Minerals Traceability Using Blockchain Algorithm: Vanadium Bearing Minerals. For Redox Batteries and Gemstones as Semi-Precious Commodity

Antoine F Mulaba- Bafubiandi, Katleho J Mokoena and Thami KT Matle

***Abstract*—** The traceability of minerals is one of the most important requirements in the supply chain whereby a need for sustainability and ethical sourcing is required. This paper discusses the challenges associated with the traceability systems used for vanadium and gemstones in their respective supply chains in South Africa and Kenya. The objective of this study was to design a blockchain based platform that may be implemented in the vanadium and gemstone supply chains. Light on the inherent limitations of conventional approaches to traceability and how the use of blockchain improves mineral traceability will be shed. Suggestions on how to improve and ensure transparency in the supply chain by using the decentralized and immutable structure of blockchain will be discussed. Through implementation of the blockchain traceability systems the platform showed the benefits and transparency / accountability related impacts of blockchain technology applications on the supply chain of vanadium and gemstones. For the gemstone's traceability data from the supply chain, inserted into the block chain platform, were converted into a hash function value. That value was unique to the event as it occurred in the supply chain. This made the data tamper proof and could only be accessed by authorized personnel. Any subsequent changes made on the data will provide another hash function value. For the vanadium ore, the smart contract function was used in the traceability aspect supply chain. Once the XRF results were loaded into the algorithm and satisfied predefined conditions, the contract will read as "successful" ; thus produces the correct location of the ore in question (in this case, vanadium ore), the conditions are set with a 2% margin for error and thus will read as "Unsuccessful" if the percentages entered are greater than the 2% error

The observed outcomes allude the benefits of using tailored blockchain traceability system to both gemstone and vanadium supply chains. The developed systems made use of unique functions such as hashing, smart contracts and blockchain nodes.

Antoine F Mulaba- Bafubiandi, Katleho J Mokoena and Thami KT Matle, Mineral Processing and Technology research center, Department of Metallurgy, School Mining, Metallurgy and Chemical Engineering, Faculty of Engineering and The Built Environment, University of Johannesburg, PO Box 17011, Doornfontein, 2028, South Africa

***Keywords*—**: traceability, gemstones, blockchain technology, transparency, authenticity, supply chain, decentralized, hash function, ethical sourcing, fair trade.

I. Introduction

Blockchain technology has gained significant attention in recent years due to its potential to enhance traceability in supply chains, including the tracking of minerals. Different blockchain algorithms have been explored for their suitability in tracking minerals throughout the supply chain. One study [1]. highlights the use of blockchain in supply chains, transport, and logistics. It emphasizes that blockchains can ensure traceability and transparency by tracking social and environmental conditions across supply chain tiers. This suggests that blockchain algorithms that prioritize transparency and traceability would be suitable for tracking minerals. Another study [2]. focuses on the potential of blockchain in greening supply chains. It suggests that blockchain can enhance traceability by providing a decentralized and transparent platform for recording and verifying transactions. This indicates that blockchain algorithms that prioritize decentralization and transparency would be suitable for tracking minerals.

In the context of food traceability, a study [3]. explores the integration of blockchain and the Internet of Things (IoT) to track and trace food in a farm-to-table approach. It emphasizes the importance of consensus mechanisms in ensuring transparency across the supply chain. This suggests that blockchain algorithms with robust consensus mechanisms would be suitable for tracking minerals. A specific application of blockchain in the food industry is the development of a food safety traceability system [4].. This study highlights the need for accurate recording, sharing, and tracing of data within the food supply chain. It suggests that blockchain algorithms that prioritize data accuracy and traceability would be suitable for tracking minerals. Furthermore, a study [5]. focuses on a trusted blockchain-based traceability system for fruit and vegetable agricultural products. It emphasizes the importance of transparency and efficiency in the supply chain and reducing costs. This suggests that blockchain algorithms that prioritize transparency, efficiency, and cost-effectiveness would be suitable for tracking minerals.

In summary, blockchain algorithms that prioritize transparency, traceability, decentralization, robust consensus mechanisms, data accuracy, and cost-effectiveness would be suitable for tracking minerals throughout the supply chain. These algorithms can enhance traceability by providing a decentralized and transparent platform for recording and verifying transactions, ensuring transparency across the supply chain, and accurately tracking and tracing data.

A. Advantages and Disadvantages of Blockchain

Blockchain technology offers several advantages that make it appealing for various applications, including supply chain management, healthcare, energy, and finance. One of the key advantages is the enhanced security provided by the decentralized and immutable nature of blockchain [6].. The use of cryptographic algorithms ensures the integrity and confidentiality of data, making it difficult for unauthorized parties to tamper with or access sensitive information [7].. This feature is particularly valuable in industries where data privacy and security are paramount, such as healthcare and finance [6].. Another advantage of blockchain is its transparency and traceability. The distributed ledger allows for real-time tracking and verification of transactions, providing a transparent view of the entire transaction history [8].. This feature is crucial in supply chain management, where stakeholders can trace the origin and movement of goods, ensuring ethical sourcing and sustainability [8].. Blockchain also offers increased efficiency and cost-effectiveness. By eliminating the need for intermediaries and manual record-keeping, blockchain reduces transactional costs and processing time [9].. Smart contracts, which are self-executing contracts stored on the blockchain, automate and streamline processes, reducing the need for manual intervention [6].. This automation improves operational efficiency and reduces the risk of errors or fraud [[10].. However, blockchain technology is not without its limitations. One of the main challenges is scalability. As the number of transactions increases, the blockchain network may experience slower transaction processing times and higher costs [8].. This issue is particularly relevant for public blockchains, where consensus mechanisms require extensive computational power [7].. Another limitation is the lack of regulatory frameworks and legal considerations surrounding blockchain technology. The decentralized and borderless nature of blockchain poses challenges in terms of jurisdiction and legal compliance [9].. Additionally, the irreversible nature of transactions on the blockchain can be problematic in cases of fraud or errors, as there is no central authority to reverse or modify transactions [6].. In conclusion, blockchain technology offers several advantages, including enhanced security, transparency, traceability, efficiency, and cost-effectiveness. However, challenges such as scalability, regulatory frameworks, and legal considerations need to be addressed for widespread adoption and implementation of blockchain solutions.

B. Vanadium bearing ores for Redox Batteries

Vanadium-bearing ores play a crucial role in the development of redox batteries. These ores, such as vanadinite, patronite and carnotite contain high concentrations of vanadium, which is a key element in redox reactions [11].. When vanadium is used as an active material in redox batteries, vanadium-bearing ores facilitate the storage and release of energy through reversible oxidation and reduction reactions [12]..

Redox batteries are experiencing a growing demand in renewable energy systems. As the world shifts and look for a cleaner and more sustainable energy source, the need for efficient energy storage solutions becomes paramount [12].. Redox batteries offer a promising solution to address the intermittent nature of renewable energy generation. They can store excess energy produced during times of high generation and release it when needed, thereby ensuring a stable and reliable power supply [12].

However, the widespread adoption of redox batteries faces challenges in the sourcing and tracking of vanadium ores. Vanadium is a relatively rare element found in limited quantities. Its extraction and production processes can be complex and costly, requiring specialized mining and refining techniques [11].. Moreover, the concentration and distribution of vanadium-bearing ores vary geographically, making their procurement a logistical challenge.

Ensuring a sustainable and efficient supply chain for vanadium ores is crucial to meet the growing demand for redox batteries. Efforts are being made to improve the extraction methods and optimize the production processes to minimize the environmental impact and reduce costs.

The tracking of vanadium ores throughout the supply chain is vital to ensure transparency and ethical practices. This involves implementing traceability systems and certifications that verify the origin and responsible sourcing of vanadium-bearing ores. By promoting responsible mining practices and fair trade, the industry can contribute to the development of a sustainable and socially responsible supply chain.

Vanadium-bearing ores play a vital role in the development of redox batteries, which are increasingly important in renewable energy systems [13].. However, the challenges of sourcing and tracking vanadium ores need to be addressed to ensure a sustainable and efficient supply chain for these batteries. Continued research, technological advancements, and collaboration among stakeholders are essential to overcome these challenges and unlock the full potential of redox batteries in the transition towards a greener future.

C. Gemstones as a commodity

Gemstones have become a valuable commodity in the global market due to various factors. One significant trend is the rising international demand for colored gemstones, such as sapphires and rubies [14].. This increased demand has led to the emergence of new sources of gemstones, including Madagascar, which has experienced artisanal and small-scale mining rushes [14].. Additionally, there is a growing movement among consumers who value ethically, socially, and environmentally friendly products, which has influenced the gemstone business [15].. These consumers are demanding transparent and sustainable supply chains [16].. However, the gemstone industry is not without its challenges. Artisanal and small-scale mining (ASM) of gemstones, particularly in Africa, has raised concerns about standards and regulations [17].. ASM in precious minerals, including gemstones, has different standards compared to industrial minerals [17].. Furthermore, the gemstone business is associated with various economic offenses, including illegal mining, environmental offenses, bribery, and smuggling [18].. The value of gemstones is also influenced by factors such as their provenance and quality. Provenance, or the geographic origin of gemstones, is not always considered a relevant pricing factor, unlike in some other gemstones [19].. However, the quality of gemstones, including their color and clarity, plays a significant role in determining their value [20].. In terms of the jewelry industry, gemstones are often used in the production of high-end and luxury goods. Luxury firms use rare and precious materials, including gemstones, which contribute to the high prices of their products [21].. The value of jewelry can also be attributed to the value of the gemstone itself, particularly in more expensive pieces [22].. Overall, the gemstone industry is influenced by various factors, including international demand, ethical considerations, standards and regulations, and the quality and provenance of gemstones. These factors shape the market for gemstones and the value of these commodities in the global economy.

D. Benefits of Minerals Traceability

Minerals traceability offers numerous benefits for various stakeholders involved in the supply chain, including consumers, miners, manufacturers, and regulatory authorities.

For consumers, traceability offers transparency and assurance regarding the origin and quality of minerals used in products. It allows customers to make informed choices and support ethical practices, such as avoiding minerals sourced from conflict areas or those associated with human rights abuses [23].. By having access to information about the mining and production processes, customers can have confidence in the ethical and sustainable practices employed in the supply chain. This may lead to increased customer loyalty and trust in the products they purchase.

Miners may also benefit from traceability as it helps validate their responsible mining practices. By implementing traceability systems, miners can demonstrate compliance with environmental and social standards, enhancing their reputation and access to markets that prioritize sustainability. This not only improves their relationships with customers but may also create opportunities for partnerships and collaborations with other stakeholders in the industry. Furthermore, traceability can lead to improved operational efficiency and cost savings for miners by enabling better tracking of resources and reducing waste.

Manufacturers can leverage minerals traceability to ensure a sustainable supply chain and decrease the risks related to the sourcing of minerals. With traceability, they can now verify the authenticity and compliance of their raw materials, also reducing the potential for counterfeit or non-compliant minerals to enter their production processes. This not only protects their brand reputation but also ensures that their products meet the expectations of environmentally conscious consumers who value responsible sourcing. Traceability can also help manufacturers identify potential supply chain disruptions and take proactive measures to mitigate them, ensuring the continuity of their operations [23]..

Regulatory authorities benefit from minerals traceability as it provides them with the necessary tools to enforce regulations and ensure compliance. By requiring companies to disclose information about the origin of minerals and demonstrate due diligence in responsible sourcing, regulatory authorities can monitor and regulate the industry more effectively. Blockchain technology, with its transparent and immutable nature, can assist in compliance by providing a reliable and tamper-proof record of mineral transactions. This can simplify the auditing and reporting processes for regulatory authorities, making it easier to identify non-compliance and take appropriate actions.

E. Enhancing Sustainability and Ethical Practices

Traceability plays a crucial role in enhancing sustainability and ethical practices in the minerals industry. By tracking the entire supply chain, from mining to manufacturing, it becomes possible to identify and address environmental and social issues [24].. Traceability encourages responsible sourcing, minimizes the negative impact on ecosystems and communities, and promotes fair trade.

Through traceability, companies can identify and address any environmental concerns associated with the extraction and processing of minerals. They can implement measures to minimize resource consumption, reduce waste generation, and mitigate the impact on biodiversity [23].. Also, traceability helps ensure that mining activities are conducted in compliance with applicable regulations and that proper reclamation and restoration practices are followed. By promoting sustainable mining practices, traceability contributes to the conservation of natural resources and the protection of fragile ecosystems.

From a social perspective, traceability enables the monitoring of labor conditions and human rights practices throughout the supply chain. It helps prevent the use of forced labor, child labor, and other exploitative practices. By promoting fair trade, traceability contributes to the development of sustainable livelihoods for workers and the overall well-being of communities in mining regions. It also allows companies to engage in responsible sourcing and support local communities by providing fair wages and contributing to social development initiatives [24]..

F. Regulatory Frameworks and Compliance

There are existing and emerging regulations aimed at ensuring minerals traceability. These regulations focus on preventing the use of minerals sourced from conflict areas or associated with human rights violations. They require companies to disclose information about the origin of minerals and demonstrate due diligence in ensuring responsible sourcing [24].. Blockchain technology can assist in compliance by providing an immutable and transparent record of mineral transactions, making it easier to verify compliance with these regulations.

Blockchain's decentralized nature and cryptographic security features make it an ideal technology for ensuring transparency and accountability in the minerals supply chain [25].. By recording every transaction on the blockchain, it becomes difficult to manipulate or falsify records, providing a reliable source of information for regulatory authorities and stakeholders. Thus, blockchain can enable the creation of smart contracts that automatically enforce compliance with regulations, streamlining the auditing and reporting processes.

By implementing traceability systems and complying with regulations, companies can demonstrate their commitment to responsible practices and gain a competitive advantage in the market. They can attract environmentally conscious consumers who value transparency and ethical sourcing, as well as secure partnerships with organizations that prioritize sustainability.

G. Security and Data Privacy

While blockchain technology offers enhanced security and transparency, concerns regarding data privacy should be addressed. Sensitive data within the minerals supply chain, such as information about mining locations or trade secrets, should be protected through appropriate encryption and access control measures. Striking a balance between transparency and data privacy is essential in ensuring the successful implementation of minerals traceability using blockchain [24]..

To address these concerns, blockchain networks can be designed with privacy-enhancing features such as zero-knowledge proofs or secure multi-party computation [25].. These techniques allow for the verification of data integrity and compliance without revealing sensitive information to unauthorized parties. Also, robust data governance frameworks and strict access controls can be implemented to ensure that only authorized individuals or entities have access to specific data within the blockchain.

By adopting strong security measures and addressing data privacy concerns, stakeholders can confidently embrace blockchain technology for minerals traceability, knowing that sensitive information is protected while transparency and accountability are maintained.

H. Future Trends and Innovations

The use of blockchain for minerals traceability is likely to continue expanding as technology advances. Future developments may include the integration of Internet of Things (IoT) devices to capture real-time information about mining and transportation processes. These devices can collect data on factors such as temperature, humidity, and location, providing a more comprehensive view of the supply chain. Smart contracts and decentralized applications (DApps) could automate compliance checks and streamline supply chain operations, reducing manual effort and potential human error [25]..

Devolpments in artificial intelligence (AI) and machine learning can create a more accurate and efficient traceability system. These technologies can analyze large datasets and identify patterns or anomalies that may indicate non-compliance or unethical practices. AI-powered algorithms can help detect and flag irregularities in the supply chain, enabling swift corrective actions and continuous improvement.

By embracing these innovations and technologies, the minerals industry can further enhance traceability, strengthen sustainability practices, and meet the increasing demand for responsible sourcing and ethical minerals supply chains. Continuous research, collaboration, and knowledge-sharing among stakeholders are essential to drive these advancements and ensure a more sustainable and transparent minerals industry.

II. RESULTS AND DISCUSSION

A. Results for gemstone Traceability

Table 1 outlined various stages in a supply chain process, which included Mining, Transportation (Mining to Processing), Processing, Transportation (Processing to Distribution), and Distribution. Each of these stages was represented as a block in a blockchain. For instance, Block 1 represented the Mining stage, while the Transportation from Mining to Processing was represented by Block 1 and Block 2, and so on. These blocks contained data specific to each stage of the supply chain, and they were assigned a unique hash value. The hash value, generated using a hash function, was a cryptographic representation of the block's data. Importantly, any alteration to the block's data would result in a different hash value, serving as a safeguard for the blockchain's integrity and security. This hash value played a critical role in linking each block to the previous one, creating a secure and tamper-evident ledger of the supply chain. Each block recorded a particular event or transaction in the supply chain, and the hash values ensured that any unauthorized changes would be detectable, thereby upholding the trustworthiness and integrity of the supply chain data.

As pointed out by [16]., Kenya faces a deficiency in project-specific traceability systems that can verify the authenticity of gemstones as they move through the supply chain. The findings indicate the potential to enhance traceability and transparency of gemstones in the supply chain by utilizing hashes to store information that cannot be tampered with without detection. Achieving this through a Private and Permissioned Blockchain means that only parties involved in the supply chain can access and update the data, thus increasing the credibility of the gemstones and overall transparency in the supply chain.

In contrast to the current traceability methods, which, as mentioned by Ouma et al. (2010), have limitations in detecting unethical practices like smuggling and child labor, the results suggest that this enhanced transparency enables stakeholders to trace the origin of each gemstone. This ensures that the gemstones are sourced ethically from legitimate mines, making it more difficult for unethical practices such as smuggling or the use of child labor to go unnoticed.

https://doi.org/10.17758/IICBE5.C1123007

Minng stage	Transportation (Mining to processing)	Processing stage	Transportation stage.	Distribution
Block 1	Block1, Block 2,	Block1, Block 2, Block 3	Block1, Block 2, Block 3, Block 4	Block1, Block 2, Block 3, Block 4, Block 5
c3246feea5dd2e ac7fd8e7159722 23b56c7dff0657 c6a4d75d386ca9 d31aaaf6	56bc7a7c6dcec4 7033d14c0fb525 e13c9965de3f27 f9449d64ebf419 a58e206b	63cb94d2b56894 443603c671f2b4 d24030b90bf248 a2336b7162e4a3 02881f75	08b90732feb237 91019caa38ef2b 968b9c4999923c e187fc16ecb3cb db8eb8d9	66f89d5577f7d3 7cc91423fe41e3 1878fd0f6e4e88 8958d4ba9b616 3f834f44e

B. Results for traceability across the Vanadium supply chain

This research developed and implemented a blockchain-based traceability system to address transparency and accountability challenges in the vanadium supply chain in South Africa [23].. Vanadium is a critical mineral seeing surging demand given its pivotal role in emerging technologies like redox flow batteries [13].. However, complexities in the current vanadium supply chain necessitate innovative traceability solutions.

Implementation of the blockchain platform demonstrated significantly improved end-to-end traceability of vanadium from mine to consumer [24].. The system provided real-time communication and immutable data records to track vanadium flows across stakeholders including miners, processors, regulators, and buyers. Smart contracts encoded supply chain events directly into the blockchain, ensuring security and trust [26].. By reducing reliance on intermediaries and manual record-keeping, blockchain technology streamlined the supply chain and minimized risks of errors or tampering.

Outcomes showed the vast capabilities of blockchain-driven traceability in the vanadium industry via enhanced transparency, accountability, and process efficiency. The decentralized structure enabled seamless multi-party collaboration across the vanadium supply network. As emerging use cases drive vanadium demand, fortifying the supply chain is critical, and blockchain presents a revolutionary opportunity. This research contributes to the advancement of responsible and sustainable vanadium production through cutting-edge traceability. It provides a model for blockchain integration to strengthen mineral supply chains worldwide.

C. Blockchain Implementation

The results show a simplified solidity smart contract for traceability based on XRF values. It assumes that the ore is from Rustenburg when the Fe_2O_3 percentage is over 50%. This contract also includes hashing for the input data. Below is a breakdown

D. Smart Contract Overview

This Solidity smart contract, named "XRFTraceability," was designed to demonstrate the basic concept of traceability for an ore sample using XRF data. It helps determine the origin of the ore based on certain XRF percentages, specifically the percentage of Fe_2O_3. The contract uses a hashing function to secure the input data and ensure its integrity.

E. Contract Components:

OreSample Struct: This struct defines the ore sample, storing its location and a hash of the input data. The location represents the origin of the ore sample (e.g., "Rustenburg" or "UNKNOWN").

Constructor: The constructor initializes the contract with an "UNKNOWN" location and an empty hash.

setXRFData Function: This function is used to set XRF data for an ore sample. It takes the following parameters:

location: The location where the ore sample is from.

XRF percentages for various elements, including Fe_2O_3Percentage, V_2O_5 Percentage, TiO_2Percentage, SO_3Percentage, and Al_2O_3 Percentage.

The function calculates a hash of the input data, including the location and XRF percentages. Then, it checks if the Fe_2O_3 percentage is greater than 50%. If this condition is met, it assigns the location "Rustenburg" to the ore sample. Otherwise, it remains "UNKNOWN."

bytes32ToString Function: This internal function is used to convert a bytes32 data type (used for the hash) to a string. It's essential for data representation.

uint2str Function: This internal function converts a uint (unsigned integer) to a string for creating the hash.

How does the Contract work?

The contract will be deployed on the Ethereum blockchain. Users interact with the contract by calling the set XRF Data function, providing XRF data, including location and element percentages. The function calculates a hash of the input data, ensuring the data's integrity and security. Based on the Fe_2O_3 percentage provided, the contract decides whether the ore sample is from "Rustenburg" (if $Fe_2O_3 > 50\%$) or remains "UNKNOWN." The final location is stored in the contract, which users can access. This contract represents a basic traceability system. In real-world applications, it can be extended to incorporate more complex logic and data, such as multiple elements and a more extensive set of criteria for determining the ore's origin. The hashing function is critical for ensuring that the data hasn't been tampered with and maintains its integrity on the blockchain.

III. CONCLUSION

This research attempted the use of blockchain-based traceability systems in the minerals supply chain, with a focus on vanadium in South Africa and gemstones in Kenya. The development of blockchain platforms proved the unicity of the data as the hash function was developed. The ore elemental composition obtained from the XRF analysis was integrated in the smart contract and derived the ore location. As demand grows for minerals like vanadium and gemstones, robust traceability is critical. This study's outcomes would contribute to supply chain advancement and responsible sourcing.

REFERENCES

[1]. Pournader, M., Shi, Y., Seuring, S., & Koh, S. L. (2019). Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. International Journal of Production Research, 58(7), 2063-2081. https://doi.org/10.1080/00207543.2019.1650976

[2]. Kouhizadeh, M. and Sarkis, J. (2018). Blockchain practices, potentials, and perspectives in greening supply chains. Sustainability, 10(10), 3652. https://doi.org/10.3390/su10103652

[3]. Tsang, Y. P., Choy, K. L., Wu, C., Ho, G., & Lam, H. Y. (2019). Blockchain-driven iot for food traceability with an integrated consensus mechanism. IEEE Access, 7, 129000-129017. https://doi.org/10.1109/ACCESS.2019.2940227

[4]. Lin, Q., Wang, H., Pei, X., & Wang, J. (2019). Food safety traceability system based on blockchain and epcis. IEEE Access, 7, 20698-20707 https://doi.org/10.1109/ACCESS.2019.2897792

[5]. Yang, X., Li, M., Yu, H., Wang, M., Xu, D., & Sun, C. (2021). A trusted blockchain-based traceability system for fruit and vegetable agricultural products. IEEE Access, 9, 36282-36293. https://doi.org/10.1109/ACCESS.2021.3062845

[6]. Kuo, T., Kim, H., & Ohno-Machado, L. (2017). Blockchain distributed ledger technologies for biomedical and health care applications. Journal of the American Medical Informatics Association, 24(6), 1211-1220. https://doi.org/10.1093/jamia/ocx068

[7]. Andoni, M., Robu, V., Flynn, D., Abram, S., Geach, D., Jenkins, D., … & Peacock, A. (2019). Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renewable and Sustainable Energy Reviews, 100, 143-174. https://doi.org/10.1016/j.rser.2018.10.014

[8]. Dutta, P., Choi, T., Somani, S., & Butala, R. (2020). Blockchain technology in supply chain operations: applications, challenges and research opportunities. Transportation Research Part E: Logistics and Transportation Review, 142, 102067. https://doi.org/10.1016/j.tre.2020.102067

[9]. Vovchenko, N. G., Андреева, A. B., Orobinskiy, A. S., & Filippov, Y. M. (2017). Competitive advantages of financial transactions on the basis of the blockchain technology in digital economy. European Research Studies Journal, XX(Issue 3B), 193-212. https://doi.org/10.35808/ersj/778

[10]. Sheel, A. and Nath, V. (2019). Effect of blockchain technology adoption on supply chain adaptability, agility, alignment and performance. Management Research Review, 42(12), 1353-1374. https://doi.org/10.1108/mrr-12-2018-0490

[11]. Bushveld Minerals, 2022. *About Vanadium.* [Online]. Available at: https://www.bushveldminerals.com/about-vanadium/ [Accessed 18 03 2023]..

[12]. Rodby, K. E., Jaffe, R. L., Olivetti, E. A. & Brushett, F. R., (2023). Materials availability and supply chain considerations for vanadium in grid-scale redox flow batteries. *Journal of Power Sources,* 560(232605). https://doi.org/10.1016/j.jpowsour.2022.232605

[13]. Kim, K. J. et al., (2015). A technology review of electrodes and reaction mechanisms in vanadium redox flow batteries. *Journal of Materials Chemistry A,* Volume 3. https://doi.org/10.1039/C5TA02613J

[14]. Walsh, A. (2015). Lost and/or left behind in a malagasy outpost of the ‘underworld of gemstones’. Critique of Anthropology, 35(1), 30-46. https://doi.org/10.1177/0308275X14557094

[15]. Shor, R. and Weldon, R. (2010). An era of sweeping change in diamond and colored stone production and markets. Gems &Amp; Gemology, 46(3), 166-187. https://doi.org/10.5741/GEMS.46.3.166

[16]. George, J., Whitten, D., Metters, R., & Abbey, J. D. (2022). Emancipatory technology and developing-world supply chains: a case study of african women gemstone miners. Journal of Operations Management, 68(6-7), 619-648. https://doi.org/10.1002/joom.1217

[17]. Jønsson, J. B. and Fold, N. (2011). Mining ‘from below’: taking africa’s artisanal miners seriously. Geography Compass, 5(7), 479-493.

[18]. Naylor, T. H. (2009). The underworld of gemstones. Crime, Law and Social Change, 53(2), 131-158. Auble, C., 2011. The Cultural Significance of Precious Stones in Early Modern England. https://doi.org/10.1007/s10611-009-9223-z

[19]. Smith, E. M., Smit, K. V., & Shirey, S. B. (2022). Methods and challenges of establishing the geographic origin of diamonds. Gems &Amp; Gemology, 58(3). https://doi.org/10.5741/GEMS.58.3.270

[20]. Wen-xing, X. and Krzemnicki, M. S. (2021). Raman spectroscopic investigation of zircon in gem-quality sapphire: application in origin determination. Journal of Raman Spectroscopy, 52(5), 1011-1021. https://doi.org/10.1002/jrs.6092

[21]. (2018). The effects of luxury firm level within the luxury industry on the level of corporate social performance. International Journal of Business and Administrative Studies, 4(6).

[22]. Volodymyr, I., Nina, M., & Kateryna, P. (2021). Commodity expertise of jewelry. The International Scientific-Practical Journal "Commodities and Markets", 39(3), 60-74. https://doi.org/10.31617/tr.knute.2021(39)04

[23]. RCS Global, (2017). *BLOCKCHAIN FOR TRACEABILITY IN MINERALS AND METALS SUPPLY CHAINS: OPPORTUNITIES AND CHALLENGES,* s.l.: RCS Global.

[24]. IBM, (2022). *Benefits of blockchain.* [Online]. Available at: https://www.ibm.com/topics/benefits-of-blockchain [Accessed 9 June 2023]..

[25]. Algorand, (2021). *Blockchain Interoperability: What Is it and Why Does it Matter?.* [Online]. Available at: https://algorand.com/resources/blog/blockchain-interoperability-what-is-it-and-why-does [Accessed 15 May 2023]..

[26]. Agrawal, T. K., Kumar, V., Pal, R., Wang, L., & Chen, Y. ((2021)). Blockchain-based framework for supply chain traceability: A case example of textile and clothing industry . *Computers & Industrial , 154*(107130). https://doi.org/10.1016/j.cie.2021.107130