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Review

Exploring Blockchain for Nuclear Material Tracking: A Scoping Review and Innovative Model Proposal

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Abstract: Ensuring safe and transparent tracking of nuclear materials in the modern era is critical for global security and compliance with international regulations. Blockchain technology, a decentralized and immutable ledger, offers a new approach to recording transactions, increasing trust without intermediaries. In this study, it was investigated whether nuclear material tracking was performed with advanced technology blockchain from past to present; it was seen that there needed to be a study on this subject in the literature, and that there was a gap. Search results proving this are presented. The authors present a model that can enable nuclear material tracking with blockchain technology, which will create a solid structure for recording and verifying every process step in the nuclear supply chain, from the creation of the first product to destruction. This model discusses how nuclear materials, which are very important to track from the beginning until they become waste, can be tracked with blockchain technology, and the contributions they can make nationally and internationally are explained. As a result of the research, it is shown that blockchain technology has the potential to pave the way for more resilient and precise nuclear supply chains by significantly increasing the security and efficiency of nuclear material tracking.

Keywords: nuclear material tracking; blockchain technology; nuclear security; supply chain security; real-time monitoring; scoping review

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1. Introduction

With the development of technology, the possibility of carrying out all transactions easily during the day increases. Applications and methods that are easier to access and more profitable in terms of cost are being used more and more daily. In this context, it is essential that the methods developed can be quickly integrated into daily life. Blockchain technology, one of the important developments of recent years, is one of these areas. This technology, defined as a publicly available digital ledger that can record transactions on multiple computers and ensure data integrity in a decentralized, distributed manner, does not require an intermediary to verify transactions [1]. Before the advent of blockchain, Chaum [2] presented the idea of digital cash, a system that relied on a central server to prevent duplication of transactions. In 1991, Stuart Haber and W. Scott Stornetta [3] published the first work on cryptographically secure blockchains. A person or group of people known as Satoshi Nakamoto developed the first blockchain idea in 2008. The

following year, Nakamoto [4] used it as the main component of the cryptocurrency Bitcoin, functioning as the public ledger for all transactions on the network. Over the years, blockchain technology has been further developed.

Blockchain structure does not depend on a single authority. A network of computer nodes is used to verify and confirm transactions. All transactions are recorded in a block and the network structure is established by connecting to the previous block. In this way, a chronological chain is achieved that cannot be changed without the approval of most of the network. Thanks to this decentralized structure, no single person or organization controls the entire system, making the system resistant to fraud and providing security. The decentralized nature of blockchain allows data to be distributed and stored across multiple nodes, making it highly resistant to hacking and cyberattacks.

Additionally, blockchain uses cryptographic algorithms to secure transactions and ensure the authenticity and integrity of data. Since intermediate processing steps are eliminated, transactions are carried out quickly and automatically. In addition to security, it is offered to users by ensuring immutability and transparency. Once a transaction is recorded on the blockchain, it becomes a permanent and unchangeable part of the ledger. This is accomplished through cryptography and consensus mechanisms that ensure the integrity of the data. Any attempt to change a transaction would require the consensus of a majority of the nodes in the network, making manipulation of records nearly impossible. This immutability increases security and facilitates auditing and accountability, as each transaction can be traced back to its origin and audited in real time. Thanks to its transparency, it is almost impossible to change or delete data without being detected, as the transactions are recorded and stored in multiple nodes on the network. Thanks to its immutability and transparency, blockchain technology can be used in sectors where trust is critical, such as healthcare, finance, and supply chain management. In addition to what has been explained, costs are reduced, and processes become more accessible, eliminating the need for intermediaries.

The blockchain structure consists of two separate structures: a database and a node network. This structure is presented in Figure 1. As the figure shows, blockchain is a shared, fault-tolerant repository that keeps track of records (transactions) in the database [5]. The blockchain database is immutable, meaning that once a transaction is recorded in a block and added to the chain, it cannot be modified or deleted. This database is maintained by a network of nodes or computers verifying and recording transactions through consensus. Blocks formed by bringing together a series of transactions are connected to the previous blocks with hashes, which are fixed-length numerical values of the data in the previous blocks. Hashes are unique alphanumeric values created by running a digital file or block of data through a mathematical algorithm. This process produces a fixed-length output specific to the original input. Hashes are critical components of blockchain technology as they provide a way to ensure data integrity and security. Blockchain networks can prevent unauthorized access and information tampering by creating a unique hash for each data block. Any change to a data block will result in a completely different hash, alerting the network to potential fraud or malicious activity.

Furthermore, every block has a timestamp denoting its creation time, a signature that verifies its accuracy and integrity, and a randomly generated number for cryptographic functions. These structures ensure that blocks are immutable even if they are public. The blockchain network comprises numerous dispersed nodes that uphold the database in a peer-to-peer network. Nodes have the ability to access the blocks, but they are unable to modify them [6].

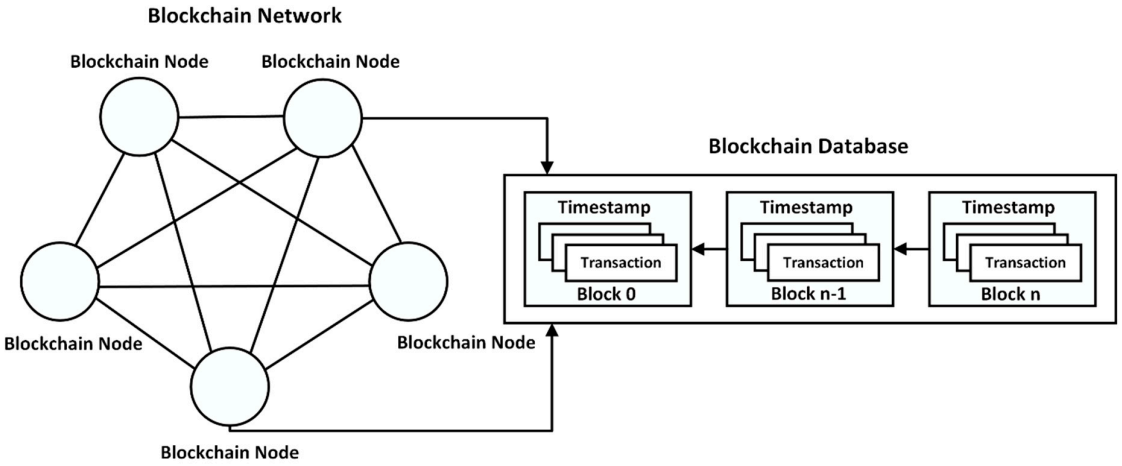


Figure 1. Blockchain architecture.

Blockchain architecture encompasses the various components, subcomponents, and layers that constitute a comprehensive blockchain system. Each layer in the system has a distinct function, ranging from data storage to network connectivity maintenance and assuring consensus. Blockchain technology encompasses various blockchains, each distinguished by its distinct characteristics and functionalities. The types of blockchain are presented below.

A. Public Blockchains:

Public blockchains are accessible to all individuals, enabling decentralized network engagement. Examples of permissionless networks, such as Bitcoin and Ethereum, let anybody join, access the ledger, and contribute to the consensus mechanism. Public blockchains are decentralized and secure frameworks that provide transparency and trustworthiness, making them suitable for various applications [7]. Public blockchains are commonly employed to facilitate cryptocurrency and decentralized applications (dApps). DApps play a crucial role in enhancing security in blockchain-based document authentication by highlighting the significance of open-source code in promoting transparency and reliability [8].

B. Private Blockchains:

Private blockchains exhibit a higher degree of centralization and are usually limited to a specific set of individuals authorized to access the network. A central entity has the authority to decide who can and cannot participate [9]. This particular form of blockchain is frequently employed in corporate environments where maintaining privacy and exerting control are of utmost significance. These blockchains are crucial for enterprise-level applications as they enable the seamless execution of smart contracts among members, facilitate business model innovation, and offer value propositions [10]. Private blockchains provide enhanced network control and are inaccessible to the general public.

C. Consortium Blockchains:

Consortium blockchains are a fusion of public and private blockchains in which a collective of organizations collaborate to manage the network. Members of a consortium blockchain have equal authority over the network and are accountable for upholding consensus. Consortium blockchains are commonly employed in businesses that require safe collaboration and information sharing across numerous stakeholders. These blockchains have effectively been utilized in industries such as shipping to improve productivity by implementing smart contracts [11]. Furthermore, they assist in transactions that are both safe and protect privacy, as demonstrated in the context of energy trading among microgrid communities [12].

D. Hybrid Blockchains:

Hybrid blockchains combine features from public and private blockchains to provide the advantages of decentralization and governance. They can also be tailored to suit a company's individual requirements, allowing for confidentiality, scalability, and management adaptability. Hybrid blockchains are becoming increasingly popular in industries that necessitate a harmonious combination of decentralization and control. An instance of this arrangement is zkCrowd, a hybrid blockchain crowdsourcing platform that was formed by merging crowdsourcing and blockchain technologies. This application combines a hybrid blockchain framework with smart contracts, binary ledgers, and binary consensus algorithms to secure communication, safeguard privacy, and authenticate transactions [13].

Ultimately, blockchain technology has numerous prospects for individuals or enterprises seeking to capitalize on its benefits. Public, private, consortium, and hybrid blockchains each include distinct characteristics and functionalities that can be tailored to fulfill specific requirements. Given the ability of various versions of blockchain to provide a secure environment, numerous studies have been conducted in various fields utilizing this technology. One of these is the discipline of finance, which is extensively utilized in the present day. One area of study in the financial sphere is utilizing the blockchain approach to sign smart contracts. Proposed in a study that offers a decentralized transaction system implemented using a smart contract, a virtual contract based on blockchain technology, the Ethereum blockchain-based system securely stores transaction details [14]. Also, it allows users to conduct fraud-free transactions worldwide in real time. A separate study implemented a payment system based on blockchain technology to enhance the security and efficiency of online transactions. The system is specifically designed to generate comprehensive transaction records organized in blocks of information, enabling users to easily retrieve specific facts such as the date and time of each transaction [15]. In another work presenting a decentralized conditional anonymous payment (DCAP) system, the authors' conditional anonymous payment (CAP) scheme is designed based on a proposed information signature. The results demonstrate the advantage of the proposed DCAP system when compared to Zerocash in terms of performance, using the same parameters and test conditions [16]. Zerocash is a system that places high importance on maintaining privacy when transferring value within a single currency [17,18]. The study proposed a novel protocol for preauthorized transactions on the blockchain to mitigate the risk of permanent fund loss resulting from erroneous money or data transfers to incorrect addresses. The findings demonstrated that implementing this protocol significantly reduces the likelihood of transaction errors and fraud by requiring all parties to reach a consensus and provide their signatures before approving the blockchain transaction [19]. Cryptocurrencies, a topic of significant discussion in recent years, are increasingly becoming integrated into everyday life through blockchain technology. Blockchain technology was initially implemented with the introduction of the cryptocurrency Bitcoin. Bitcoin is a decentralized digital currency that functions on a peer-to-peer network, enabling direct transactions without the involvement of intermediaries like businesses or governments. It is now the most prevalent use case of blockchain technology [20]. Ethereum, similar to Bitcoin, is another widely used blockchain technology. Ethereum is a secure, decentralized, open-source blockchain platform that operates without contracts. Vitalik Buterin [21] proposed it in 2013. A literary writer drew a comparison between Ethereum and Bitcoin [22]. Although Ethereum is acknowledged to be more efficient and versatile than Bitcoin, it is implied that it offers a greater variety of usage possibilities and technological capabilities. As cryptocurrencies become more widely used, new methods are emerging for conducting money laundering operations. Advancements in data contributions in this field have facilitated thorough analyses of the intersections between risk-based anti-money-laundering (AML) assessment systems and legislation for financial management [23].

The healthcare industry is another domain where blockchain technology is being applied. The initial authors developed a framework in the shape of a blockchain specifically tailored for patient-centered telemedicine. This framework, called HapiChain, aims to enhance the availability, scalability, and resilience of medical processes [24]. This ar-

chitecture is constructed to ensure security and scalability for decentralized applications (DApps) through isolation, smart contracts, distributed storage, and blockchain protection via Ethereum. Utilizing blockchain technology is another sophisticated approach provided as a privacy-conscious platform within a blockchain environment for storing healthcare data in the cloud. This technology guarantees both secure and private handling and sharing of healthcare data [25].

Blockchain technology is being more acknowledged for its capacity to augment diverse forms of cybersecurity and its aptitude to uphold privacy [26]. Hawk is a decentralized smart contract system that ensures transaction confidentiality without storing it in plain text on the financial blockchain. It enables secure transactions between vulnerable copies and offers compensation in the event of a breach or cancellation [27]. Cybersecurity models play a crucial role in safeguarding the data in advanced health applications. In order to address this issue, a group of developers have suggested implementing homomorphic elapid security (LGE-HES) using Lionized Golden Eagle to enhance the cybersecurity of blockchain in healthcare networks [28]. The widespread use of blockchain technology is primarily driven by its ability to ensure secure access and secrecy in data storage mechanisms. Regarding the information repositories utilized in blockchain studies, it is essential to note that most blockchain structures function as data stores, making this statement accurate. For a sales presentation in the data storage industry, a novel IoT server platform is suggested as an alternative to the conventional approach of server construction. This platform utilizes a blockchain of sensors to store data [29].

Blockchain architecture can be applied to regulate transactions involving property acquisitions, sales, and leases in the real estate industry. Blockchain technology can also be employed in the commercial real estate industry, particularly in the administration of commercial buildings, to monitor and record transactions such as leasing agreements, maintenance records, and changes in ownership. This approach enhances confidence among all pertinent stakeholders, ensuring the utmost precision in transactions. The authors developed a blockchain framework for online bidding systems based on a tree topology. This approach enhances both the security and efficiency of online bidding [30]. Another study in the real estate industry explores the application of blockchain technology for developing smart contracts in real estate transactions, specifically for renting residential or commercial properties. This study highlights the potential of blockchain to increase the number of available properties [31]. The examples provided demonstrate that blockchain is a versatile framework deeply integrated into our everyday lives and can be customized to suit specific requirements.

A tracking system is one of the approaches developed using blockchain technology. Product tracking is monitoring the movement of a product, asset, or data from origin to its final recipient or user. Hence, every transaction during the process is meticulously documented on the blockchain, making it exceedingly difficult to manipulate or alter these data. Additionally, it is employed for verification. Due to the immutable and transparent nature of the information on the blockchain, it offers significant benefits in product verification, fraud prevention, and supply chain efficiency. Blockchain technology enhances transparency and responsibility in supply chains, facilitating the tracking of product journeys from raw material providers to final customers [32]. Developing a material tracking system using blockchain technology involves a sequence of procedures aimed at guaranteeing transparency and security. Every stage of this procedure is crucial for documenting and confirming the source and journey of materials and goods, from their inception to their final destination with the consumer. Before developing material tracking systems using blockchain technology, a comprehensive needs analysis is conducted to identify requirements and establish objectives. Next, the blockchain structure is chosen, and the characteristics of the data pieces are determined. Access to the system is granted to participants based on their eligibility, and the management of permissions is established. Smart contracts are subsequently generated to facilitate significant interactions. Integration

is accomplished by gathering real-time data using sensors and QR codes. Ultimately, the system undergoes rigorous testing and is subsequently placed into operation.

Blockchain technology enables a wide range of tracking functions. An initial instance of this can be illustrated through medication monitoring. Blockchain technology is employed in the pharmaceutical sector to guarantee the secure delivery of medications to consumers and to mitigate the risk of fraudulent activities. It provides a transparent and secure approach to tracking pharmaceutical medications, resulting in increased speed and efficiency [33]. Proposed in the literature are blockchain-based solutions that aim to enhance the supply chain system and address the issue of transparency in the current pharmaceutical distribution system [34]. Pharmaceuticals are documented on the blockchain at each phase, commencing from the manufacturing process. These tools allow users to effortlessly retrieve information regarding every phase of drug production, including their origin, tracking from manufacturers to end users, authenticity, and expiration dates [35]. As a case study, the blockchain can record essential transportation circumstances, such as temperature monitoring of pharmaceuticals, enabling verifying their transfer under suitable settings.

Another domain pertains to financial transactions. The blockchain method enables the seamless availability of currencies and currency derivatives. For instance, the utilization of blockchain technology in international money transfers has the potential to enhance the velocity and safety of transactions. Conventional banking systems typically involve the use of intermediaries and can be time-consuming when it comes to transferring funds between different countries. Nevertheless, utilizing blockchain technology enables the execution of monetary transfers via a decentralized network that validates transactions. The decentralized nature of this structure reduces the time required to complete transactions to a matter of hours or even minutes while also eliminating the expenses associated with intermediary organizations. Blockchain-based tracking systems are essential for guaranteeing the dependability of information acquired by public and government institutions, particularly in financial transactions [36]. The efficacy of blockchain in guaranteeing the security, traceability, integrity, item tracking, and access control of financial transaction data renders it a significant instrument for enhancing financial tracking and security [37]. Furthermore, due to the immutable and transparent nature of storing every transaction record on the blockchain, the likelihood of fraud and errors is diminished, and any worries regarding transaction fees are eradicated [38]. These characteristics enhance financial stability, particularly for transactions of significant value.

Blockchain can be utilized to monitor the entirety of the supply chain in agriculture and animal husbandry, commencing with the origin of food goods. Walmart and IBM have utilized blockchain technology to identify the origin of food products and promptly address potential food safety concerns. This system can trace the origin of a food product, monitor its processing, and track its journey to the market shelves. This system enables the tracking of ingredients from manufacturers to end customers, ensuring transparency and trust in the product journey [39]. This strategy is employed to promptly address food safety scandals and expeditiously withdraw problematic goods from the market. Blockchain technology's decentralized and transparent nature fosters trust by reducing knowledge asymmetry in goods supply networks [40].

Another domain is the authentication process of high-end merchandise, such as bags, clothing, watches, and other luxury items, aimed at combating the production and distribution of counterfeit goods. Blockchain technology has been utilized to create systems that monitor and track these products from the moment they are produced. This approach effectively eradicates any uncertainties regarding the genuineness of the merchandise. Enhancing supply chain management enables organizations to ensure the traceability and provenance of luxury products [41]. It can be confirmed that valuable gemstones and diamonds were extracted in a lawful manner and in compliance with ethical guidelines. Various organizations have highlighted the need to utilize blockchain technology to provide traceability and prevent counterfeiting in supply chains. This application can be directly

implemented in the luxury goods market [42]. De Beers uses blockchain technology to monitor the diamond supply chain, starting with the mining stage and ending with the delivery to the jeweler. Thus, customers can authenticate the origin of the diamond they are acquiring [43].

Blockchain technology is well suited for validating the genuineness and ownership chronology of artworks and rare artifacts. The distributed blockchain database guarantees the precise representation of transaction data for valuable art pieces, creating an unchangeable record of art transactions [44]. The art sector benefits greatly from the potential of blockchain technology, as it plays a crucial role in promoting budding artists, resolving ownership disputes, and guaranteeing the genuineness of digital artworks [45]. Every piece of artwork is accompanied by a digital certificate that contains comprehensive details about the ownership and exhibition history of the artwork. This measure assists in deterring counterfeiting and maintaining the intrinsic worth of the creations.

The origin and assembly of car parts are crucial factors in the automobile sector for ensuring safety and compliance. The industry's intricate supply chains, substantial data volumes, and significant infrastructure make it an ideal target for incorporating blockchain technology, which provides advantages such as enhanced transparency, security, and efficiency [46]. By utilizing blockchain technology, monitoring the movement of individual components from creation to integration can enhance the security and excellence of automobiles.

Blockchain technology verifies the quantity of energy generated from renewable sources like wind or solar and the tracking and certification of its origin. As an illustration, the blockchain can record the quantity and source of energy generated by solar panels or wind turbines. This enables the exchange of this energy for certifications that verify its green credentials. This promotes openness and incentivizes the utilization of sustainable energy sources. Furthermore, blockchain technology can facilitate the exchange of green electricity certificates, optimize the distribution of energy resources in microgrid networks, and enable decentralized energy management in the context of renewable energy sources [47]. The study's authors devised a system that utilizes the Internet of Things (IoT) and blockchain technology to quantify electricity production for safe and decentralized data recording accurately [48]. Blockchain technology has the potential to be applied to nonrenewable energy sources such as fossil fuels and nuclear energy. This structure is characterized as a potent catalyst for secure energy commerce, particularly for fossil energy resources and nuclear energy resources in smart grids [49,50]. Blockchain technology's reliability can be harnessed for resource tracking, carbon-free trading, and energy delivery.

When the examples given above are examined, it can be seen that the quality and security of tracking processes are increased by using blockchain technology. Thanks to blockchain technology, wide and comprehensive usage areas are offered in the field of material tracking. All of these are designed to meet specific needs in industries and increase the transparency of processes.

Nuclear Material Tracking with Blockchain Technology

Nuclear materials are substances utilized in various fields, such as energy production, medicinal uses, manufacturing, and scientific study. These compounds possess energy, particularly at the atomic nucleus level, or qualities that allow them to release this energy. The primary characteristics of these substances are their elevated energy density and radioactivity. Nuclear materials can be naturally occurring or purposefully created and can be broadly classified into two primary groups: radioisotopes and nuclear fuels. Radioisotopes, or radionuclides, are isotopes of elements with unstable atomic nuclei that undergo radioactive decay, generating energy and transforming into more stable isotopes or different elements. Many types of radiation, including alpha, beta, and gamma rays, are emitted during this transition process. Radioisotopes find applications in medical imaging procedures and in the monitoring of water resources and oil pipelines. Radioisotopes have a crucial role in the medical profession, specifically in diagnostic imaging techniques like positron emission

tomography (PET) and in treating diverse illnesses, including cancer [51]. The medical field has shown interest in advancing radiotherapy, which utilizes diagnostic and therapeutic radionuclides of the same element. This method enables the utilization of chemically similar radiopharmaceuticals for both imaging and subsequent treatment, which is referred to as the radiotherapy idea [52]. Nuclear fuels are materials utilized for generating energy in nuclear reactors and nuclear armaments. A study in this subject highlighted the significance of technical readiness levels for advanced nuclear fuels and emphasized their crucial role in completing the nuclear fuel cycle [53]. A different investigation highlighted the significance of safety, dependability, and cost-effectiveness in guaranteeing the enduring viability of nuclear energy as a sustainable energy option [54]. Nuclear fuels consist of the necessary components for nuclear fission or fusion reactions, which have the potential to produce substantial amounts of energy. Fission is the process of dividing large atomic nuclei and releasing energy. In contrast, fusion is the process of merging small atomic nuclei to create larger atomic nuclei and also releasing energy. Campbell et al. [55] conducted a study on fission, explicitly focusing on high-energy delayed gamma spectroscopy for analyzing spent nuclear fuel. The work highlights the significance of precise measuring methods for fissile materials. Manheimer et al. [56] are prominent researchers on the subject of fusion. Fusion breeding is a sustainable energy strategy that utilizes fusion reactions to fuel nuclear fission reactors, promoting long-term energy sustainability. First, the example of uranium (uranium-235 and uranium-238) can be given. Uranium-235 is the primary fissile material utilized in nuclear power reactors. Several studies are being conducted to examine uranium compounds important in the initial stages of the nuclear fuel cycle, such as uranium ore concentrates and other uranium compounds [57–59]. Enriched uranium is utilized for energy generation in reactors, but natural uranium can be employed in a less enriched state in some types of reactors. Plutonium-239 is a nuclear fuel that is often acquired by the reprocessing of leftover uranium fuel. It has the capability to be utilized for both generating electricity and manufacturing nuclear bombs. Weapons-grade plutonium is distinguished from plutonium produced in nuclear reactors by its low proportion of the 240Pu isotope, with 240Pu/239Pu ratios typically below 0.07 [60,61]. The release of plutonium isotopes into the environment as a result of nuclear accidents or weapons testing is a cause for concern due to the potential risks of internal radiation exposure [62]. The research of Pu-239 nuclear fuels is a multidisciplinary field encompassing various fields like isotope analysis, environmental monitoring, and reactor performance. Thorium is regarded as a promising fuel for upcoming nuclear reactor technologies and can serve as a substitute for current uranium-based systems. A study demonstrated that the utilization of thorium alongside plutonium in nuclear energy generation exhibited potential in diminishing the buildup of persistent transplutonium nuclides and addressing apprehensions regarding managing nuclear waste [63]. A separate investigation employed pebble bed reactors with thorium-based nuclear fuel as a means to address the constraints associated with natural uranium resources. An analysis was conducted to examine the combustion efficiency and the criticality level [64]. Thorium-based nuclear fuels have great potential for advancing nuclear energy technology, with research primarily focused on reactor designs, fuel cycle efficiency, and economic feasibility. Nuclear materials are regulated to ensure safety and protect the environment, primarily because of their high energy density and radiation characteristics. Rigorous safety standards are implemented throughout the manufacturing, utilization, and disposal of these materials and are scrutinized by international agreements. An example organizational chart of the use of nuclear materials is given in Figure 2. Here, nuclear fuels are first obtained. The nuclear fuel is then brought to the purity required for fission, and the enriched fuel is loaded into the reactor. Then, fission reactions of atomic nuclei with neutrons are initiated, and the energy is converted into heat. In this process, the heat in the reactor turns into water vapor, and the high-pressure steam drives the turbines. Working turbines produce electricity. The electricity produced is distributed through transmission lines, and radioactive waste is stored and managed safely.

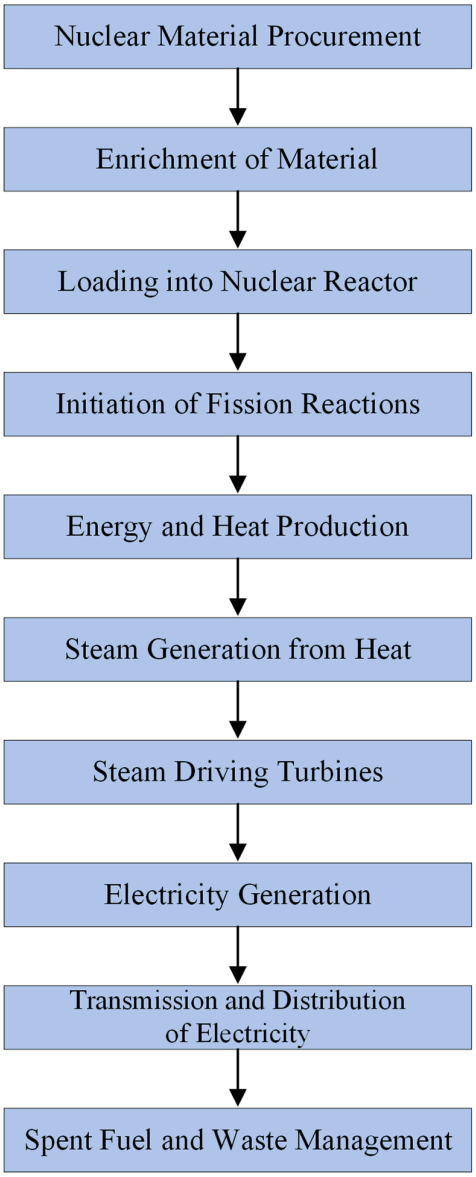


Figure 2. Sample organizational chart for nuclear material use.

Nuclear materials have many significant applications, encompassing energy generation and healthcare. These applications significantly contribute to a diverse array of diagnostic and therapeutic objectives [65–68]. One of the main applications is in the domain of nuclear medicine. Radiopharmaceuticals, which are nuclear compounds, are utilized for medical imaging. Radioactive isotopes are utilized in PET (positron emission tomography) scans to identify cancer cells and other irregularities. The positron emitter isotopes are crucial in diagnosing and planning treatments by identifying the unique metabolic activity of specific organs or tissues. In addition, radiation is a significant application of nuclear technology that plays a crucial part in the treatment of cancer. Cancer treatment utilizes radioactive elements to target and eradicate cancer cells specifically. This intervention effectively regulates the growth of malignant tissue by inhibiting or eliminating the proliferation of cancerous cells. Radiation therapy can be employed in conjunction with or as an alternative to surgery or chemotherapy in the treatment of cancer, thereby enhancing the likelihood of successful cancer treatment outcomes.

Moreover, nuclear technology is crucial in the functioning of numerous imaging systems employed for diagnostic purposes in the field of healthcare. For instance, among conventional imaging methods like magnetic resonance imaging (MRI) and computed

tomography (CT), technologies like nuclear magnetic resonance imaging (NMR) also yield significant information. These techniques utilize the characteristics of radioactive substances to generate precise images of interior organs, serving as a crucial tool for detecting various health issues.

Nevertheless, there are also apprehensions regarding the utilization of radioactive elements in healthcare. Effectively managing dangers associated with radiation exposure is of the utmost importance. Consequently, the field of nuclear medicine is governed by stringent regulations and necessitates implementing proper safety measures. Nevertheless, the application of nuclear technology in healthcare has substantial promise for enhancing diagnostic and treatment procedures and enhancing patients' quality of life.

The nuclear materials utilized and supervised in healthcare often consist of radioactive isotopes or radioactive compounds. These materials are crucial in a wide range of diagnostic and therapy methodologies. One example of them is technetium-99m (Tc-99m). It is a highly prevalent radioactive isotope and an essential radionuclide. Tc-99m-labeled radiopharmaceuticals are used in about 70% of all nuclear medicine operations [69]. This substance has versatile applications in several fields, both for diagnosing and treating different organs and tissues [70]. It is utilized in medical imaging examinations, particularly SPECT (single photon emission computed tomography) scans, to acquire functional pictures of various organs. Tc-99m is utilized in various diagnostic procedures, including bone scintigraphy, thyroid scans, and kidney function testing. It is a crucial component in around 80–85% of all nuclear medicine operations and cannot be substituted by other radionuclides [71]. In recent years, it has substantially contributed to the advancement of nuclear medicine [72].

Iodine-131 (I-131) is employed for the management of thyroid disorders, specifically thyroid cancer and hyperthyroidism. Due to its brief radioactive half-life, this substance is extensively utilized in medical diagnostic and therapy operations as it is specifically absorbed by the thyroid gland. The utilization of I-131 in the field of nuclear medicine may be dated back to 1941, highlighting its extensive duration in clinical practice [73]. Radioactive iodine specifically targets and treats the thyroid tissue by settling in it. I-131 is commonly employed as an adjuvant therapy following surgery to eliminate residual thyroid tissue and eradicate metastases [74,75]. I-131 is mostly generated as a secondary product of uranium fission in nuclear reactors employed for energy generation. Efficient methods for capturing and immobilizing I-131 in both air and groundwater are necessary to control radioiodine waste in the environment.

The isotope fluorine-18 (F-18) is employed in several diagnostic imaging techniques in healthcare, specifically in PET (positron emission tomography) scans. F-18 is utilized in PET imaging to provide high-resolution images that aid in accurately diagnosing various medical disorders [76]. The utilization of F-18 in PET imaging has played a vital role in determining the extent of malignancy, tracking treatment progress, and identifying the return of the illness in patients with cervical and ovarian cancer [77]. Furthermore, using digital photographic image analysis with liquid scintillators has significantly improved estimating fluorine emission spectra. This has greatly contributed to advancements in medical imaging applications, specifically in treating tumors or cancers that require electron beam irradiation [78,79]. An essential factor in the manufacturing of F-18 involves using sophisticated technology like cyclotrons to generate radioisotopes. The production procedure entails subjecting the target material to proton irradiation, which initiates nuclear processes leading to the creation of fluorine-18. F-18 is subsequently integrated into biologically active compounds by chemical means to create radiotracers used in PET imaging.

The cobalt-60 (Co-60) isotope is a highly radioactive isotope that finds extensive use in different applications, particularly in healthcare, where it is a crucial source in radiotherapy devices. Its accurate and reproducible treatment capabilities make it the "gold standard" for device calibration in the medical field [80]. Gamma radiation, being highly concentrated, selectively targets and eradicates cancer cells, making it a commonly employed method in cancer therapy [81]. The utilization of Co-60 in healthcare includes radiation therapy

systems, including Co-60 MRI-guided radiation therapy, which is now under evaluation for treating illnesses such as prostate neoplasms and head and neck neoplasms [82]. In addition, Co-60 is utilized in brachytherapy, where the distribution of doses is similar to that of Ir-192. Thus, it becomes a financially efficient substitute [83].

Iridium-192 is a radioactive isotope utilized in the healthcare field for radiotherapy. This isotope is utilized in cancer treatment, particularly in a technique known as brachytherapy. Brachytherapy is a medical procedure that entails the placement of a radioactive source either directly or near the cancer cells in order to eradicate them. The radioisotope is commonly employed in brachytherapy applications because of its favorable characteristics, including a half-life of 74 days and medium-energy gamma radiation [84,85]. Ir-192 is placed into the tumor via a tiny capsule or needle, allowing radiation to be administered directly to the tumor cells. By employing this approach, the impact on healthy tissues is minimized, leading to enhanced therapy efficacy. The utilization of pinhole cameras in real-time monitoring systems has facilitated the visualization of Ir-192 radiation sources during therapy, enhancing treatment accuracy and patient safety [86]. Precise tracking of the position and duration of Ir-192 during high-dose-rate (HDR) brachytherapy is crucial for accurately administering radiation to tumors, underscoring its significance in cancer treatment [87]. A comparative analysis assessed the treatment results of Co-60 and Ir-192 sources in HDR brachytherapy for cervical cancer. This emphasizes the extensive utilization of Ir-192 due to its efficacy and lower dimensions. In addition, research has enhanced quality assurance procedures in radiotherapy by examining the dosimetric precision of film dosimetry systems for Ir-192 brachytherapy sources [88].

Gallium-67 (Ga-67) is employed to diagnose infections and inflammations. It is employed for diagnostic purposes in some types of cancer and particular illnesses. It is utilized in nuclear medicine and molecular imaging to assist in identifying and assessing lymphoma by its capacity to gather in active lymphoma cells [89]. Gallium-67 scintigraphy has been recognized in the field of oncology for its exceptional capacity to offer valuable insights into tumor viability, treatment response, and tumor differentiation. It also serves as a therapeutic agent in diagnosing and treating cancer patients. The significance of Ga-67 scintigraphy in clinical decision making has been well established [90,91]. Furthermore, Ga-67 scintigraphy is valuable for identifying ongoing inflammation and aids in diagnosing and monitoring several inflammatory disorders [92].

Tracking nuclear materials is crucial for both domestic and global security. Tracking these substances is crucial for upholding nuclear nonproliferation, environmental safety, and medical safety regulations. Nuclear material tracking employs sophisticated equipment and comprehensive reporting systems. The approaches encompass radiation monitoring, physical containment, electronic monitoring, and worldwide auditing and reporting. Radiological tracking is a technique that consistently measures the position and amount of radioactive substances. Typically, this monitoring is conducted using portal monitors and hand detectors. These devices are utilized at entrance locations such as borders and airports and play a crucial role in identifying and preventing the illicit transportation of radioactive materials. Furthermore, environmental radiation monitors play a crucial role in safeguarding the environment by promptly detecting any leaks or unusual occurrences in the vicinity of nuclear sites. Physical containment refers to safeguarding nuclear items to prevent unauthorized physical access. This is accomplished through intricate security mechanisms and stringent access controls. Surveillance cameras, intrusion detection systems, and multiple layers of security obstacles are employed. Electronic surveillance systems, such as GPS tracking systems and sensor networks, monitor and safeguard nuclear items during transportation and storage. The International Atomic Energy Agency (IAEA) and similar organizations carry out regular inspections and employ reporting systems to ensure that nuclear materials are utilized in compliance with international norms.

In this study, the studies in the literature will be examined in general, and the existing literature focused on nuclear material tracking with blockchain technology will be synthesized. It will contribute to the determination of future research topics. If there is a gap

in the literature, this will be determined, and a modeling method on this subject will be presented. We believe this will be a guiding study for authors studying the researched topic. We aim to provide the current state of nuclear material tracking with blockchain technology. For this purpose, a scoping review was conducted focusing on the determined research questions (RQ):

RQ1: Which nuclear materials are tracked with blockchain technology?
RQ2: By what methods are nuclear materials tracked using blockchain technology?
RQ3: What advantages can blockchain offer compared to traditional methods of tracking nuclear material?
RQ4: How can a blockchain-based tracking system increase reliability in trading nuclear materials?
RQ5: What is blockchain's impact on security and privacy issues in nuclear material tracking?
RQ6: How can a blockchain-based system help track nuclear materials and reduce losses and leaks in the supply chain?
RQ7: How can the use of blockchain in tracking nuclear material contribute to nuclear nonproliferation efforts?
RQ8: What challenges might applications of blockchain technology on nuclear material tracking face?
RQ9: How can a blockchain-based nuclear material tracking system comply with international nuclear safety standards and increase interstate cooperation?
RQ10: What role could blockchain technology's impact on nuclear material tracking play in implementing international nuclear agreements?

2. Methodology

Utilizing blockchain technology has immense promise in tracking and tracing nuclear materials, particularly in safeguarding data integrity and ensuring a transparent record of their movement. This technology enhances global security and attempts to prevent the spread of nuclear weapons by offering transparency, secure data management, adherence to international regulations, resistance to tampering with smart contracts, and ensuring the integrity of nuclear material management systems. Implementing blockchain technology in tracking nuclear materials can effectively address the security and record-keeping challenges faced in these domains. Blockchain, a technology that shows great potential for tracking nuclear energy components with significant value and consumption costs, is a viable subject for research and development in this industry.

2.1. Research Method

The framework created by Arskey and O'Malley [93] was used for this scoping review. For this study, searches were conducted for the research questions using Google Scholar, Scopus, and Web of Science (WoS) databases in April 2024. The Google Scholar database is a broad and easily accessible research engine and was chosen because it offers information from a wide range of disciplines and sources. The Web of Science is a multidisciplinary database chosen because it offers high-quality and comprehensive research in the sciences, arts, social sciences, and humanities. Scopus is a comprehensive database containing citation information and abstracts across various disciplines. ScienceDirect provides comprehensive and detailed information in the fields of science, technology, medicine, and social sciences. ProQuest facilitates users' research and learning by offering a diverse range of databases and tools tailored for academic, business, government, and public libraries. Engineering Village is a comprehensive research platform that specifically focuses on engineering and technical subjects. The search strategies applied are given in Table 1. In order to include similar studies, the words and word groups "radioactive", "radioisotope", and "nuclear fuel", which indicate nuclear materials, were also included for detailed search. Since the intended results could not be achieved with the search method among the given years, the search method was expanded and applied to all years. When we look at past and

present studies, it is observed that no study has been conducted on this subject. The fact that nuclear material cannot be tracked using blockchain methods shows that an area that can be studied in the literature has been opened (RQ1, RQ2).

Table 1. Search strategies in databases.

Database	Search Strategy
Google Scholar	all: nuclear material tracking OR traceability with blockchain technology "radioactive" OR "radioisotope" OR "nuclear fuel" "nuclear material"
Web of Science	((ALL = (nuclear material tracking)) AND ALL = (blockchain)) AND ALL = (("radioactive" OR "radioisotope" OR "nuclear fuel"))
Scopus	ALL ("nuclear material") AND ("tracking" OR "traceability") AND ("blockchain") AND ("radioactive" OR "radioisotope" OR "nuclear fuel") AND PUBYEAR > 2019 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, "ar"))
ScienceDirect	"nuclear material" AND ("tracking" OR "traceability") AND "blockchain" AND ("radioactive" OR "radioisotope" OR "nuclear fuel") AND PUBYEAR > 2019 AND PUBYEAR < 2025
ProQuest	"nuclear material tracking" OR "radioisotope tracking" OR "nuclear fuel tracking" OR "radioactive material tracking" AND "blockchain"
Engineering Village	("nuclear material") AND ("tracking" OR "traceability") AND ("blockchain") AND ("radioactive" OR "radioisotope" OR "nuclear fuel")

2.2. Inclusion and Exclusion Criteria

Only articles were searched for the scoping review to prove this gap in the literature. Book chapters and abstract papers were not included in the search. The research was conducted for the period between January 2020 and April 2024. The search was conducted only on studies whose language was English. As stated before, there has been no study on tracking nuclear and radioactive materials used in different areas using blockchain technologies.

Tracing nuclear material is very sensitive and crucial, serving as a critical element of national and international security. Conventional approaches employ systems that rely on paperwork and physical monitoring to handle this operation, which can be susceptible to security and efficiency issues. The implementation of blockchain technology has the potential to introduce substantial advancements in monitoring and control procedures within this domain. Blockchain's decentralized structure, transparency, and immutable record capabilities can greatly aid in preventing tampering, safeguarding data integrity, and enhancing interprocess cooperation in monitoring nuclear materials. Contrary to central databases in conventional approaches, blockchain guarantees that transactions and records are recorded in a manner that cannot be changed. This promotes the comprehensive tracking of the whole path of nuclear materials from their origin to the point of use. This technology provides robust encryption and ensures the integrity of data. Every block is connected to the previous block by cryptographic means. By employing this method, efforts to control and penetrate the system are rendered more arduous. The decentralized structure of the system mitigates the chance of failure resulting from a single component. Compared to traditional systems, it provides the potential for automation, allowing transactions to be carried out automatically when specific circumstances are satisfied. Streamlining the number of agents and control points in conventional systems can enhance efficiency by minimizing expenses and manual procedures. These opportunities enable the implementation of security protocols with greater effectiveness. The advantages provided by blockchain could have a significant impact on influencing the future of nuclear material tracking (RQ3). Furthermore, the blockchain system will document every stage of the nuclear material tracking process, guaranteeing that all material transfers, beginning from its origin, are meticulously recorded. By implementing this approach, every transaction may be readily subjected to auditing, ensuring that crucial details such as the origin, recipient, and date of material acquisition are consistently accessible. The encryption of recorded data in immutable blocks added to the chain guarantees their dependability. By eradicating

fraudulent activities, the occurrence of human errors and interventions can be averted. Blockchain technology enables efficient and safe data sharing among regulatory bodies across several countries, facilitating trading nuclear materials. An unbroken tracing line will be established on the blockchain, a powerful tool to prevent illicit trade or material loss. This technology will enhance transparency and resistance to manipulation during the verification and recording of transactions. These characteristics will enhance the security and dependability of nuclear material commerce, reducing risks in the sector. They will also address the needs of both trading parties and regulatory bodies. Furthermore, the fact that it is accessible to the public may result in transaction history and other data being viewable to a broad spectrum of people. In this context, it is necessary to strike a balance between the security benefits offered by transparency and the necessity for confidentiality in order to safeguard sensitive information. Confidentiality can be safeguarded by implementing access control systems that restrict access to specific information to only authorized individuals. To enhance data confidentiality, privacy rules can be enforced with security measures by implementing cryptographic techniques, such as zero-knowledge proofs. Attaining the equilibrium between privacy and security is crucial for efficiently utilizing technology (RQ4, RQ5).

Blockchain technology will enhance the secure and efficient administration of nuclear materials, hence minimizing losses and leaks in the supply chain. Blockchain technology provides the potential to meticulously document every step of the process, from production to the final consumers. Every transaction on the blockchain is logged with a timestamp, and these records are publicly visible, ensuring complete traceability. Any abnormal situations can be quickly detected, reported, and addressed with real-time data by identifying the responsible parties. Immutable records are created because the processes conducted are known sequentially. This capability enables precise identification of the most recent secure position of the substance in situations involving loss or leakage. This promotes responsibility and the expectation of being answerable for one's actions. Furthermore, smart contracts executed on the blockchain will have the capability to guarantee the automatic enforcement of specific criteria across the whole supply chain, ensuring that nuclear materials are transported in strict adherence to established protocols and legal laws. This approach aims to prevent the transportation and unauthorized deployment of nuclear weapons. Cryptographic security measures will safeguard against external intrusions and unlawful entry. Integrating blockchain technology into various technical solutions has streamlined audit processes, ensuring seamless coordination between nuclear material tracking, data management systems, and logistical software. Expediting the approval and recording of transactions would enhance efficiency and coordination across the whole supply chain, reducing costs. Since the records are easily available and subject to scrutiny by international auditors and regulatory authorities, any anomalies or irregularities can be promptly identified, allowing for appropriate actions to be taken. Adhering to this approach guarantees the lawful and secure transportation of materials without including illicit substances or engaging in smuggling activities. This facilitates the more efficient enforcement of international standards and treaties aimed at curbing the illicit spread of nuclear weapons (RQ6, RQ7).

Despite the numerous advantages outlined in utilizing blockchain technology for tracking nuclear material, it also presents certain challenges. These growing problems can pressure the technology's efficient implementation and widespread adoption. Technical skills and expertise are necessary for the installation and management of it. Integrating with preexisting supply chain systems can pose challenges, particularly when dealing with antiquated and conventional systems. In order to properly utilize blockchain technology, all players must possess a comprehensive understanding of the technology and be able to adjust to these novel systems. As the number of transactions increases, blockchain networks may encounter performance problems. In the context of extensive nuclear supply chains that require rapid processing of numerous transactions, the speed and cost of blockchain technology can pose a notable concern. The transparency of information in these

systems can provide a drawback when handling sensitive data, such as nuclear material. Privacy protection may require the use of additional cryptographic mechanisms and access constraints. Certain blockchain solutions, particularly those that rely on mining, may necessitate substantial energy consumption. This can result in environmental sustainability concerns. While blockchain ensures data immutability, it is essential that the data being added to the blockchain are correct and trustworthy from the outset. Inputting inaccurate or insufficient data into the system can result in misleading outcomes and erroneous judgments. Significant modifications may be necessary to ensure that workflows can adjust to this new technology, particularly in complicated and regulated procedures such as nuclear material tracking. Developing, implementing, and maintaining models with this technology may incur substantial expenditures. Due to the nascent nature of blockchain technology, the absence of widely recognized standards and protocols can pose challenges in achieving cross-application compatibility. Standardizing interaction and data exchange between different blockchain systems is crucial in domains of global significance, such as nuclear material tracking. Nuclear material tracking is governed by stringent rules at both national and international levels. Blockchain technology may face challenges in adhering to these standards and operating under legal systems. Moreover, the level of technology acceptability and legislative frameworks can differ among countries, posing challenges to international collaboration. To address these difficulties, it is necessary to implement organizational and legislative measures in order to establish suitable solutions. Advancements and guidelines in these domains can optimize the potential of blockchain technology in tracking nuclear materials (RQ8).

A nuclear material tracking system that utilizes blockchain technology leverages the critical attributes of blockchain to adhere to global nuclear safety regulations. By leveraging the distinctive attributes of blockchain technology, the management of nuclear materials can be guaranteed to be secure and transparent. International auditors and authorized parties in the blockchain system will have continuous visibility into material movements and access to this data, guaranteeing precision and transparency. Smart contracts will be used to implement international security restrictions. The presence of an immutable record for any modification performed on the blockchain enables a constant and immediate chance for auditing. Blockchain technology can be developed to adhere to international nuclear safety and control laws. This entails organizing the blockchain by the guidelines and regulations established by agencies like the International Atomic Energy Agency (IAEA). The system can be configured to automatically enforce these restrictions, ensuring that every transaction and recording complies with international law. When designing blockchain systems, adhering to international legal and ethical norms is crucial. Furthermore, regularly revising international standards will guarantee coherence among various nations and organizations. Implementing backup protocols for blockchain systems and incorporating contingency plans safeguards against data loss and system failures in the context of nuclear material tracking. Blockchain technologies enable multinational cooperation by easing data exchange among nations and organizations. This collaboration guarantees the efficient execution of global security protocols and standards. Enhancing the capacity of blockchain systems to store and archive data over extended periods is crucial for complying with international regulatory standards. This guarantees the preservation of historical data and ensures that governments have continuous access to precise information, particularly in fields like long-term nuclear waste management and control. Interstate collaboration can be enhanced by implementing safe data control and sharing measures. Blockchain technologies facilitate international cooperation among regulatory bodies from various nations. This technology enables data exchange and coordination among several authorities, promoting cooperation on shared standards and protocols. The Non-Proliferation Treaty (NPT), Comprehensive Nuclear-Test-Ban Treaty (CTBT), International Atomic Energy Agency (IAEA) Assurance Agreements, and Nuclear Security Summits are examples of agreements and rules that safeguard international collaboration. The NPT is a treaty designed to inhibit the spread of nuclear weapons [94]. The pact mandates that non-nuclear-weapon nations are

prohibited from developing nuclear weapons, while nuclear-weapon states are required to make progress toward disarmament. The Comprehensive Nuclear Test Ban Treaty (CTBT) seeks to prohibit all types of nuclear testing [95]. This treaty enforces a comprehensive prohibition on nuclear detonation testing to thwart the proliferation of nuclear armaments and constrain the enhancement of current weaponry. The International Atomic Energy Agency (IAEA) functions as a global platform for advancing the nonmilitary application of nuclear energy and overseeing the utilization of nuclear materials [96]. The Nuclear Security Summits [97], initiated in 2010 and ongoing, aim to enhance global collaboration in nuclear material security and counterterrorism efforts. The implementation of a nuclear material tracking system utilizing blockchain technology will enable effective intervention and minimize the utilization of dirty weapons, commonly known as dirty bombs. These weapons are typically created by combining radioactive materials with conventional explosives and have been a subject of significant concern in recent years. These explosives are created by mixing them with radioactive elements like uranium, plutonium, or other radioactive isotopes that are manufactured for medical and industrial purposes. If a dirty bomb is detonated, the initial consequences involve injuries caused by the explosion, heat burns, and contamination with radioactive materials. The emission of radioactive materials can result in extensive contamination and possible health hazards, impacting large regions for extended durations [98]. The initial detonation disperses radioactive substances throughout the surrounding surroundings. Radioactive emissions result in widespread radioactive pollution, although radiation levels typically do not pose a serious threat. The explosion has the potential to harm structures and individuals directly. Individuals who have been affected by radiation may experience several types of injuries, such as acute radiation sickness, skin burns, and internal contamination resulting from inhaling or ingesting radioactive particles [99]. For instance, introducing a contaminated weapon into a water source will result in the dissemination of pollutants across the whole drinking water supply, impacting all individuals, flora, fauna, and other organisms that rely on that water. This is reminiscent of a biological weapon. Including radioactive material in everyday garbage harms individuals who come into contact with recycling and waste disposal. Over time, the dispersion of radioactive substances in the environment might result in persistent pollution and pose enduring health hazards. The utilization of dirty weapons may also give rise to psychological consequences, leading to broad social turmoil and terror. Effective communication tactics customized for various demographics, particularly those with low literacy levels, can enhance public comprehension of the hazards linked to radiological terrorism and promote adherence to prescribed measures [100]. Decontaminating soiled portions of a firearm will require significant time and financial resources. This will have a detrimental impact on the country's economy. Dirty weapons are often weapons designed for utilization by terrorist organizations to instill widespread terror and destabilize economic and social structures. Due to the availability of some radioactive elements for medicinal or industrial purposes, accessing these materials may be quite straightforward. Implementing blockchain technology to track nuclear items can effectively mitigate the risk of unauthorized access, ensuring international dependability and safeguarding the safety of both citizens and visitors. The detection and regulation of radioactive materials are crucial security measures in mitigating the risk of dirty bomb threats. By implementing blockchain technology, the risk of radioactive materials being stolen and utilized to create dirty bombs will be greatly diminished. This will be achieved by establishing a new system that is more transparent and dependable than conventional methods. Furthermore, the entire transportation process will be closely monitored, from waste disposal to waste control. While dirty weapons may not be as devastating as nuclear weapons, they are nonetheless regarded as a significant menace because of the enduring health and environmental consequences caused by radiation (RQ9, RQ10).

Due to the essential reasons and critical results mentioned above regarding nuclear materials and radioactive substances, a model that can be used for a blockchain-based nuclear material tracking system will be presented in the Section 3.

3. Results and Discussion

Article searches were carried out after the search method and inclusion and exclusion criteria were determined. As a result, five results were obtained from Google Scholar [101–105], three results were obtained from the Scopus database [102,106,107], and one result was obtained from the Web of Science database [108]. The other searched databases found no results related to the research subject. When these results obtained from the advanced search were examined, it was seen that none of the articles was related to this subject. When viewed in this context, there appears to be a gap in the literature on nuclear material tracking with blockchain technology.

The research findings, as outlined in the methodology section, demonstrate that blockchain technology, commonly employed in various domains such as monitoring food products like grain and tracking high-value jewelry transportation, can prove highly advantageous and effective in the tracking of nuclear materials. Therefore, we believe that the development of a model for the transportation and tracking of nuclear and radioactive materials, particularly those employed in the healthcare sector, can have significant benefits at both the national and international levels.

There are many studies on sample materials that are as important as nuclear and radioactive materials and whose monitoring is critical both nationally and internationally. These studies encompass the surveillance of grain and oily food supply chains, implementing ethical hunting techniques, and transporting fresh products within the food sector [109,110]. Additionally, they involve monitoring product sustainability information and verifying authenticity for luxury fashion brands within the clothing industry [111]. Furthermore, efforts are made to prevent the circulation of counterfeit medicines in the pharmaceutical industry [112]. Moreover, the tracking of digital IDs and service histories for automobiles [113] and the transportation of delicate and sensitive electronic components for high-tech products are also examined [114]. Within jewelry extraction and development, key practices encompass verifying the ethical origins of jewelry, safeguarding it, overseeing the production process, and tracing its ownership history [115]. When the sample products are tracked, it is seen that blockchain is used to track all products due to its different features. Here, an importance ranking can be made according to the desired features. Thanks to this, similar blockchain structures can be created by finding the most similar product to nuclear materials. First of all, when we look at technological devices, their prices seem high. However, blockchain is used in this sector to monitor the production and distribution processes and ensure quality control. Afterward, when we look at the automobiles, it can be seen that the blockchain structure is used due to the high possibility of fraud. When the clothing industry is examined similarly, it aims to see a transparent supply chain by verifying the product's authenticity. The pharmaceutical/medicine industry and food are vital for human health, and preventing fraud and distributing faulty/defective products are among the primary goals in these sectors. The purpose of distributing jewelry does not serve a single purpose. In addition to preventing counterfeiting, ethical source control and ownership history are very important. In addition, their originality is also essential, and they are precious from the moment they first appear. The graph that can be drawn according to the order of importance based on these features is presented in Figure 3.

Given the examples provided, it is reasonable to develop a model using blockchain technology to track high-value materials such as jewels and diamonds. These materials require careful transportation and have strict regulations. Therefore, it is logical to create a blockchain-based model that ensures both financial security and minimizes degradation and sensitivity. This paper presents the overall design of a radioactive material tracking system that can be developed.

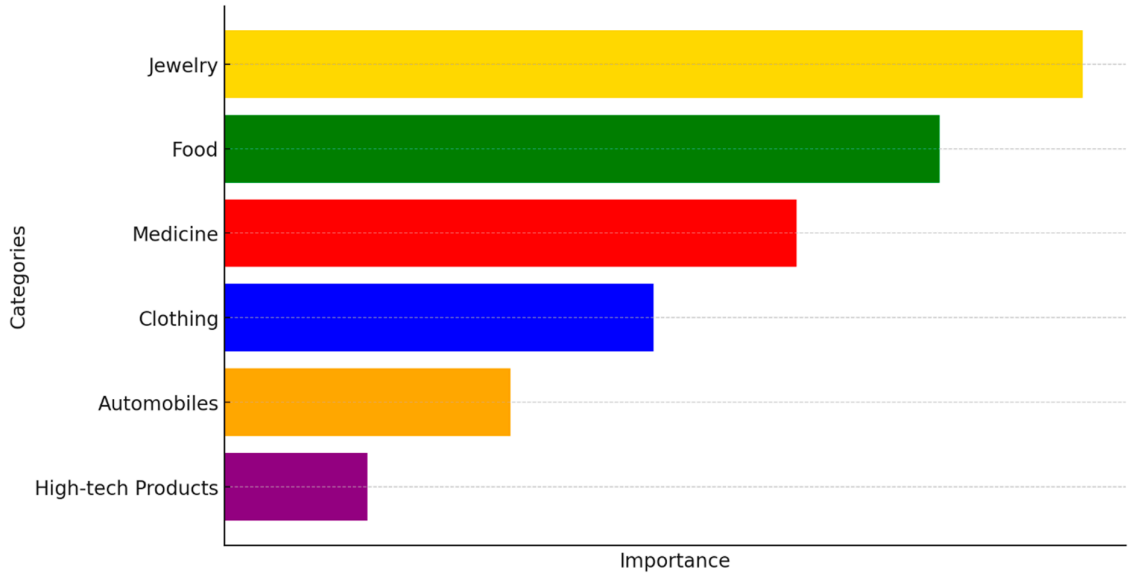


Figure 3. Importance of tracking materials using blockchain.

The primary objective of utilizing blockchain for jewelry and diamond tracking is to accurately monitor the origin, possession, and transportation of jewels across the supply chain. Tracking applications for diamonds and jewelry, which monitor the entire supply chain from mine to sale, encourage ethical practices through transparent recording systems [116–118]. This approach often relies on a set of fundamental procedures. Firstly, digital certification ensures that the origin of every diamond is digitally verified, beginning from its mining location. The initial entry is recorded on the blockchain when diamonds are extracted from the earth. The attributes of the diamond (cut, color, clarity, carat) are then documented on the blockchain, resulting in the establishment of a digital identity associated with these data. During the subsequent phase, diamonds and stones are meticulously documented on the blockchain alongside every transaction. The operations encompassed in this scope are mining, shipping, processing, certification, and sale. Diamond certification bodies assess and validate diamonds, with the resulting data recorded on the blockchain. The blockchain records wholesalers' and retailers' buy and sale transactions during the sales process. By employing smart contracts at every stage, the fulfillment of specific requirements is automatically validated, and these transactions are then appended to the chain. Upon the ultimate consumer's purchase, the blockchain is updated with the final buyer's information. During these transactions, various parties include miners who extract the mineral and perform the initial registration, processors who refine the diamond, certifying bodies, distributors and retailers, and, ultimately, the end customers. The procedure consistently leverages blockchain's immutability, security, and transparency attributes. Furthermore, due to the implementation of a time stamp at every stage, the precise date and time of the transaction are recorded and preserved. During the operation of institutions, all participants in the supply chain are linked to the blockchain network and contribute their transactions to this network. Given the meticulous and efficient nature of the transportation procedure, we believe that employing the blockchain system for tracking nuclear material would be a natural and practical approach.

In order to achieve this objective, we propose the utilization of blockchain technology to create a nuclear material tracking system with the following characteristics: The primary objective of the initial model under development is to effectively and reliably oversee the sourcing, ownership, and transportation of nuclear materials across the complete supply chain while ensuring their security. The origins of radioactive material undergo digital certification at the point of extraction or production. Subsequently, the attributes of the radioactive material, such as quantity, level of purity, kind, and other relevant details, are documented on the blockchain. Through this procedure, a digital identity is generated

for the nuclear material. A record is created on the blockchain when nuclear materials are extracted, generated, processed, and refined. The blockchain also includes the assessment and certification of materials by certification authorities and the purchase and sale transactions conducted by wholesalers and power plants. Additionally, it incorporates information about end users. Every transaction is autonomously checked and appended to the blockchain upon confirmation. The system's reliability is enhanced by implementing automated transactions and verification processes. Throughout this procedure, various entities participate, including individuals responsible for extracting and documenting nuclear materials, facilities involved in processing and purifying nuclear materials, organizations responsible for inspecting the safety and appropriateness of nuclear materials and those operating power plant facilities, and, ultimately, the ultimate purchasers, such as energy companies or government institutions. Once the nuclear materials are transferred to the end user, the blockchain system records the duration of their presence within the user or organization to ensure the continuous availability of information. There are several reasons why the diamond tracking model with blockchain technology cannot be directly applied to nuclear material tracking. For diamond tracking, which is the basis, tracking of diamond material can be started directly as soon as it is mined, but not all nuclear materials can be tracked directly. The tracking process begins after some nuclear materials are enriched or given nuclear properties. In addition, the physical probability of diamonds disappearing on Earth is 0%. Nevertheless, nuclear materials possess a finite lifespan. The attached timestamp will provide data regarding the duration of usability of the materials. Consistently monitoring nuclear material in storage regions with a limited half-life and securely storing this information using blockchain technology will be crucial for effectively managing long-term security and environmental hazards. Half-life is the period required for the quantity of a radioactive isotope to fall by half of its initial amount. This phenomenon takes place via a natural occurrence known as radioactive decay. Every nuclear isotope has a distinct half-life. Understanding the concept of half-life is crucial for comprehending the gradual decrease in the activity of radioactive substances over time and determining the necessary safety measures and storage conditions for these chemicals in the long run [119]. The system will incorporate each nuclear material's half-life and life cycle as a feature during blockchain certification, and this information will be actively monitored. Transportation procedures for radioactive material nearing expiration or not being utilized will be consistently documented on the blockchain until proper waste disposal is conducted. By following this approach, waste tracking can be effectively put into practice. The capacity to effectively monitor nuclear material approaching the end of its useful life will greatly diminish the potential for the development of weapons that are contaminated or harmful. Software integrated into the blockchain will effectively manage half-life processes. During this procedure, nuclear materials that have reached the end of their half-life will be eliminated from the blockchain model, transferred to storage, and kept from being used ineffectively, thereby avoiding any drawbacks. Implementing this system will guarantee that data regarding all stages, from the origin of nuclear materials to their ultimate utilization, are meticulously documented in a safe and immutable way. Furthermore, the utilization of blockchain's decentralized ledger technology will provide immediate data accessibility for all pertinent participants, eliminating the necessity for involvement from central authorities. This will provide significant advancements, particularly in identifying security breaches and detecting illicit movements of materials. Nevertheless, the obstacles in using a blockchain-powered tracking system encompass exorbitant transaction expenses and apprehensions regarding data confidentiality. Nevertheless, these challenges can be surmounted gradually with the advancement of technology and the implementation of more streamlined blockchain protocols. Utilizing blockchain technology for nuclear material tracking might be a groundbreaking innovation in managing nuclear materials, as it enhances security and transparency standards. The initial organizational chart of the model planned to be created is presented in Figure 4.

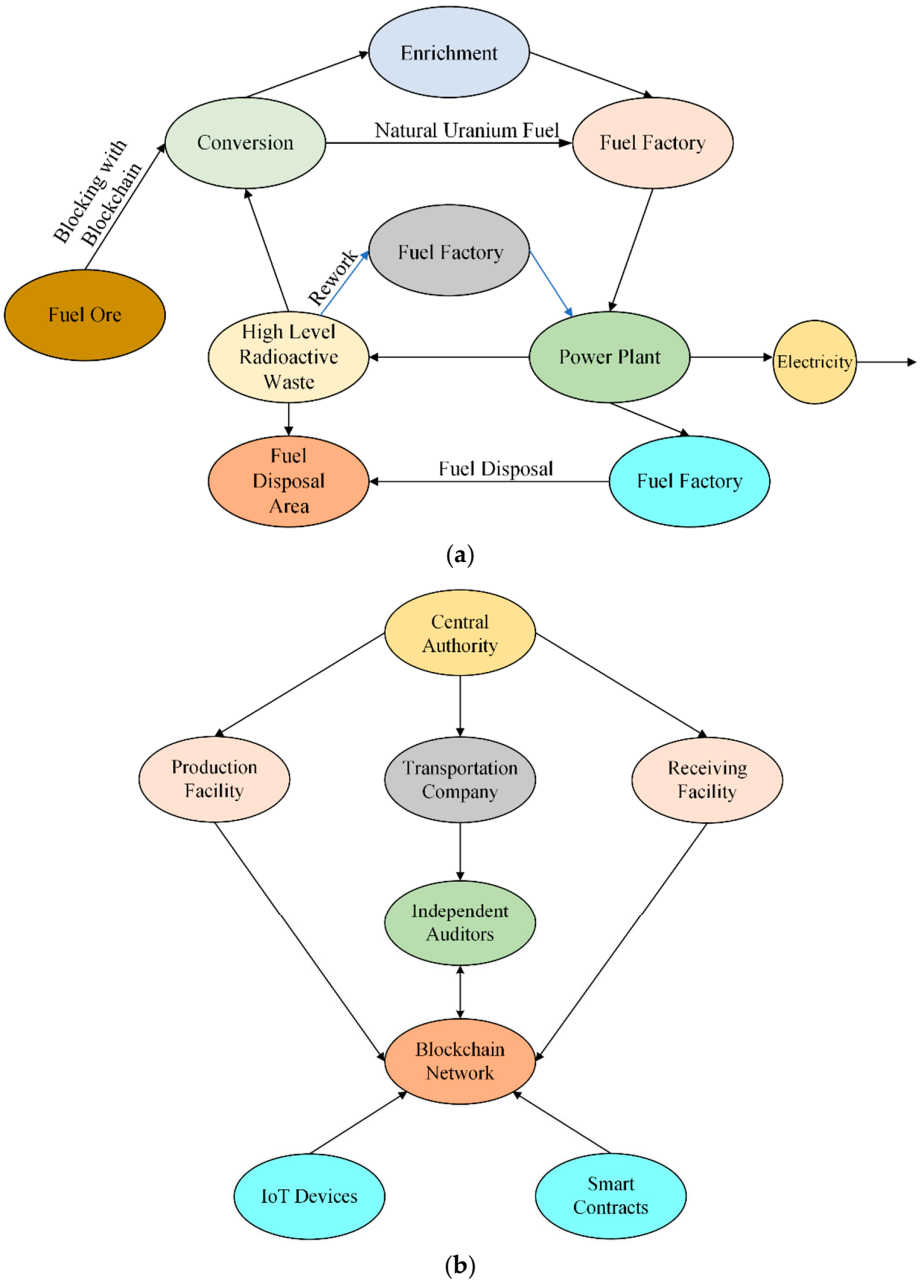


Figure 4. (**a**) Preprocessing of nuclear material and waste fuel. (**b**) Organizational diagram for nuclear material tracking using blockchain.

Figure 4 presents the first organizational chart of the model planned to be created. It is divided into two parts: part a, preprocessing of nuclear material and waste fuel; and part b, organizational diagram for nuclear material tracking using blockchain.

The nuclear fuel cycle is given in Figure 4a. Here, after the fuel ore is blocked with blockchain technology, processing, conversion, and enrichment operations are carried out. All transactions in this process are recorded in the blockchain. After the enrichment process, electricity is produced from the ores brought to the fuel factory. In this process, high-level radioactive waste left over from the power plant is sent to the fuel disposal area and destroyed there. In order to reprocess high-level radioactive waste, it is sent back to the fuel factory, and operations continue in a small cycle within the larger cycle.

Figure 4b shows the path followed with the final product obtained due to the previous processes (electricity is an example here). Figure 4b shows that the central authority is the designated entity responsible for making decisions about tasks and transactions. This

section does not pertain to the blockchain's architecture but serves as a depiction of the operational aspect of the concept. This is the first phase of the procedure that guarantees the retrieval of nuclear material, its certification, and inspection. Furthermore, this division is responsible for establishing policies and implementing overall control. Production facilities store data about the manufacturing and packaging of nuclear material. In this context, the blockchain is utilized to store and track production data, while smart contracts are generated to ensure the traceability of materials. Transportation companies transporting nuclear materials maintain a constant stream of data to the blockchain by gathering information using GPS, sensors, and IoT devices during transit. Throughout the transit process, materials are meticulously monitored, and all movements are documented on the blockchain. Receiving facilities, such as nuclear power plants and government institutions, utilize blockchain technology to verify deliveries and record material consumption information. Independent auditors regularly audit the complete established process and blockchain records. By utilizing the analysis of the records, they will provide a report.

Blockchain technology can be an effective tool for tracking and safeguarding nuclear materials. Primarily, nondigital material should be incorporated into the blockchain. Lack of digital availability can impede the process of tracking and verifying material. Blockchain technology can establish a connection between the physical and digital realms. Initially, through physical tagging, radioactive materials can be affixed with RFID tags or QR codes with distinct identifying numbers. Each movement or transaction of the substance is meticulously scanned and logged on the blockchain using these tags. Integrating IoT devices makes it possible to continually monitor the location, condition, and environmental factors of materials using IoT sensors. The data gathered by these sensors are immediately transferred to the blockchain. Authorized people can manually input nondigital data onto the blockchain using manual inputs. These procedures are facilitated by verification and auditing protocols.

Blockchain technology offers various features to prevent fraud and counterfeit critical nuclear materials. The crucial aspect at this juncture is that the data stored in the blockchain, which consist of unalterable records, cannot be modified subsequently. This guarantees the honesty and dependability of the data. Furthermore, with cryptographic verification, every transaction undergoes verification through cryptographic signing. This ensures that only individuals with proper authorization can make modifications. Furthermore, smart contracts are generated and autonomously execute transactions upon fulfilling specific circumstances. This reduces the occurrence of human mistakes and the need for human involvement.

Blockchain technology can enhance the physical security of nuclear materials by integrating physical and digital safeguards. There is a suggestion that this assembly should be divided into multiple stages. It is possible to achieve real-time materials tracking through IoT sensors and GPS devices by utilizing first-stage real-time monitoring. The integration of these data into the blockchain enables immediate tracking. The blockchain can effectively prevent illegal access by implementing a second stage known as access control, which determines the individuals or entities permitted to access particular data. When paired with physical security measures, this offers robust protection. By utilizing the third step, one can develop systematic audits and frequently examine the data stored in the blockchain to detect any irregularities or breaches in security. Using these stages, blockchain technology has been developed into a robust tool for securely and transparently tracking and controlling nuclear materials. Establishing a connection between the physical and digital realms can thwart fraudulent activities and seamlessly integrate with existing physical security measures. These suggestions would increase the efficient integration of blockchain technology in the nuclear sector.

Blockchain technology enhances the traceability of nuclear materials in the energy sector by documenting their travels in a transparent and unchangeable manner. This measure aids in deterring illegal commerce and reducing potential security weaknesses. Smart contract integration streamlines supply chain operations by automating procedures,

minimizing the need for manual intervention and enhancing operational efficiency. This enables the Ministry of Energy to optimize the utilization of its resources at a national level. The implementation of automated transaction recording enables adherence to regulatory requirements and expedites the auditing procedures. This facilitates the more efficient fulfillment of regulatory obligations in the energy industry. Furthermore, the ability to monitor nuclear materials in real time allows for swift and immediate action in emergency scenarios. The energy ministry has the ability to promptly respond to potential security breaches. The generated concept offers numerous benefits in terms of both health and energy efficiency. Efficient monitoring of nuclear materials aids in mitigating radiation hazards and safeguarding public wellbeing. The health ministry should adopt a more proactive approach to prevent any radiation breaches. Blockchain technology enhances the safety of tracking radioisotopes employed in medical applications. It facilitates the secure and transparent sharing of medical data, hence enhancing patient safety and elevating the quality of healthcare. Blockchain-based solutions offer immediate and precise information to the Ministry of Health in the event of potential nuclear accidents or radiation leakage. This facilitates swift crisis management and safeguards public health.

4. Conclusions

Blockchain technology, being a decentralized ledger system, allows for secure data storage and sharing without relying on a central authority. Every block in the blockchain contains a sequence of transactions, and these blocks are interconnected using cryptographic techniques to create a chain. This architecture guarantees that data are stored in a way that cannot be changed and are easily visible. This scoping review aimed to investigate the application of blockchain technology in tracking radioactive materials from the past to the present. However, no studies have been conducted on this specific subject thus far. Upon reviewing the available research on this topic, it was determined that the utilization of technology will lead to substantial advancements in the management of nuclear materials, primarily due to the enhanced security and transparency it offers. The immutability and traceability aspects of blockchain will help prevent unlawful activities by reducing security vulnerabilities in the transit and storage of nuclear items. Moreover, the incorporation of smart contracts enables the enhancement of operational efficiency through the automation of supply chain activities. As the authors, we assert that our research fills a vacuum in the literature on nuclear material tracking utilizing blockchain technology by presenting a highly useable model that incorporates the basic stages of a practical blockchain model. The proposed methodology was developed by analyzing previously published studies on radioactive material tracking and integrating the characteristics of blockchain technology. This study is crucial at both national and international levels due to the necessity of international tracking of nuclear materials in addition to national efforts. To foster international trade, nations must cultivate mutual trust. Implementing the blockchain model, which is capable of tracking nuclear materials, will yield substantial revenues for authorities in the commercial, energy, and healthcare sectors. The broad applicability of the blockchain model could facilitate the improvement of global standards and enhance international cooperation in the domain of nuclear material safety. This model will enable the implementation of measures to prevent the use of dirty bombs and thwart the efforts of dangerous individuals. The objective is to alleviate societal concerns over nuclear materials by implementing a technologically advanced and dependable transportation system. The future implementation of blockchain technology will enhance the effectiveness and reliability of nuclear security measures.

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