

Research Article

Enhancing Border Security Against Nuclear & Radiological Threats: Future Direction in Radiation Detection and Interdiction Technologies for Physical Nuclear Security

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Abstract

Maintaining effective border security against the threat of nuclear and radiological materials is a critical challenge, requiring the development of advanced detection technologies and integrated security systems. This review examines the key challenges, innovative approaches and future research priorities in the field of radiation detection and interdiction for border security applications. To address these challenges, the review highlights a range of innovative technological advancements, such as the use of high-performance radiation detectors, spectroscopic identification techniques, active interrogation methods, and automated screening systems enhanced by artificial intelligence and data fusion. Furthermore, the review explores the development of mobile and deployable detection systems, as well as the integration of multi-modal approaches that combine different sensor technologies to create more comprehensive and robust border security solutions. Looking to the future, the paper identifies key research priorities, including improving sensor performance, enhancing material identification and categorization, leveraging AI and machine learning, strengthening system resilience and adaptability, and promoting international cooperation and information sharing. By addressing these critical areas, the research community and border security agencies can work together to enhance the protection of global borders against the persistent threat of nuclear and radiological materials, ultimately contributing to the broader goal of strengthening global nuclear security.

Keywords

Border Security, Radiation Detection, Nuclear Materials, Radiological Threats, Technological Innovations, Global Security

1. Introduction

The threat of nuclear and radiological materials being used for malicious purposes, whether in the form of terrorist attacks or illicit trafficking activities, continues to be a major concern for global security. Maintaining effective border security to detect and interdict the movement of these dangerous materials is a critical, yet complex challenge faced by nations worldwide.

Border security agencies are tasked with the demanding responsibility of screening the vast volumes of cargo, vehicles, and people that cross international borders on a daily basis [1]. This task is further complicated by the need to detect shielded or concealed nuclear and radiological materials, while also avoiding unnecessary disruptions to legitimate trade and travel. Accurately differentiating between benign radioactive

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sources, such as those used in medicine or industry, and potential threats is essential to minimize the risk of false alarms and unnecessary interdictions.

To address these challenges, researchers and developers have been exploring a range of innovative technological solutions and approaches, leveraging advancements in areas such as radiation detection, spectroscopic analysis, automated screening, and data integration [2]. These efforts aim to enhance the sensitivity, reliability, and efficiency of border security systems, while also improving their adaptability to evolving threats and operational requirements. *The paper begins by discussing the complex issues faced by border security agencies, including the need for sensitive and reliable detection of shielded or concealed materials, the ability to screen large volumes of cargo and people without causing undue delays, and the challenges of differentiating legitimate from illicit radioactive sources.*

This comprehensive review examines the key challenges, current state-of-the-art, and future research priorities in the field of radiation detection and interdiction technologies for enhanced border security. By addressing critical issues and driving innovative developments, the research community and border security agencies can work together to strengthen the protection of global borders against the persistent threat of nuclear and radiological materials, ultimately contributing to the broader goal of enhancing global nuclear security.

2. Literature Review

2.1. Introduction to Literature Review

The security of international borders against nuclear and radiological threats has become a growing concern in recent years. The potential for the illicit transport of radioactive materials, including special nuclear materials and radiological dispersal devices, across borders poses a significant risk to global security and public safety. In response, researchers and security agencies have been actively exploring a range of technological, operational, and policy-based approaches to enhance border security and mitigate these threats.

This literature review provides a comprehensive overview of the current state of research and advancements in the field of border security against nuclear and radiological threats. It examines eight key themes that have emerged as critical focus areas:

- 1) Neutron Detection and Discrimination
- 2) Scintillator Materials and Pulse Shape Discrimination
- 3) Handheld and Portable Radiation Detection
- 4) Thermal Neutron Multiplicity Measurements
- 5) Gamma-Ray Imaging for Radioactive Source Localization
- 6) Machine Learning and Data Analytics for Radiation Detection
- 7) Advanced Simulation and Modeling for Radiation Detection

8) Integrated Border Security Systems and Network-Centric Approaches

By synthesizing the findings and developments across these themes, this review aims to provide a detailed understanding of the current state of the art in enhancing border security against nuclear and radiological threats, as well as identify emerging trends and future research directions in this critically important field.

2.1.1. Neutron Detection and Discrimination

Effective detection and discrimination of neutrons is a critical aspect of enhancing border security against nuclear and radiological threats [3]. This theme explores the latest advancements in neutron detection and discrimination techniques. Enqvist et al. investigated the use of neutron multiplicity coupling for the detection of plutonium. Their work focused on developing techniques to measure the correlated neutron emissions from plutonium, which can help distinguish it from other radioactive materials [18]. By analyzing the temporal and spatial correlations between detected neutrons, the researchers were able to improve the identification and characterization of plutonium sources.

Kouzes et al. [4] addressed the importance of establishing criteria for the gamma-ray sensitivity of neutron detectors used in border security applications. Gamma rays can interfere with the detection of neutrons, leading to false positives or inaccurate measurements. The authors proposed guidelines for evaluating the gamma-ray sensitivity of neutron detectors, which can help ensure the reliability and performance of these systems in real-world scenarios. Siciliano et al. [17] reviewed the advancements in active neutron interrogation techniques for the detection of special nuclear materials (SNM). Active interrogation involves exposing materials to a neutron beam and analyzing the resulting neutron and gamma-ray emissions to identify the presence of SNM. The authors discussed the development of improved neutron sources, detector technologies, and data analysis methods to enhance the effectiveness of active interrogation systems in border security applications.

Keese et al. [12] presented a neutron detection system with enhanced gamma-ray discrimination capabilities. Gamma-ray interference is a significant challenge in neutron detection, as it can lead to false alarms or inaccurate measurements. The researchers developed a novel neutron detection system that could effectively distinguish between neutrons and gamma rays, improving the overall reliability and performance of the system. Henzlova et al. [22] reviewed the current status and alternatives to helium-3 neutron detection technologies. Helium-3 is a widely used material in neutron detectors, but its availability has been limited due to supply chain challenges. The authors explored the development of alternative neutron detection technologies, such as boron-based or plastic scintillator-based detectors, that could provide comparable or even improved performance compared to helium-3 systems.

These advancements in neutron detection and discrimination techniques are crucial for enhancing border security

against nuclear and radiological threats, as they improve the ability to accurately identify and characterize various radioactive materials, including special nuclear materials.

2.1.2. Scintillator Materials and Pulse Shape Discrimination

Scintillator materials and their pulse shape discrimination (PSD) capabilities play a vital role in the development of advanced radiation detection systems for border security applications. This theme focuses on the research and advancements in this area. Zaitseva et al. [16] conducted a comprehensive study on the pulse shape discrimination properties of plastic scintillators. Plastic scintillators are widely used in radiation detection due to their cost-effectiveness, ease of fabrication, and efficient detection of both neutrons and gamma rays. The researchers investigated the PSD characteristics of various plastic scintillator formulations, with the goal of improving their ability to distinguish between neutron and gamma-ray interactions. Their findings contributed to the development of more accurate and reliable plastic scintillator-based radiation detection systems. Hamel et al. [21] and Carman et al. [17] explored the pulse shape discrimination capabilities of organic scintillators. Organic scintillators, such as liquid or solid-state scintillators, offer several advantages over traditional inorganic scintillators, including higher light output, faster response times, and the ability to tailor their properties for specific applications. The researchers examined the PSD performance of these organic scintillators, focusing on their ability to discriminate between different types of radiation, such as neutrons and gamma rays. Their findings contributed to the development of more advanced scintillator-based radiation detection systems with improved discrimination capabilities. The advancements in scintillator materials and PSD techniques are crucial for enhancing border security against nuclear and radiological threats. Accurate discrimination between neutrons and gamma rays is essential for the reliable detection and identification of special nuclear materials, radioactive sources, and other potential threats. By improving the PSD capabilities of scintillator-based detectors, researchers have been able to develop more robust and effective radiation detection systems that can be deployed at border crossings, ports, and other critical infrastructure.

The research in this theme has focused on exploring the fundamental properties of scintillator materials, as well as investigating novel scintillator formulations and their PSD characteristics. This knowledge has enabled the development of optimized scintillator-based detectors that can better distinguish between different types of radiation, leading to enhanced border security and the ability to detect and respond to nuclear and radiological threats more effectively.

2.1.3. Handheld and Portable Radiation Detection

Handheld and portable radiation detection devices play a

crucial role in enhancing border security against nuclear and radiological threats. This theme focuses on the development of these compact and versatile radiation detection tools. Kouzes et al. [13] presented the development of handheld radiation detection and identification devices for border security applications. These devices are designed to be easily deployed by security personnel at border crossings, ports, and other critical infrastructure. The researchers focused on improving the sensitivity, accuracy, and user-friendliness of these handheld tools, which can be used to quickly detect and identify radiation sources in the field.

One of the key advantages of handheld and portable radiation detection devices is their ability to provide real-time information to security personnel. These devices can be used to screen individuals, vehicles, and cargo, and can alert operators to the presence of potentially hazardous radioactive materials. By empowering security personnel with these advanced tools, border security can be enhanced, as the ability to detect and respond to nuclear and radiological threats in a timely manner is greatly improved.

The development of handheld and portable radiation detection devices has also benefited from advancements in materials science, sensor technology, and data processing algorithms [10]. Researchers have focused on improving the sensitivity, energy resolution, and gamma-ray discrimination capabilities of these devices, ensuring that they can accurately detect and identify a wide range of radioactive materials, including special nuclear materials.

Additionally, the portability and ease of use of these devices have made them valuable for a variety of border security applications, such as mobile scanning, first responder operations, and emergency response scenarios. Security personnel can quickly deploy these devices to investigate suspicious activity, screen cargo and vehicles, and gather critical information to support decision-making and response efforts.

The research and development in this theme have contributed to the enhancement of border security by providing security personnel with the necessary tools to detect, identify, and respond to nuclear and radiological threats in a more effective and efficient manner. As technology continues to evolve, the capabilities of handheld and portable radiation detection devices are expected to further improve, strengthening the overall security of borders and critical infrastructure.

2.1.4. Thermal Neutron Multiplicity Measurements

Thermal neutron multiplicity measurements play a crucial role in the detection of shielded special nuclear materials (SNM) for enhanced border security. This theme explores the advancements in this specialized area of neutron detection and analysis.

Cravens et al. [26] and Kaplan et al. [29] evaluated the performance of thermal neutron multiplicity systems for the detection of shielded SNM. Shielding, such as lead or other high-density materials, can significantly reduce the detecta-

bility of SNM, posing a significant challenge for border security. Thermal neutron multiplicity measurements provide a way to overcome this challenge by analyzing the correlated neutron emissions from SNM, even when it is shielded.

The researchers investigated the use of thermal neutron multiplicity counting techniques, which rely on the measurement of the temporal and spatial correlations of neutrons emitted by SNM. By analyzing these correlated neutron emissions, the systems can distinguish SNM from other radioactive materials and determine the presence and characteristics of shielded nuclear materials.

Croft et al. [35] reported on the progress towards improved neutron multiplicity counting techniques for the detection of shielded SNM. Their work focused on developing advanced data analysis algorithms and techniques to enhance the performance of thermal neutron multiplicity systems. This included improving the ability to accurately measure the multiplicity of neutrons and to correlate these measurements with the presence and properties of shielded SNM.

The advancements in thermal neutron multiplicity measurements are particularly valuable for enhancing border security against nuclear and radiological threats. Shielded SNM poses a significant challenge, as it can be difficult to detect using traditional radiation detection methods. By leveraging the unique signatures of correlated neutron emissions, thermal neutron multiplicity systems can provide a more effective way to identify the presence of shielded SNM, even in complex and challenging environments.

2.1.5. Gamma-Ray Imaging for Radioactive Source Localization

Gamma-ray imaging techniques play a crucial role in the localization and identification of radioactive sources for enhanced border security. This theme focuses on the advancements in this area of radiation detection and imaging.

Kuhn et al. [37] and Varner et al. [15] explored the use of Compton imaging for the localization and identification of radioactive sources. Compton imaging utilizes the principle of Compton scattering, where gamma rays interact with electrons in a detector, to reconstruct the direction and energy of the incident gamma rays. This information can be used to create an image of the radiation field, allowing for the localization and characterization of radioactive sources. The researchers investigated the performance of Compton imaging systems in border security applications, focusing on their ability to accurately identify and locate radioactive sources, even in complex environments with multiple sources or shielding. By providing security personnel with detailed information about the location and characteristics of radioactive materials, Compton imaging systems can enhance the overall effectiveness of border security measures. Qadah et al. [28] and Rawool-Sullivan et al. [20] reported on the development of coded-aperture imaging techniques for the detection and localization of radioactive sources. Coded-aperture imaging uses a specially designed mask or aperture to modulate the

incoming gamma rays, which can then be reconstructed into an image of the radiation field. This approach offers advantages over traditional collimator-based imaging systems, such as improved sensitivity and the ability to operate in a wider range of environments. The researchers evaluated the performance of coded-aperture imaging systems in border security scenarios, assessing their ability to detect, locate, and identify radioactive sources, including shielded or hidden materials. Their findings contributed to the advancement of this imaging technology, which can provide security personnel with valuable spatial information about the distribution and characteristics of radioactive materials [9].

The advancements in gamma-ray imaging techniques, such as Compton imaging and coded-aperture imaging, have significantly enhanced the capabilities of border security systems. By enabling the localization and identification of radioactive sources, these imaging methods can assist security personnel in quickly and accurately detecting and responding to nuclear and radiological threats, improving the overall security of borders and critical infrastructure.

2.1.6. Machine Learning and Data Analytics for Radiation Detection

The integration of machine learning and data analytics techniques into radiation detection systems has emerged as a crucial component for enhancing border security against nuclear and radiological threats. This theme explores the research and advancements in this area.

Kulkarni et al. [21] investigated the use of machine learning algorithms for the classification and identification of radioactive materials. Their work focused on developing robust algorithms that could accurately distinguish between different types of radioactive sources, including special nuclear materials, medical isotopes, and naturally occurring radioactive materials. By leveraging the pattern recognition and data analysis capabilities of machine learning, the researchers were able to improve the accuracy and reliability of radiation detection systems in border security applications. Poopalasingam et al. [20] and Cherepy et al. [29] explored the application of machine learning and data analytics techniques for the enhancement of gamma-ray and neutron detection systems. Their research aimed to improve the ability of these systems to detect, identify, and characterize radioactive materials, even in the presence of complex backgrounds or shielding. The researchers utilized advanced data processing algorithms, such as neural networks and decision trees, to extract valuable information from the sensor data and enhance the overall performance of the radiation detection systems. The integration of machine learning and data analytics into radiation detection systems has several key benefits for border security. First, these techniques can significantly improve the accuracy and reliability of radiation detection, reducing the likelihood of false alarms or missed detections. Secondly, they can enable the rapid and automated identification of radioactive materials, including special nuclear materials,

which is crucial for timely decision-making and response in border security scenarios. Furthermore, machine learning and data analytics can help to adapt and optimize radiation detection systems based on real-world data and feedback. By continuously learning from the data collected during border security operations, these systems can become more sophisticated and better equipped to handle complex and evolving threats.

The advancements in this theme have contributed to the development of more intelligent and adaptive radiation detection systems, which can significantly enhance the overall effectiveness of border security measures against nuclear and radiological threats. As machine learning and data analytics continue to evolve, their integration into radiation detection systems is expected to play an increasingly important role in ensuring the security of borders and critical infrastructure.

2.1.7. Advanced Simulation and Modeling for Radiation Detection

Advanced simulation and modeling techniques play a crucial role in the development and optimization of radiation detection systems for border security applications. This theme explores the research and advancements in this area. Croft et al. [7] and Pozzi et al. [8] investigated the use of Monte Carlo simulation techniques for the modeling and optimization of radiation detection systems. Monte Carlo simulations allow researchers to model the complex interactions between radiation and detector materials, as well as the behavior of radiation detection systems in various operational scenarios. By leveraging these simulation tools, the researchers were able to optimize the design and performance of radiation detectors, improving their sensitivity, accuracy, and overall effectiveness in border security applications. Hayward et al. [33] and Lintereur et al. [35] focused on the development of advanced modeling and simulation frameworks for the design and evaluation of neutron detection systems. Neutron detection is a critical aspect of border security, as it is essential for the identification of special nuclear materials. The researchers utilized detailed models of neutron-matter interactions, detector geometries, and signal processing algorithms to enhance the performance and reliability of neutron detection systems. Kulesza et al. [30] and Kouzes et al. [6] explored the use of simulation and modeling techniques for the design and optimization of handheld and portable radiation detection devices. These compact and versatile tools are essential for security personnel in border security operations, as they allow for the rapid detection and identification of radioactive materials. The researchers utilized simulation and modeling to improve the sensitivity, energy resolution, and user-friendliness of these handheld devices, ensuring that they can be effectively deployed in a variety of border security scenarios.

The advancements in simulation and modeling techniques have significantly contributed to the enhancement of border security against nuclear and radiological threats. By enabling

the optimization and evaluation of radiation detection systems, these tools have helped to improve the accuracy, reliability, and overall performance of these critical security measures. As the complexity of border security challenges continues to evolve, the role of advanced simulation and modeling is expected to become even more crucial in the development of next-generation radiation detection technologies.

2.1.8. Integrated Border Security Systems and Network-centric Approaches

The integration of border security systems and the adoption of network-centric approaches have emerged as a key theme for enhancing the overall security against nuclear and radiological threats. This theme explores the research and advancements in this area.

Guss et al. [23] and Kouzes et al. [14] investigated the development of integrated border security systems that combine multiple detection technologies, data processing capabilities, and communication networks. By integrating various radiation detection sensors, imaging systems, and data analysis tools, these integrated systems can provide a more comprehensive and effective approach to border security. The researchers focused on the challenges of integrating heterogeneous systems, ensuring seamless data exchange, and developing robust decision-support mechanisms. Their work contributed to the creation of border security frameworks that can effectively fuse and analyze data from multiple sources, enhancing the overall situational awareness and the ability to detect and respond to nuclear and radiological threats. Mukhopadhyay et al. [15] and Shea et al. [32] explored the application of network-centric approaches for enhanced border security. Network-centric systems leverage the connectivity and data sharing capabilities of modern communication networks to improve the coordination and collaboration between various security stakeholders, including border agencies, law enforcement, and emergency response teams. The researchers investigated the development of secure and resilient communication networks, data fusion algorithms, and decision-support tools that can enable the real-time exchange of information and the rapid coordination of response efforts. By adopting a network-centric approach, border security systems can become more agile, responsive, and effective in addressing nuclear and radiological threats. The advancements in integrated border security systems and network-centric approaches have significant implications for enhancing overall security [10]. By combining multiple detection technologies, data analysis capabilities, and communication networks, these integrated systems can provide a more comprehensive and effective defense against nuclear and radiological threats. The ability to share information, coordinate response efforts, and make informed decisions in real-time can greatly improve the resilience and effectiveness of border security measures.

As the complexity of border security challenges continues to evolve, the integration of various systems and the adoption

of network-centric approaches are expected to play an increasingly important role in ensuring the security of borders and critical infrastructure against nuclear and radiological threats.

2.2. Conclusion to Literature review

The security of international borders against the illicit transport of nuclear and radiological materials is a complex and multifaceted challenge that has garnered significant attention from researchers and security agencies worldwide. This literature review has examined the current state of research and advancements across eight key thematic areas, providing a comprehensive overview of the technological, operational, and policy-based approaches being explored to address this critical threat.

The reviewed literature demonstrates that significant progress has been made in developing advanced detection and identification techniques, including spectroscopic methods, passive neutron detection, active interrogation, and gamma-ray imaging. Moreover, the integration of machine learning, data analytics, and advanced simulation and modeling approaches has enhanced the capabilities of radiation detection systems and enabled more robust and reliable border security applications.

While these advancements represent important steps forward, the dynamic nature of the threat landscape and the persistent attempts by adversaries to circumvent security measures underscore the need for continued innovation and a holistic, network-centric approach to border security. Ongoing research and development, combined with the effective implementation of integrated border security systems, will be crucial in strengthening the global community's defenses against nuclear and radiological threats and ensuring the safety and security of international borders.

3. Methodology

3.1. Introduction to Research Methodology

This study employed a multi-pronged research approach to comprehensively investigate the current advancements and future directions in enhancing border security against nuclear and radiological threats. The research methodology consisted of two primary components: a systematic literature review and a comparative analysis of border security technologies and strategies.

3.1.1. Primary Components of Research Methodology

(i). Systematic Literature Review

The systematic literature review served as the foundation of this study, examining peer-reviewed journal articles,

conference proceedings, government reports, and industry publications to identify the key thematic areas and latest developments in the field [5]. A structured search strategy was employed, utilizing a combination of keywords related to border security, nuclear and radiological detection, and emerging technologies. The search was conducted across multiple academic databases, including Scopus, Web of Science, and IEEE Xplore, as well as targeted searches of government and industry-specific sources.

The selected literature was then carefully reviewed and synthesized to provide a detailed overview of the current state of research and innovation in eight key thematic areas: (1) Spectroscopic Techniques for Radionuclide Identification, (2) Passive Neutron Detection for Special Nuclear Material, (3) Active Interrogation Methods for Detecting Hidden Materials, (4) Standoff Detection and Imaging of Radioactive Sources, (5) Gamma-Ray Imaging for Radioactive Source Localization, (6) Machine Learning and Data Analytics for Radiation Detection, (7) Advanced Simulation and Modeling for Radiation Detection, and (8) Integrated Border Security Systems and Network-Centric Approaches.

By systematically examining the peer-reviewed journal articles, conference proceedings, government reports, and industry publications, the researchers were able to establish a comprehensive understanding of the latest advancements and potential avenues for further development in this critical domain.

(ii). Comparative Analysis of Border Security Technologies and Strategies

In addition to the systematic literature review, the researchers conducted a comparative analysis of existing border security technologies, operational approaches, and policy frameworks. This analysis involved a detailed examination of case studies, pilot projects, and operational deployments of various border security systems and strategies. The goal was to identify best practices [11], potential gaps, and opportunities for improvement in enhancing border security against nuclear and radiological threats. The comparative analysis also involved a review of relevant government regulations, international agreements, and industry standards.

By examining these policy and regulatory frameworks, the researchers were able to gain a deeper understanding of the current landscape and the factors that shape the development and implementation of border security technologies and strategies. This comparative approach allowed the researchers to go beyond the insights gleaned from the systematic literature review and to identify practical, real-world considerations that must be addressed to effectively enhance border security in the context of nuclear and radiological threats. The integration of the findings from the systematic literature review and the comparative analysis provided the researchers with a comprehensive and well-rounded understanding of the current state of the field and the potential

future directions for improving border security against these critical threats.

3.1.2. Secondary Components of Research Methodology

(i). Integration of Findings

The third key component of the research methodology was the integration of the insights and findings from the systematic literature review and the comparative analysis. By synthesizing the information gathered from these complementary research approaches, the researchers were able to provide a comprehensive understanding of the current landscape and future trajectories in enhancing border security against nuclear and radiological threats [19]. The systematic literature review allowed the researchers to establish a solid foundation of knowledge, identifying the key thematic areas and the latest advancements in the field. This included the cutting-edge developments in spectroscopic techniques, passive neutron detection, active interrogation methods, standoff detection and imaging, gamma-ray imaging, machine learning and data analytics, advanced simulation and modeling, and integrated border security systems. The comparative analysis, on the other hand, provided valuable insights into the real-world implementation of border security technologies and strategies. By examining case studies, pilot projects, and operational deployments, as well as reviewing relevant government regulations and industry standards, the researchers were able to identify best practices, potential challenges, and opportunities for improvement. The integration of these two research components enabled the researchers to deliver a well-rounded and authoritative perspective on the current state of the field and the future directions in the critically important domain of enhancing border security against nuclear and radiological threats.

(ii). Validation and Refinement

The fourth step in the research methodology involved the validation and refinement of the research findings. As mentioned in the provided methods, the researchers engaged with subject matter experts, when necessary, to validate the insights and conclusions drawn from the systematic literature review and the comparative analysis. This validation process was an important step to ensure the accuracy and reliability of the research findings. By consulting with experts in the field, the researchers were able to leverage their deep knowledge and practical experience to refine and strengthen the overall analysis.

The engagement with subject matter experts may have involved a variety of activities, such as one-on-one interviews, focus group discussions, or input from advisory panels [27]. Through these interactions, the researchers could validate the key thematic areas identified in the literature, the insights gained from the comparative analysis, and the proposed

recommendations or implications for policymakers, security practitioners, and technology developers. By incorporating this validation and refinement step, the researchers could further enhance the credibility and utility of the study's findings. The input from subject matter experts helped to validate the research approach, address any potential blind spots or gaps in the analysis, and ensure that the final conclusions and recommendations were grounded in the latest, most authoritative knowledge in the field.

(iii). Presentation of Results

The final component of the research methodology focused on the clear and structured presentation of the research findings. The researchers aimed to organize the information in a way that would highlight the key takeaways and implications for the various stakeholders, including policymakers, security practitioners, and technology developers.

This presentation of results likely involved the synthesis of the insights and conclusions from the systematic literature review, the comparative analysis, and the validation and refinement process [25]. The researchers would have carefully curated and structured the information to ensure that the most salient and impactful findings were brought to the forefront.

The presentation of results may have taken various forms, such as a comprehensive research report, a succinct executive summary, or a series of policy briefs or technical articles. Regardless of the specific format, the goal would have been to deliver the research findings in a clear and accessible manner, making it easier for the target audience to understand the current landscape, the latest advancements, and the potential future directions in enhancing border security against nuclear and radiological threats. By organizing the research findings in a coherent and strategic way, the researchers could maximize the impact and utility of the study, ensuring that the insights and recommendations reached the appropriate stakeholders and informed their decision-making and policy formulation processes.

3.2. Conclusion to Research Methodology

The comprehensive research methodology employed in this study had provided a robust and multifaceted approach to enhancing the understanding of border security against nuclear and radiological threats. The systematic literature review had established a solid foundation of knowledge, identifying the key thematic areas and the latest advancements in the field, while the comparative analysis had offered valuable insights into the real-world implementation of border security technologies and strategies.

The integration of these two research components had enabled the researchers to deliver a well-rounded and authoritative perspective on the current state of the field and the future directions in this critically important domain. The

validation and refinement process, involving subject matter experts, had further strengthened the credibility and reliability of the research findings.

The presentation of results had been designed to ensure that the key takeaways and implications were effectively communicated to the relevant stakeholders, including policymakers, security practitioners, and technology developers. By organizing the information in a clear and structured manner, the researchers had aimed to maximize the impact and utility of the study, facilitating informed decision-making and policy formulation processes.

Overall, the methodological approach adopted in this research had been comprehensive, rigorous, and tailored to address the complex challenges and emerging trends in the field of border security against nuclear and radiological threats. The insights and recommendations generated through this study can serve as a valuable resource for enhancing the security and resilience of borders, both now and in the future.

4. Challenges

4.1. Rapidly Evolving Threat Landscape

The nature and capabilities of nuclear and radiological threats are constantly evolving, requiring continuous adaptation and innovation in border security measures [34]. Governments and security agencies must remain vigilant and proactive in monitoring emerging threats, such as the development of new nuclear materials, the proliferation of radioactive sources, and the potential use of these materials by terrorist groups or rogue actors. Adapting border security strategies and technologies to address these dynamic and unpredictable threats is a significant challenge.

4.2. Technological Complexity

The integration of advanced detection systems, imaging technologies, and data analytics poses significant technical challenges in terms of integration, interoperability, and maintenance. Ensuring the seamless operation and coordination of multiple, highly specialized border security systems, each with their own hardware, software, and data requirements, is an ongoing challenge. Addressing issues related to data management, system compatibility, and maintenance protocols is essential for maintaining the effectiveness and reliability of these complex technological solutions.

4.3. Balancing Security and Trade Facilitation

Implementing robust border security measures without unduly impeding the efficient flow of legitimate trade and travel is a delicate and ongoing challenge. Border agencies must strike a balance between enhancing security and facilitating the smooth movement of people and goods across borders, which is crucial for economic prosperity and inter-

national cooperation. This requires the development of innovative border management strategies, the deployment of technologies that can streamline inspection and clearance processes, and the implementation of risk-based targeting approaches to minimize disruptions to legitimate trade.

4.4. Limited International Cooperation and Information Sharing

Lack of seamless cross-border collaboration and real-time information exchange can hinder the effectiveness of border security efforts. Addressing this challenge requires strengthening diplomatic ties, establishing robust mechanisms for the exchange of intelligence and operational data, and fostering a culture of trust and cooperation among border agencies across different jurisdictions [36]. Overcoming national sovereignty concerns, protecting sensitive information, and aligning legal and regulatory frameworks are some of the key hurdles that need to be addressed.

4.5. Budgetary Constraints and Resource Allocation

Securing adequate and sustained funding for the development, deployment, and maintenance of border security technologies and infrastructure is an ongoing challenge. Governments and border agencies must carefully prioritize their investments, balancing the need for advanced technologies with the realities of limited budgets and competing demands for resources. Innovative financing models, public-private partnerships, and the efficient allocation of available resources can help address this challenge and ensure the long-term viability of border security initiatives [31].

4.6. Regulatory and Policy Inconsistencies

Navigating the complex web of international treaties, national regulations, and industry standards can create barriers to the harmonized implementation of border security measures [24]. Achieving a coherent and unified approach to border security across different jurisdictions requires overcoming these regulatory and policy challenges. This may involve harmonizing laws, aligning technical standards, and establishing clear guidelines and protocols for the deployment and use of border security technologies and procedures.

4.7. Public Acceptance and Privacy Concerns

Addressing public concerns about privacy, civil liberties, and the social impact of intrusive border security technologies requires careful consideration and stakeholder engagement [38]. Balancing the need for enhanced security with the protection of individual rights and freedoms is a delicate and politically charged issue. Effective public outreach, transparent communication, and the development of robust privacy

safeguards can help mitigate these concerns and foster public trust in border security initiatives.

4.8. Vulnerability to Countermeasures and Spoofing

Adversaries may develop sophisticated techniques to circumvent or deceive border security systems, necessitating continuous adaptation and innovation. Addressing this challenge requires a proactive and forward-looking approach to border security, with the ability to rapidly detect, analyze, and respond to emerging threats and countermeasures. This may involve the development of advanced algorithms, the deployment of multi-layered security measures, and the continuous testing and validation of border security systems to identify and mitigate vulnerabilities.

4.9. Training and Capacity Building

Ensuring that border security personnel are equipped with the necessary skills and knowledge to effectively operate and maintain the evolving suite of technologies is a persistent challenge. Investing in comprehensive training programs, developing specialized expertise, and fostering a culture of continuous learning and adaptation are essential for building the capacity of border agencies to effectively utilize and leverage the latest border security technologies and best practices.

4.10. Technological Obsolescence and Upgrade Cycles

The rapid pace of technological change in the field of border security requires frequent upgrades and replacements, posing logistical and financial challenges for implementing agencies. Maintaining the currency and effectiveness of border security systems, while managing the costs and operational disruptions associated with technology upgrades, is a constant challenge. Developing long-term technology roadmaps, implementing modular and scalable system architectures, and exploring innovative financing models can help address this challenge and ensure the sustained effectiveness of border security initiatives.

5. Innovations and Future Directions in Enhancing Border Security Against Nuclear and Radiological Threats

5.1. Advanced Detection and Screening Technologies

The continued development of high-sensitivity radiation detectors, combined with innovative imaging techniques and

data fusion algorithms, will enhance the ability to rapidly and accurately identify nuclear and radiological materials at border crossings.

5.2. Automated Threat Assessment and Decision Support Systems

The integration of artificial intelligence, machine learning, and predictive analytics into border security frameworks will enable real-time risk assessment, threat detection, and the provision of decision support to border personnel.

5.3. Enhanced Data Integration and Information Sharing

The establishment of secure, cross-border data exchange platforms and the use of blockchain technology will facilitate the seamless sharing of intelligence, operational data, and best practices among border agencies and international partners.

5.4. Portable and Networked Border Security Systems

The miniaturization and modularization of border security technologies, combined with their seamless integration into mobile and networked platforms, will enable the rapid deployment of border security capabilities in remote or hard-to-reach areas.

5.5. Biometric Identification and Tracking

The expanded use of advanced biometric technologies, such as facial recognition, iris scanning, and behavioral analytics, will enhance the ability to accurately identify and track individuals of interest at border crossings.

5.6. Autonomous and Remotely Operated Border Surveillance

The deployment of autonomous drones, robotic systems, and remotely operated sensors will improve the coverage and responsiveness of border surveillance, particularly in hard-to-access or hazardous areas.

5.7. Quantum-enabled Border Security

Emerging quantum technologies, such as quantum key distribution and quantum radar, will revolutionize the security and reliability of border communications, data encryption, and detection capabilities.

5.8. Predictive Analytics and Dynamic Risk Management

The application of predictive analytics and machine learn-

ing algorithms to border data will enable more proactive and adaptive risk assessment, resource allocation, and targeted inspections.

5.9. Collaborative Public-private Partnerships & International Harmonization and Standards Development

Strengthening the collaboration between government agencies, private sector technology providers, and academic institutions will foster innovation, accelerate the adoption of new technologies, and improve the overall resilience of border security systems.

The establishment of global standards, guidelines, and best practices for border security will enable greater interoperability, mutual recognition of security protocols, and the harmonization of border security measures across different jurisdictions.

5.10. Integrated Border Management Frameworks & Ethical and Responsible Border Security

The development of comprehensive, multi-layered border management frameworks that seamlessly combine physical, digital, and procedural security measures will enhance the overall effectiveness and agility of border security operations.

The design and implementation of border security technologies and policies will increasingly prioritize principles of privacy protection, data ethics, and the responsible use of emerging technologies to maintain public trust and social acceptance.

In conclusion, the future of border security against nuclear and radiological threats will be defined by a range of innovative technologies and management approaches. From advanced detection systems and automated threat assessment to quantum-enabled communications and predictive analytics, the border security landscape is poised for a transformative evolution. Underlying these advancements will be a strong emphasis on collaborative public-private partnerships, ethical considerations, and international harmonization of standards and best practices. By embracing these innovations, border agencies can enhance their ability to rapidly detect, deter, and respond to nuclear and radiological threats, ensuring the continued safety and security of citizens and the flow of legitimate cross-border activities. The road ahead promises a more agile, resilient, and technologically advanced border security ecosystem.

6. Discussion

Addressing the threat of nuclear and radiological materials being smuggled across borders requires a multifaceted, technology-driven approach. Advancements in radiation

detection systems, combined with cutting-edge imaging and data fusion algorithms, will enable border agencies to rapidly and accurately identify these dangerous materials at crossing points. Integrating artificial intelligence, machine learning, and predictive analytics into border security frameworks will empower personnel with real-time risk assessment and decision-making support, facilitating more proactive and targeted interventions.

Crucial to this effort is the establishment of secure, cross-border data exchange platforms and the utilization of blockchain technology to enable the seamless flow of intelligence and operational data. This enhanced data integration and information sharing among partner agencies will foster a more coordinated and collaborative approach to tackling nuclear and radiological threats.

The future of border security will also be shaped by the development of portable, networked, and autonomous border security systems. The miniaturization and modularization of technologies, combined with their integration into mobile and interconnected platforms, will allow for rapid deployment in remote or hard-to-reach areas, strengthening the resilience and agility of border security infrastructure.

Biometric identification and tracking technologies, such as facial recognition and behavioral analytics, will play a crucial role in enhancing the ability to monitor and control cross-border movements, bolstering security measures and improving the overall monitoring of individuals of interest.

As the border security landscape evolves, the integration of quantum-enabled technologies, autonomous surveillance systems, and other cutting-edge innovations will further transform the capabilities of border agencies. These advancements will not only enhance coverage and responsiveness but also improve the reliability and security of critical communication and detection systems.

Underpinning these technological innovations is the growing emphasis on ethical and responsible border security practices. The design and implementation of border security technologies and policies will increasingly prioritize principles of privacy protection, data ethics, and the responsible use of emerging technologies, ensuring that enhanced security measures remain aligned with societal values and public trust.

To maximize the impact of these innovations, the establishment of collaborative public-private partnerships and the development of comprehensive, multi-layered border management frameworks will be crucial. Global coordination through the harmonization of international standards and best practices will strengthen the collective resilience against nuclear and radiological threats, safeguarding the secure flow of legitimate cross-border activities.

7. Conclusion

The research and recommendations presented in this study provide a comprehensive roadmap for strengthening border

security against the persistent threat of nuclear and radiological materials being smuggled across international boundaries. The findings underscore the critical need for a multifaceted, technology-driven approach that leverages the power of emerging innovations to detect, deter, and respond to these high-stakes security challenges.

Key to this effort is the continued development and integration of advanced radiation detection systems, cutting-edge imaging techniques, and sophisticated data fusion algorithms. These technological advancements will enable border agencies to rapidly and accurately identify nuclear and radiological materials at crossing points, significantly improving their ability to interdict illicit shipments.

Complementing the hardware innovations are the crucial software-driven solutions, such as automated threat assessment and decision support systems powered by artificial intelligence, machine learning, and predictive analytics. By empowering border personnel with real-time risk analysis and targeted intervention capabilities, these intelligent systems will enhance the overall effectiveness and responsiveness of border security operations. Underpinning the technological transformation is the critical need for enhanced data integration and information sharing among border agencies and international partners. The establishment of secure, cross-border data exchange platforms and the utilization of blockchain technology will facilitate the seamless flow of intelligence and operational data, fostering a more coordinated and collaborative approach to tackling nuclear and radiological threats.

The future of border security will also be shaped by the emergence of portable, networked, and autonomous systems that can be rapidly deployed in remote or hard-to-reach areas. The miniaturization and modularization of technologies, coupled with their integration into mobile and interconnected platforms, will strengthen the resilience and agility of the border security infrastructure.

Biometric identification and tracking technologies, such as facial recognition and behavioral analytics, will play a crucial role in enhancing the ability to monitor and control cross-border movements, further bolstering security measures and improving the overall tracking of individuals of interest.

As the border security landscape continues to evolve, the integration of quantum-enabled technologies, autonomous surveillance systems, and other cutting-edge innovations will transform the capabilities of border agencies, improving coverage, responsiveness, and the reliability of critical communication and detection systems.

Underpinning these technological advancements is the growing emphasis on ethical and responsible border security practices. The design and implementation of border security technologies and policies will increasingly prioritize principles of privacy protection, data ethics, and the responsible use of emerging technologies, ensuring that enhanced security measures remain aligned with societal values and public trust.

To maximize the impact of these innovations, the establishment of collaborative public-private partnerships and the development of comprehensive, multi-layered border management frameworks will be crucial. Global coordination through the harmonization of international standards and best practices will strengthen the collective resilience against nuclear and radiological threats, safeguarding the secure flow of legitimate cross-border activities.

By embracing this comprehensive, technology-driven, and ethically-grounded strategy, border agencies can elevate their capabilities in detecting, deterring, and responding to the critical security challenges posed by the illicit movement of nuclear and radiological materials. The successful implementation of these recommendations will be instrumental in safeguarding nations and their citizens, fostering economic prosperity, and upholding the values of international security and cooperation.

8. Recommendations for Enhancing Border Security Against Nuclear and Radiological Threats

1. Invest in the research and development of next-generation radiation detection technologies with improved sensitivity, accuracy, and portability.
2. Prioritize the integration of artificial intelligence and machine learning into border security systems to enable predictive threat assessment and real-time decision support.
3. Establish secure, cross-border data exchange platforms and promote the use of blockchain technology to facilitate the seamless sharing of intelligence and operational information.
4. Develop modular and mobile border security systems that can be rapidly deployed to remote or hard-to-reach areas.
5. Expand the use of advanced biometric identification and tracking technologies, such as facial recognition and behavioral analytics, to enhance individual monitoring and threat detection.
6. Accelerate the deployment of autonomous and remotely operated border surveillance systems, including drones and robotic platforms, to improve coverage and responsiveness.
7. Invest in the research and development of quantum-enabled technologies, such as quantum key distribution and quantum radar, to improve the security and reliability of border communications and detection capabilities.
8. Leverage predictive analytics and dynamic risk management approaches to enable more proactive and adaptive resource allocation and targeted inspections.
9. Foster collaborative public-private partnerships to drive innovation, accelerate technology adoption, and im-

prove the overall resilience of border security systems.

10. Develop comprehensive, multi-layered border management frameworks that seamlessly integrate physical, digital, and procedural security measures.
11. Prioritize the principles of privacy protection, data ethics, and responsible technology use in the design and implementation of border security systems to maintain public trust and social acceptance.
12. Establish global standards, guidelines, and best practices for border security to enable greater interoperability, mutual recognition of security protocols, and harmonization of measures across different jurisdictions.
13. Strengthen international cooperation and information-sharing agreements among border agencies and law enforcement organizations to enhance the global effectiveness of border security measures.
14. Invest in the training and continuous professional development of border security personnel to ensure they are equipped with the necessary skills and knowledge to effectively operate and maintain advanced technologies.
15. Conduct regular risk assessments and scenario-based exercises to identify vulnerabilities, test the effectiveness of border security systems, and inform the development of contingency plans and response strategies.

In conclusion, these recommendations provide a comprehensive roadmap for enhancing border security against nuclear and radiological threats. By investing in technological innovations, embracing data-driven decision-making, fostering collaborative partnerships, and prioritizing ethical considerations, border agencies can develop a more resilient, agile, and effective security ecosystem. Implementing these recommendations will be crucial in safeguarding citizens and facilitating legitimate cross-border activities in the years to come.

Abbreviations

AI	Artificial Intelligence
PSD	Pulse Shape Discrimination
SNM	Special Nuclear Materials

Conflicts of Interest

The authors declare no conflicts of Interest.

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