Ann PUBLISHER Journal Engineering Sciences (Improsci)
e-ISSN 3031-7088
p-ISSN 3032-3452

Utilization of Nuclear Technology in Supply Chains: A Review of the Literature

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Abstract
Background. Nuclear technology has strategic potential to enhance the safety, quality, traceability, and resilience of modern supply chains. However, existing studies remain fragmented across industrial sectors, highlighting the need for an integrative synthesis of its contributions to supply chain management.
Aims. This study aims to identify, classify, and analyze nuclear technology applications across supply chain activities, focusing on their potential benefits, implementation challenges, and relevance to Indonesia.
Methods. We conducted a narrative literature review using a targeted literature search and thematic synthesis of scientific publications and reports from national and international institutions published between 2014 and 2025.
Result. The findings identify six major application domains: (1) food irradiation to improve food safety and extend product shelf life; (2) isotope analysis for product traceability and authenticity verification; (3) radioisotope tracers for industrial process monitoring and energy supply chains; (4) non-destructive testing to maintain logistics infrastructure integrity; (5) radiation sterilization in pharmaceutical and healthcare supply chains; and (6) radiation detection technologies to strengthen international trade security. The synthesis indicates that these applications can potentially support quality assurance, risk mitigation, and operational reliability. Nevertheless, implementation remains constrained by investment costs, infrastructure limitations, workforce competencies, radiation safety regulations, and public acceptance. The study's conceptual contribution lies in integrating six nuclear technology application domains into a cross-sectoral supply chain management perspective.
Conclusion. The findings suggest that nuclear technology could strengthen the competitiveness of Indonesian supply chains, provided that cross-sector collaboration, regulatory frameworks, and empirical assessments of operational performance are further developed.

Keywords: nuclear, technology, food irradiation, product traceability, supply chain.

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INTRODUCTION

A supply *chain* is an integrated system that involves various organizations, resources, activities, and processes to produce and distribute products from raw material suppliers to end consumers. In the development of the global economy, supply chain management is no longer solely oriented towards cost efficiency and speed of distribution, but also includes product safety, traceability, infrastructure integrity, operational sustainability, and the ability to deal with various risks and uncertainties. Chopra and Meindl (2016) emphasized that the effectiveness of supply chain management is determined by the ability to integrate strategies, planning, and operations to create value and increase competitiveness. Therefore, technological transformation is one of the strategic needs in the development of modern supply chains.

One of the technologies that has the potential to support this transformation is nuclear technology. Although it has been more associated with energy generation and defense applications, nuclear technology has a much wider spectrum of uses, especially in the food, health, manufacturing, energy, and international trade security sectors. Peaceful *uses of nuclear technology* include food irradiation, isotope analysis, radiotracer use, *non-destructive testing*, radiation sterilization, and radioactive material detection systems. These applications offer measurement, quality control, preservation, and detection capabilities that can support the reliability of production and distribution activities (FAO & IAEA, 2024; World Nuclear Association, t.t.).

In the food sector, irradiation is one of the applications of nuclear technology that has been used to improve product safety, control pathogenic microorganisms, reduce post-harvest damage, and extend the shelf life of certain commodities. This technology has the potential to support the efficiency of food distribution, especially in supply chains that have long delivery distances and require consistent quality control. FAO and IAEA (2024) emphasized the importance of nuclear engineering in supporting scientific evidence-based food safety standards. In addition, the IAEA (2018) developed an isotope analysis approach to improve traceability and verification of the origin of food products, so that it can help detect counterfeits, increase trade transparency, and strengthen consumer confidence.

The use of nuclear technology is also growing in the industrial and health sectors. The use of radioisotopes as tracers allows for fluid flow monitoring, leak identification, and evaluation of industrial process performance, especially in the oil and gas industry. Meanwhile, industrial

radiography allows the examination of material and infrastructure integrity without damaging the components being tested (World Nuclear Association, t.t.). In the pharmaceutical sector, Hasanain et al. (2014) examined the use of gamma radiation for the sterilization of pharmaceutical active ingredients, excipients, and drug products. Bhatia and Pillai (2022) also reviewed the potential of ionizing radiation in vaccine development. These findings show that nuclear technology has relevance at various stages of the supply chain, ranging from raw material processing, process control, quality assurance, to product readiness for distribution.

From the perspective of global trade security, nuclear detection technology has an important role in monitoring the movement of goods through ports, logistics terminals, and border areas. IAEA (2020) developed a collaborative research project on the use of nuclear detection technology to support safe and secure trade. This approach is geared towards improving the ability to identify radiological and nuclear threats while maintaining the smooth flow of legitimate trade. Thus, nuclear technology not only serves as an instrument for processing and testing products, but also as part of the international supply chain risk control and security system.

State of the Art. Previous studies have shown that the use of nuclear technology has developed in various fields with relatively specific research focuses. Hasanain et al. (2014) focused on the sterilization of pharmaceutical products, while Bhatia and Pillai (2022) discussed ionizing radiation technology in vaccine development. IAEA (2018) emphasized the application of nuclear engineering for food traceability, while IAEA (2020) reviewed nuclear detection systems to support trade security. FAO and IAEA (2024) highlighted the contribution of nuclear engineering to food standards and safety. On the other hand, Wahyuni and Arfidhila (2019) discussed the importance of traceability in the halal food supply chain. The literature shows that various technologies already have functions and benefits that are relevant to supply chain activities, but the discussion tends to be oriented to specific sectors, technologies, or applications.

Research Gap. Based on the literature reviewed, there is a need to integrate findings on the application of nuclear technology into a more comprehensive perspective of supply chain management. First, discussions about nuclear technology are still scattered in the fields of food, pharmaceuticals, energy, industry, and trade security, so that the relationship between technology functions and supply chain stages has not been mapped in an integrated manner. Second, the benefits of nuclear technology are more often explained based on their technical functions, while

their relationship with supply chain performance indicators, such as operational efficiency, product loss reduction, traceability, infrastructure integrity, and risk mitigation, still requires further synthesis. Third, the challenges of nuclear technology implementation that include investment, infrastructure readiness, human resource competence, radiation safety regulations, and public acceptance need to be analyzed within the framework of cross-sectoral implementation. Fourth, in the Indonesian context, the relationship between the development of nuclear technology and the need to improve the competitiveness of the national supply chain still requires a more structured study, including the opportunity for its integration with digital traceability systems.

The urgency of this study is increasingly relevant for Indonesia as a country that has agriculture, food, energy, manufacturing, and trade sectors with diverse supply chain characteristics. Loss of post-harvest products, the need to improve food safety, quality control of export products, and the reliability of distribution infrastructure are problems that can be areas of application of nuclear technology. The National Research and Innovation Agency (BRIN) has encouraged the development of food irradiation technology through the National Program for Safe Food Radiation (Radiana) as one of the efforts to extend the shelf life of agricultural products and reduce food loss (Irfan, 2025). However, the use of this technology still faces challenges related to the availability of facilities, implementation costs, regulatory readiness, and public perception. This condition shows the need for an approach that not only considers technical feasibility, but also the suitability of technology with the needs and characteristics of the national supply chain system.

Novelty. The conceptual novelty offered by this article lies in the preparation of a cross-sectoral synthesis of the use of nuclear technology based on its functions and contributions to the supply chain management system. Different from studies that focus on specific technical applications, this study groups the use of nuclear technology into six main domains, namely (1) food irradiation for food safety and security, (2) isotope techniques for product traceability and verification, (3) radioisotopes as a tracker in industrial processes and energy supply chains, (4) non-destructive testing to ensure infrastructure integrity, (5) radiation sterilization in pharmaceutical and health supply chains, and (6) radiation detection technology to support global trade security. The six domains are analyzed in relation to supply chain activities, potential operational benefits, implementation challenges, and their relevance to supply chain development

in Indonesia. This novelty is integrative and conceptual, not in the form of the development of new nuclear technology or empirical proof of improving supply chain performance.

Based on this background, this study aims to identify, classify, and synthesize the use of nuclear technology in various supply chain sectors through a narrative literature review approach with thematic synthesis. In particular, the research is directed to (1) map the form of application of nuclear technology at various stages and functions of the supply chain; (2) analyze its potential contribution to safety, quality, traceability, efficiency, and operational resilience; (3) identify supporting factors and obstacles to implementation; and (4) formulate implications and directions for further research relevant to the development of national supply chains. The results of the study are expected to provide a conceptual foundation for academics, industry players, and policymakers in evaluating opportunities for the safe, effective, and sustainable use of nuclear technology.

METHODS

This study uses a narrative literature review approach with a thematic search and synthesis strategy. Source search was carried out on scientific databases and portals such as ScienceDirect, PubMed, Frontiers, the official website of the International Atomic Energy Agency (IAEA), Food and Agriculture Organization (FAO), the World Nuclear Association, the national scientific conference portal (Talenta Conference Series), as well as official news of national research institutions (ANTARA News) as a source of contextual information about implementation in Indonesia.

The search keywords used included a combination of terms such as "nuclear technology supply chain", "food irradiation traceability", "radioisotope tracer industry", "non-destructive testing radiography", "gamma sterilization pharmaceutical", "nuclear security detection technology", as well as Indonesian equivalents such as "supply chain nuclear technology" and "Indonesian food irradiation". The inclusion criteria included indexed scientific publications, official reports of international/national institutions, and official news articles containing data and statements from research institution officials, with a publication range of 2014 to 2025 to maintain the relevance and up-to-date of the information. The identified sources were then analyzed thematically and synthesized into several domains of the use of nuclear technology in the supply chain, as presented in the results and discussion sections.

DISCUSSION

Supply Chain and Technology Adoption Needs

An efficient and resilient supply chain requires technological support at every node, from planning, procurement, production, to distribution (Chopra & Meindl, 2016). The complexity of global supply chains—involving various countries, regulations, and quality standards—demands the availability of instruments capable of ensuring product safety, the authenticity of goods origin, the integrity of logistics infrastructure, and the monitoring of cross-border goods traffic. It is in this context that nuclear technology finds its relevance, as the principles of nuclear physics such as ionizing radiation and radioisotope decay offer measurement, detection, and sterilization capabilities that are difficult to replace with conventional technologies.

Food Irradiation for Food Security and Security

One of the most mature applications of nuclear technology in the supply chain is food irradiation, which is the process of exposing food products to X-rays, electron beams, or gamma rays to ensure food safety, control spoilage and post-harvest pests, meet phytosanitary requirements, and eliminate foodborne pathogens such as bacteria (IAEA, n.d.). This technique has been regulated and used commercially in many countries, with the Codex Alimentarius Commission—established by FAO and WHO in 1963—serving as a harmonious reference for international food standards (IAEA, n.d.).

FAO and IAEA (2024) affirm that nuclear engineering is an important instrument in measuring, managing, and controlling food safety while complementing the One Health approach in agricultural systems. Through the FAO/IAEA Joint Centre for Nuclear Engineering in Food and Agriculture, which has been established since 1964, the two institutions coordinate more than 25 collaborative research projects annually involving more than 400 international research institutions, as well as support around 200 national and regional technical cooperation projects annually (FAO & IAEA, 2024).

In Indonesia, the National Research and Innovation Agency (BRIN) through the Nuclear Energy Research Organization (ORTN) is encouraging the use of irradiation technology to reduce

national food loss which reaches around 50 million tons per year with a loss value of around Rp500 trillion (Irfan, 2025). Irradiation technology is considered to be able to extend the shelf life of agricultural products without lowering nutritional value, leaving no chemical residues, and can be applied to heat-sensitive products after packaging (Irfan, 2025). More than 60 countries have used this technology, and irradiated tropical fruit products are considered safer and more environmentally friendly than chemical fumigation (Irfan, 2025). To accelerate its adoption, BRIN initiated the National Program for Safe Food Radiation (Radiana) as a forum for research collaboration between the government, the private sector, and academia, with one of the development focuses in East Kalimantan (Irfan, 2025). However, the limitations of irradiation facilities, high operational and logistical costs, public perception of irradiation food safety, and the need for clearer regulation and cross-agency coordination are still the main challenges for the implementation of this technology in Indonesia (Irfan, 2025).

Isotope Techniques for Product Traceability and Verification

In addition to ensuring food safety, nuclear engineering also plays an important role in traceability and verification of product authenticity throughout the supply chain. Isotope ratio measurements can be used as a "fingerprinting" technology to trace the origin of a food product, thus helping to detect false labels and false product origin claims (IAEA, n.d.).

As a concrete form of this effort, IAEA (2018) carried out a Coordinated Research Project (CRP) entitled "Implementation of Nuclear Techniques to Improve Food Traceability" which was approved on February 7, 2018. This project aims to build reliable analytical techniques and databases to determine food provenance through isotope ratio analysis combined with multi-element analysis, with three main objectives, namely the application of analytical techniques for food traceability verification, the development of a database of isotope composition and element concentrations from authentic samples in a sustainable manner, and the development of an origin data interpretation model to verify labeling claims (IAEA, 2018). Until this project is running, at least 16 scientific publications, 24 training programs for S1 to S3 students, and 15 standard operating procedures (SOPs) have been produced in various member countries (IAEA, 2018). The IAEA (2018) emphasizes that such initiatives are important to address food fraud that threatens

food security, fair trade, consumer health, and legitimate economic sustainability, especially in developing countries.

This isotope-based traceability capability has high relevance to the need for a traceability system in the halal food supply chain, as emphasized by Wahyuni and Arfidhila (2019) in their literature review on traceability in the halal food supply chain. A credible traceability system is considered crucial to ensure the integrity of the halal status of a product throughout the supply chain, from raw materials to the final product (Wahyuni & Arfidhila, 2019). Thus, isotope techniques have the potential to be a scientific complement that strengthens the halal certification and traceability system as well as Indonesian food export certification, although the synergy between the two has not been widely explored in the national literature and is one of the research gaps that need to be followed up.

Radioisotopes as Trackers in Logistics and Oil and Gas Industry

In the industrial sector, radioisotopes are widely used as tracers to monitor fluid flow, detect leaks, and measure equipment wear (World Nuclear Association, n.d.). Because the concentration of short-lived isotopes used is very small and is detected without leaving residues in the environment, this technique is a safe and effective option, especially in the oil and gas sector to determine the area of a production field (World Nuclear Association, n.d.).

Tracer technology service providers such as Tracerco use chemical and radioisotope tracers to track the flow, presence, and behavior of liquid and gaseous fluids throughout the production process (Tracerco, n.d.). In drilling activities, smart tracers provide important insights related to fluid flow in conventional and non-conventional reservoirs, so that production performance analysis can be carried out at a lower cost than conventional logging equipment (Tracerco, n.d.). This technology is also used to monitor the condition of subsea assets, maintain pipeline integrity, ensure flow assurance, and support pipeline commissioning processes (Tracerco, n.d.). In the context of the energy supply chain, this kind of real-time monitoring capability provides important visibility into the upstream segment, helping to reduce the risk of operational disruptions and high inspection costs.

Non-Destructive Testing for Supply Chain Infrastructure Integrity

Gamma radiography allows non-destructive testing (NDT) of metal components and weld joints without damaging the object being tested. In contrast to X-ray equipment that requires a power supply and a fixed location, radioactive sources can be brought directly to the site that needs inspection (World Nuclear Association, n.d.). This technique has even been used to assess the structural integrity of post-disaster buildings, such as in the 2015 Nepal earthquake, the 2020 Beirut explosion, and the 2023 Turkey earthquake (World Nuclear Association, n.d.).

In addition to radiography, radiation-based gauging techniques also play an important role in production quality control. The IAEA estimates that there are hundreds of thousands of such measuring devices operating in various industries around the world (World Nuclear Association, n.d.). Measuring devices are still used to monitor production quality in mines, processing plants, and oil platforms, while portable measuring devices are used to measure soil compaction and asphalt density (World Nuclear Association, n.d.). Commonly used isotopes include Cobalt-60 with a half-life of 5.27 years for gamma sterilization and radiography, and Iridium-192 with a half-life of 73.8 days for detecting defects in metals (World Nuclear Association, n.d.). In the context of supply chains, these capabilities are particularly relevant to maintain the reliability of strategic logistics infrastructure such as distribution pipelines, storage tanks, ports, and warehousing facilities without having to significantly halt operations.

Radiation Sterilization in the Supply Chain of Pharmaceuticals, Medical Devices, and Vaccines

In the health supply chain, gamma radiation-based sterilization is an effective terminal sterilization method for various pharmaceutical products. Hasanain et al. (2014) explained that gamma irradiation works by breaking the chemical bonds of microorganisms so as to produce free radicals that attack the nucleic acids of these microorganisms. This method is considered to have a superior safety profile compared to conventional sterilization methods because it does not require excessive heat or exposure to toxic chemicals, and offers better sterility assurance with lower validation requirements than aseptic processing (Hasanain et al., 2014).

Its application scope includes pharmaceutical active ingredients (APIs), excipients, finished drug products, and combination products of drugs and medical devices, and has been recognized by both the European Pharmacopoeia and the United States Pharmacopoeia (Hasanain et al., 2014). However, challenges such as the loss of potential active substances, the formation of radiolysis byproducts, and the reduction in polymer molecular weight need to be considered, although they can be mitigated through dose optimization and adjustment of irradiation conditions (Hasanain et al., 2014).

The use of ionizing radiation has also begun to be developed at the upstream stage of the health supply chain, namely vaccine development. Bhatia and Pillai (2022) reviewed the use of ionizing radiation technology—including electron beams, X-rays, and gamma rays—to inactivate pathogens in the vaccine development process while maintaining an immunogenic epitope. The potential for the development of a more stable vaccine platform at room temperature through this approach can reduce dependence on cold chains, thus contributing directly to simplifying and strengthening the resilience of vaccine distribution supply chains, especially in areas with limited refrigeration infrastructure (Bhatia & Pillai, 2022).

Nuclear Security and Radiation Detection at Global Trade Nodes

In addition to acting as an enabler of production and quality, nuclear technology also contributes to maintaining the security of global supply chains from the threat of illicit circulation of radioactive materials. The IAEA (2020) initiated the Collaborative Research Project "Facilitation of Safe and Secure Trade Using Nuclear Detection Technology" which was approved on July 2, 2020 and began to be actively running on April 20, 2022 until the planned completion of July 1, 2026, involving six participating countries, namely Iran, Laos, Saudi Arabia, South Africa, Tanzania, and Vietnam.

The project aims to improve nuclear security detection systems at international trading points without hindering the smooth flow of legitimate trade, while addressing the need for detecting illicit circulation of radioactive materials and other contraband (IAEA, 2020). Development focuses include strengthening passive detection methods through radiation portal monitors to assess container load data, integrating active technologies such as X-rays and neutrons for element analysis, development of integrated systems that combine passive and active

approaches, development of algorithms and software for multi-technology data integration, and increasing understanding of legitimate radioactive goods shipping practices (IAEA, 2020). IAEA (2020) also emphasized the dual-use strategic value of this detection equipment, namely that in addition to strengthening nuclear security, the same equipment can also support the detection of explosives, narcotics, and commercial fraud at ports and other cross-border checkpoints.

The presence of radiation detection systems at these global trade nodes makes nuclear security one of the standard layers of security in the international supply chain ecosystem, on par with X-ray container scanning to detect contraband in general, but with a particular focus on radiological and nuclear threats.

Synthesis, Opportunities, and Implementation Challenges

Based on the above mapping, the use of nuclear technology in the supply chain can be synthesized into six main domains, namely: irradiation for food safety and security; isotope techniques for product traceability and authenticity; radioisotopes as traces in oil and gas industry and logistics; non-destructive tests for infrastructure integrity; radiation sterilization in health and vaccine supply chains; and radiation detection for global trade security. These six domains show that the contribution of nuclear technology to supply chains is cross-sectoral—including food, energy, health, and trade security—and operates at various stages of the supply chain, from upstream (production and raw materials) to downstream (distribution and border surveillance). Widyani et al. (2026) found that optimizing FSCM performance contributes to improving food security and food system sustainability. The established conceptual framework is anticipated to provide a foundation for subsequent empirical investigations and a guideline for creating cooperative-oriented food policy. Timotius & Hermawan (2026) identified that logistics challenges arise from internal elements (warehouse capacity, WMS systems, reliance on courier partners) and external influences (seasonal demand variability and swings in fuel prices). The enhancement plan emphasizes refining inventory management, broadening logistical collaborations, streamlining routes, and augmenting tracking visibility. Immediate suggestions encompass the evaluation of courier contracts, the creation of logistical command centers, and the implementation of consumer communication initiatives. Prolonged suggestions encompass the establishment of regional fulfillment networks, the integration of WMS-TMS-AI technologies, and

the creation of self-sustaining last-mile fleets. Kartini et al. (2026) This study's primary contribution is the establishment of a cohesive conceptual and mathematical framework that connects production line balance with supply chain efficacy via the flexible management of production intervals.

Factors driving the success of implementation identified from various sources include cross-sectoral collaboration between governments, industry, and academia (Irfan, 2025), support for international guidelines and standards from institutions such as the IAEA, FAO, and the Codex Alimentarius Commission (IAEA, n.d.; FAO & IAEA, 2024), and the harmonization of standard operational regulations and procedures (IAEA, 2018). In contrast, recurring challenges have emerged in various domains including the high investment costs of irradiation facilities and detection equipment, the limited skilled workforce in the field of nuclear engineering, the need for clear radiation safety regulations, the low perception of risk and public acceptance, as well as the challenge of integrating nuclear technology with existing digital supply chain management systems, such as blockchain-based traceability systems (Irfan, 2025; Wahyuni & Arfidhila, 2019).

In the Indonesian context, BRIN's efforts through the Radiana Program show a positive initial commitment to mainstreaming nuclear technology in the national food supply chain (Irfan, 2025). However, research that specifically measures the quantitative impact of nuclear technology on supply chain performance in Indonesia—for example, on logistics cost efficiency, food loss rates, and export competitiveness—is still very limited and is a research opportunity that needs to be pushed forward, including the potential synergy between isotope techniques and halal traceability systems (Wahyuni & Arfidhila, 2019) as well as integration with modern supply chain digital platforms.

Nuclear power is increasingly a pivotal element of clean and sustainable energy frameworks, supporting both decarbonization goals and energy security amid the global shift toward net-zero emissions. As electrification expands in sectors such as transportation, industry, and digital infrastructure, demand for dependable, low-carbon baseload power is rising. At the same time, the rapid growth of energy-intensive applications such as artificial intelligence, data centers, and advanced manufacturing is putting unprecedented pressure on electrical infrastructure, underscoring the critical importance of dispatchable, high-density energy sources. In this changing environment, nuclear energy is reemerging as a significant option. Policy shifts among leading

economies, including the United States, the European Union, and Asia, indicate a renewed recognition of nuclear energy as an essential complement to intermittent renewable resources. Aspirations to increase worldwide nuclear capacity thrice by 2050 highlight the magnitude of the impending problem. Nevertheless, this revitalized impetus also reveals inherent weaknesses within the existing nuclear fuel cycle (De Donno, 2026). Raineri et al. (2025) propose a comprehensive framework to aid less industrialized nations in the adoption of nuclear energy (NE) for peaceful applications, taking into account the associated obstacles and potential. It emphasizes the urgent requirement for sustainable and secure energy alternatives, suggesting NE as a feasible choice. The research intends to explore the technical, social, economic, regulatory, and policy dimensions of NE's evolution and its extensive uses beyond traditional power generation, including industrial processes, healthcare applications, agricultural improvements, and mining operations, specifically focusing on underdeveloped areas. Utilizing a comprehensive analysis of current methodologies, the article delineates and analyzes obstacles to NE implementation as well as approaches to alleviate these challenges. Research indicates that NE may significantly contribute to economic development and technological advancement, possibly catalyzing the formation of new industries in these nations. Nonetheless, substantial impediments—specifically governance, societal acceptance, safety, security, expertise development, and financial acquisition—present formidable difficulties. The study asserts that a systematic and coordinated implementation of NE is crucial for fostering socio-economic development and environmental sustainability in less industrialized nations. It underscores the imperative for thorough planning and global cooperation to completely realize NE's potential, promoting a diverse strategy to address the recognized challenges.

Martin and Abbt (2020) In 2018, the European Commission, through its General Directorates Joint Research Center and Energy, initiated a project titled “Modernisation and Optimization of the European Nuclear Supply Chain” to address the supply chain issues confronting European utilities and licensees of nuclear facilities, particularly nuclear power plants, including the obsolescence of structures, systems, and components (SSCs) and the challenges in sourcing new suppliers for safety-critical SSCs. This document serves as the initial project deliverable, aimed at evaluating the degree of concern among utilities and licensees in European nations with active nuclear facilities regarding supply chain difficulties, as well as the feasibility of implementing solutions that involve greater utilization of non-nuclear industry standard

components and equipment for safety-related SSCs or SSCs developed in accordance with alternative nuclear codes and standards. The substance of this study derives from responses to a survey distributed by the European. Wealer and von Hirschhausen (2020). Owing to its intricate technological nature, the dual production of electricity and nuclear armaments, together with its substantial fixed expenses, nuclear energy represents a notably complicated commodity that presents unique obstacles for governmental economic (or industrial, defense, innovation, etc.) policies. Similar to other industries, the issue of appropriately delineating private and public responsibilities emerges here as well, namely with "competition and planning," while considering knowledge factors, incentive frameworks, transaction expenses, and an equitable allocation of profits and obligations. The nuclear industry necessitates an upstream framework comprising a knowledge repository, institutional and physical infrastructure (locations, transportation, waste management, etc.), together with legal and institutional frameworks. In this manuscript, we utilize the "system good analysis" formulated by Beckers et al. (2012) and Gizzi (2016) within the nuclear power industry, delineating archetypal organizational frameworks for the value-added phases of the nuclear front-end (mining, conversion, enrichment, fuel fabrication), the construction of nuclear power facilities, decommissioning, and long-term storage, along with the pertinent interfaces among these phases. The primary objective of this overview document is to allocate responsibilities, privileges, and obligations to organizations ("stakeholders") along the many phases of the value chain and to delineate the interface issues. We employ an institutional economics framework that emphasizes the allocation choices and production interactions between public entities and private individuals. Alongside a comprehensive overview, we focus on the nuclear energy value chain's back end, including facility decommissioning and the disposal of radioactive waste in both the short and long term.

Quiroga-Barriga et al. (2025). Nuclear energy has evolved profoundly in recent decades, driven by technological advances, shifting safety imperatives, and the urgent need to address climate change. This research offers an extensive analysis of the historical progression, existing advancements, and future potential of nuclear energy as a pivotal low-carbon asset. This systematic literature review followed Kitchenham’s technique and covered peer-reviewed publications and institutional documents from 2000 to 2025. Significant developments analyzed include the implementation of Small Modular Reactors, Generation IV technology, and fusion systems, as

well as advances in safety standards, waste management, and regulatory frameworks. Comparative environmental analyses confirm nuclear power's low life-cycle CO2 emissions and high energy density compared with alternative energy sources. Nonetheless, significant obstacles persist, including high capital costs, long construction timelines, complex waste management, and public acceptance concerns. The examination highlights that nuclear energy, although not an exclusive remedy, is an essential element of a varied and sustainable energy portfolio. Effective integration will depend on flexible governance, global collaboration, and greater public involvement. The results endorse the significance of nuclear energy in meeting global decarbonization objectives, contingent on maintaining safety, fairness, and environmental stewardship.

Sustainability has become critically important in modern scientific research, especially because of its strong societal effects. In this framework, the energy sector becomes a crucial focal point. Nuclear energy emerges as a potential pathway for clean and sustainable energy; however, this claim lacks broad support. Scientific literature lacks a thorough investigation of discussions on the sustainability of nuclear energy. (Amir & Zeler, 2024).

CONCLUSION

This literature review shows that nuclear technology has a significant and multidimensional role in supporting modern supply chains, including food safety through irradiation, traceability and authenticity of products through isotope techniques, monitoring of industrial processes through radioisotope tracing, ensuring infrastructure integrity through non-destructive testing, sterilization of health products and vaccines, and global trade security through radiation detection systems. This diversity of applications confirms that nuclear technology is not just an energy issue, but a strategic cross-sector instrument for supply chain resilience and competitiveness.

In Indonesia, initiatives such as the Radiana Program initiated by BRIN are an important first step, but their implementation is still faced with challenges in infrastructure, financing, regulation, and public acceptance. Therefore, closer collaboration is needed between the government, industry, and academia, accompanied by strengthening radiation safety regulations in harmony with international standards, as well as continuous public education on the benefits and safety of nuclear technology.

This study has limitations because it is mostly sourced from international agency reports and official news, so further empirical research—both quantitative and qualitative—is needed that specifically measures the impact of the application of nuclear technology on supply chain performance indicators, such as cost efficiency, reduction of food loss, and increased export competitiveness, especially in the Indonesian context. Future research is also suggested to explore the potential of integrating isotope techniques with blockchain-based digital traceability systems to strengthen transparency and consumer trust in the supply chain of halal food and products.

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