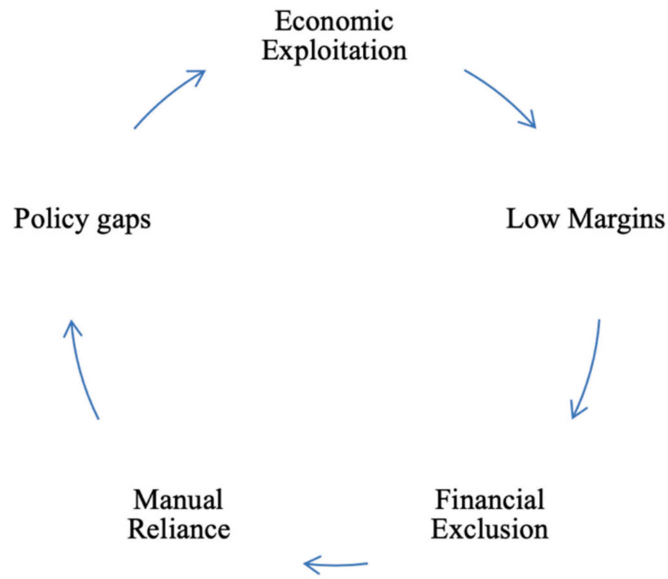

Fig. 2. Interconnected barriers to blockchain adoption in Zambian ASM sector.

4.5. Key implications

Economic: Reducing intermediary dependence via blockchain could increase profit margins by 15–30 %, enabling reinvestment in technology. Structural: Institutional partnerships are vital to co-design financing mechanisms and infrastructure upgrades. Technological: Context-specific blockchain interfaces (e.g., SMS-based platforms) are needed to accommodate low-digital literacy users. This synthesis reveals that overcoming ASM's technology adoption challenges requires not only technological innovation but also systemic reforms to dismantle entrenched economic and institutional inequities.

4.6. Development of business model for ASM sector

The Business Model Canvas simplifies all key business model elements and helps to analyze a business model's strengths, weaknesses, opportunities, and challenges (Osterwalder & Pigneur, 2010). A blockchain-driven business model has embedded costs and is technology-intensive. Currently, this technology is being exploited by only one mine in Zambia: Gemfields's Kagem Emerald Mine. This mining company is too large to be considered as an ASM and is therefore outside the scope of this study but is used to gain insights into the successful use of a blockchain-driven business model in gemstone mining in Zambia.

Since no ASM operators were found to be using blockchain due to lack of awareness, lack of resources and skills (as reported by respondents), an alternative candidate for a blockchain-driven business model in the ASM sector becomes clear: the associations that represent the interests of ASM operators. There are many small scale and artisanal miners in different mining projects countrywide and mining associations in Zambia represent these clients. The two most visible and historically established associations with a joint membership of over 700 members were considered: (1) Chambers of Gemstones and Mines of Zambia; (2) Emerald and Semi-Precious Stones Mining Association of Zambia (ESMAZ). Only ESMAZ had operational mines in recent time in its membership, making it the best candidate for blockchain-driven business model development.

4.7. Current business model of ESMAZ, a mining association

ESMAZ consists of over 500 members, primarily ASM operators, although many are currently inactive. The association's primary objectives are to assist and regulate ASM operations by providing training, technical support, and facilitating market access. ESMAZ aims to improve working conditions, promote responsible mining practices, and support the formalization of ASM activities to foster sustainable development in the sector.

However, the association faces significant challenges due to limited resources, as it heavily relies on subscriptions from a declining membership base. This financial constraint restricts its operational capacity, resulting in a lean secretariat that lacks sufficient resources to effectively fulfill its mission. While the staff possesses essential skills, they often need to subcontract specialized services. The association has basic office infrastructure, including computers and printers, which are primarily used for routine administrative tasks.

ESMAZ must explore innovative solutions to overcome these obstacles and achieve sustainability within its membership. BSBM could address many of the challenges faced by ASM operators by enhancing transparency in supply chains, improving market access, and fostering responsible mining practices. ESMAZ can leverage blockchain technology. In such a scenario, ESMAZ can be in a position to facilitate better tracking of minerals, ensure compliance with sustainability standards, and ultimately create a more equitable environment for ASM operators. This approach could lead to improved livelihoods for members while aligning with global demands for ethical sourcing in the mining sector.

4.8. Blockchain-enabled sustainable business model developed for ASM associations

The observation that only one company in the Zambian gemstone space uses blockchain in its business model is cardinal to the development of a business model that is suited to the context. Lessons were drawn from the success story of Kagem emerald mine in developing the following business model suited for an ASM association in Zambia. This section addresses RQ3.

4.8.1. Key partnerships

BSBM implementation is technology-intensive and relatively costly for an ASM to deploy. Key partners required include, (1) universities and research institutes for innovation and skilled human resource required for the establishment, maintenance and technical support of the blockchain platform; (2) the blockchain platform service provider to offer blockchain software as a service; (3) miners and ASM operators to form the membership base of the ASM association; (4) suppliers of mine-related products and services as vital members of the mining business ecosystem; (5) internet service providers to offer excellent internet connectivity (6) financial service providers to support smooth transactions; (7) Government units, agencies and NGOs for better monitoring and co-creation of solutions for environmental and social safeguards.

4.8.2. Key activities

Training, accreditation, monitoring and network-building are the most important activities required for building trust and competence within the membership of the ASM association. One of the most important outcomes for the ASM association should be a dramatic increase in the establishment of operational mines among the membership. For the past decade, the ratio of ASM members to members with operational mines has been dismal. An ASM association must have a robust operational communication strategy in place to allow increased access to information, training, and diversified services that it offers.

4.8.3. Value proposition

The ASM association that deploys a BSBM must augment its scope of value creation. This must encompass the social and environmental wins that are possible when members of the business ecosystem co-create rather than compete or remain aloof. The business can create value for the clients (membership) while creating better work environments for the workers (occupational health gains). The ultimate winners are the society that shares the environment in which the mines operate. Clients can expect to see their productivity increase and their social capital improve as they benefit the members of their business ecosystem. Clients need expertise, investment, visibility, and networking opportunities which are all delivered on the broader platform.

4.8.4. Customer relationships

The client-base is increased to include the other members of the business ecosystem including suppliers of goods and services to the mines as well as other less formal stone crushers and artisanal miners. This different to the current approach of limited membership to mining license holders. These diverse types of clients require the ASM association to remain flexible and sensitive to the unique needs presented. In this scenario, the relationship with mine license holders has already been established, but effort and an appropriate cost must be expended in developing the relationships with a diversified client base.

4.8.5. Customer segments

The ASM association is creating value for their oldest clients (ASM operators) by giving them access to resources that can improve their productivity, profit, and capitalization. However, it is important to note that in this blockchain-driven business model, the diversified customer segments have equal importance. This is because their synergistic input and participation is required to deliver gains to the whole network sustainably in the short and long run.

4.8.6. Key resources

A pool of required expertise in blockchain technology, biotechnology, nanotechnology, chemistry, occupational health, various fields of mining, biodiversity, social sciences, and business is available from the diverse Zambian universities and research institutions. The Copperbelt University in particular, is uniquely positioned as a key resource due to its history and proximity to the mining center of Zambia. The Copperbelt University hosts the Africa Centre of Excellence for Sustainable Mining (established and supported by the World Bank) and enjoys a rich relationship with new and historic mines of all operational scales in the region. In this context, "Track and trace technology" can be accessible to the ASM association and its membership when they leverage partnerships with the knowledge centers. These centres have suitable accreditation, instrumentation and trained staff eager to increase their innovation outputs. The ASM and its membership can share in resulting profits and intellectual property with forward-thinking staff members of the knowledge centres.

The success of this business model depends on accessible reliable Internet. Zambia has seen increased investments in this sector, including the establishment of The Zambia Information and Communications Technology Authority (ZICTA), which is a statutory body established under the Information and Communication Technologies Act No. 15 of 2009. It exists to regulate the Information and Communication Technology (ICT) sector in Zambia and enhance the adoption of ICTs in the country with the goal of enabling the transition to a digital economy.

4.8.7. Channels

Social media and online resources are accessible cost-effective channels to reach all customer segments. Historically, ASM associations have been vocal in the press, giving comments on issues affecting their membership. The ASM association in this business model must move beyond the traditional use of these channels and use them to offer training, resources, opportunities for networking and more. These channels can also be used to give visibility to their membership by showcasing members who are delivering value to their business ecosystem and improving their social-economic context.

4.8.8. Cost structure

The cost of subscription to a blockchain platform service provider is approximately $6000 annually within a pricing regime depending on numbers of users. This cost is prohibitive to the typical ASM operators, who would have to sacrifice their productivity to invest these funds in blockchain subscription. The ASM association does not traditionally make products, so it is in a better position to use funds raised from subscriptions to invest in the blockchain platform. The ASM association can create pricing systems that distribute the prohibitive costs of blockchain implementation across the membership of the association, resulting in very affordable subscription fees with meaningful benefits to its clients. The association can also attract funding and grants from NGOs and government to fund this cost.

4.8.9. Revenue streams

In addition to access fees to the restricted mining areas, the ASM association can create a tier-based subscription pricing system that allows members to pay basic rates for access to basic services and premium rates for access to services. Separate rates for accreditation and "track and trace" services can raise more income. The sale of subsidized knowledge products in partnership with knowledge centers can have the dual impact of increasing the competence and skills in the membership as well as establishing the ASM association as a knowledge center. A valuable halo effect of co-authored knowledge products is the increased visibility and authority of all partners in the field.

5. Discussion

5.1. Implications for academics

The integration of blockchain into ASM sector advances theoretical discourse on SBMs by demonstrating how decentralized technologies can reconcile economic, social, and environmental value creation and extend their application to low-tech, informal sectors. By revealing a clear path to operationalization BSBMs, this study addresses critical gaps in SBM literature, which has historically focused on high-income, formalized industries (Bocken et al., 2014b; Lüdeke-Freund, 2013).

The BSBM framework challenges traditional assumptions about innovation adoption in resource-constrained settings. While prior research emphasizes technological readiness, our results reveal that lack of institutional support and financial exclusion are more salient barriers in ASM (Kshetri, 2022). This aligns with institutional theory, which posits that systemic inequities, not technical complexity, often hinder innovation (North, 1993). The BSBM's reliance on mining associations as intermediaries (e.g., ESMAZ) also introduces a novel stakeholder-centric approach to blockchain deployment, diverging from corporate-led models like De Beers' Tracr.

Table 5 highlights how BSBM disrupts conventional business models by embedding transparency and accountability into core operations. Academically, this underscores the need to reframe SBMs as collaborative ecosystems rather than firm-centric strategies. Future research should explore hybrid governance models that balance decentralization (blockchain's strength) with centralized oversight (e.g., regulatory bodies) to address ASM's unique challenges.

5.2. Implications for practitioners

Our study provides ASM operators, policymakers, and allied industry stakeholders with a comprehensive framework for enhancing both sustainability and profitability through strategic blockchain implementation. There are three broad action areas emerge from the proposed model – operational efficiency, capacity building, and policy collaboration - each offering specific blockchain-enabled interventions that can be implemented immediately or phased in strategically over time. The **Operational efficiency** gains are realized through smart contracts that automate compliance tasks, including mineral-certification data uploads and payment processing, eliminating costly intermediaries and reducing transaction fees by approximately 30–50 % based on early deployments. The blockchain's immutable ledger simultaneously empowers cooperative leaders to establish verifiable mine-to-market traceability, documenting each handoff in real-time to bypass exploitative brokers and command premium prices for ethically-sourced traceable emeralds. Secondly, **Capacity building** initiatives address the digital skills gap prevalent among miners through targeted mobile-first tutorials and community workshops that translate complex blockchain concepts into accessible everyday language, enabling operators to independently manage digital wallets and signature protocols. Strategic partnerships with fintech platforms provide crucial secondary support through micro-loans and pay-as-you-go data packages that distribute the upfront costs of blockchain adoption, ensuring that cash-constrained operations are not excluded from technological innovation. Finally, **Policy and collaboration** mechanisms accelerate sector-wide transformation when regulators tie license renewals to blockchain-based reporting dashboard usage, creating incentives that naturally increase voluntary compliance as operators recognize that clean, real-time data reduces bureaucratic paperwork and expedites approval processes. However, sustainable sector transformation requires multi-stakeholder coalitions linking ASM associations such as ESMAZ with technology vendors and non-governmental organizations to create inclusive forums for designing site-specific solutions, sharing implementation costs, and surfacing critical local knowledge that would otherwise remain invisible to both policymakers and software developers.

The BSBM's dual academic-practical relevance lies in its capacity to bridge theoretical frameworks with the context-specific reality. For academics, it provides a replicable model for studying technology adoption in informal sectors. For practitioners, it offers scalable strategies to dismantle systemic barriers (e.g., middlemen dependency) while aligning ASM with global sustainability agenda like the SDGs. Collaborative efforts grounded in both rigorous research and pragmatic innovation are essential to transform ASM from a site of exploitation to one of ethical resilience.

6. Conclusion

This study found that the current level of blockchain adoption among Zambian ASM operators is non-existent. However, the success of KAGEM's blockchain-based emerald business signals that unrealized opportunities are available for ASMs to exploit.

The main barriers that hinder blockchain adoption among ASMs include access to finance, structural challenges and technological gaps.

This study underscores the transformative potential of blockchain technology, particularly through the BSBM, in addressing systemic challenges within the ASM sector. The research highlights actionable outcomes, demonstrating how BSBM's integration of smart contracts can automate regulatory compliance, minimize transaction costs, and streamline mineral traceability. By leveraging blockchain's immutable ledger, ASM operators can bypass exploitative intermediaries, directly access premium markets, and secure fair prices for ethically sourced minerals—strengthening both economic returns and sustainability outcomes. This offers the basis for the integration of blockchain into a sustainable business model for ASMs.

Crucially, the findings emphasize the policy implications of scaling BSBM adoption. Governments and regulatory bodies could incentivize compliance by linking mining licenses to mandatory blockchain-based reporting systems, ensuring transparency in supply chains. Such policies would not only reinforce accountability but also attract ethical investors and buyers committed to environmentally and socially responsible practices. Additionally, public-private partnerships could support infrastructure development to enable broader blockchain adoption, particularly in resource-limited ASM communities.

By prioritizing these interventions, stakeholders can transform the ASM sector into a driver of equitable growth, aligning operational efficiency with global sustainability agendas. This model offers a tangible alternative to conventional approaches, which frequently neglect environmental stewardship and social equity, positioning blockchain as a cornerstone for ethical mineral trade in the 21st century.

6.1. Challenges and limitations

The integration of BSBM into sub-Saharan Africa's ASM sector faces critical limitations. The study's reliance on a small sample size of eleven interviews - a constraint echoed in broader blockchain-ASM research limits generalizability, particularly given the sector's geographic and operational diversity (Al Amin, Nabil, Baldacci, & Rahman, 2023). Existing studies, including this one, are further hindered by short-term perspectives, which obscure insights into long-term impacts on livelihoods, environmental sustainability, or community well-being (Bodemer, 2023). Context-specific barriers such as inconsistent internet access, low digital literacy, and high blockchain implementation costs compound these issues (Su, Zhang, Peng, Saeidi, & Tirkolaee, 2023). Data integrity risks persist due to the lack of automated validation mechanisms (e.g., Internet of Things sensors), while fragmented stakeholder collaboration and regulatory ambiguities undermine trust in decentralized systems (Pólvora, Nascimento, Lourenço, & Scapolo, 2020).

6.2. Recommendations and future directions

To address these gaps, longitudinal studies are critical to evaluate BSBM's long-term socio-economic and environmental impacts, employing larger, representative samples to enhance generalizability (Bodemer, 2023). Research should also investigate synergistic relationships between middlemen-free supply chains, transparency, and accountability, as these dynamics are pivotal for fostering trust and sustainability in ASM communities *(T. M.* Tan & Saraniemi, 2023*;* Toufaily & Zalan, 2024*)*. Comparative analyses of blockchain solutions tailored to ASM contexts are needed to identify best practices and assess scalability, given the variability in platform maturity and effectiveness (Tönnissen & Teuteberg, 2020). Finally, interdisciplinary research must explore the interplay between technological innovation, policy frameworks, and community-led initiatives - such as integrating blockchain with existing systems and developing capacity-building programmes to ensure equitable and sustainable ASM development (Ukoba, Medupin, Yoro, Eterigho-Ikelegbe, & Jen, 2024). Policymakers and practitioners should prioritize multi-stakeholder partnerships to align incentives, address power imbalances, and translate technological potential into tangible community benefits.

CRediT authorship contribution statement

D. Owuor: Writing – original draft, Software, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **T.K. Taylor:** Writing – review & editing, Validation, Supervision, Conceptualization. **S. Simushi:** review and editing, Validation, Supervision. **M. Mutondo:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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