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LITERATURE REVIEW ON RECENT TECHNOLOGICAL METHODOLOGIES IN DETECTION AND IDENTIFYING CBRN AGENTS

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ABSTRACT
The necessity of identifying and detecting Chemical, Biological, Radiological, and Nuclear (CBRN) agents has increased in recent years, as their detection is critical to addressing increasing global security threats. Advances in technology, the rise of bioterrorism, and the development of sophisticated weaponry have spurred the need for innovative detection methods. This paper reviews recent progress in CBRN detection, emphasizing the integration of advanced technologies such as ion mobility spectrometry, hyperspectral imaging, and biosensors. The role of nanotechnology in enhancing sensor sensitivity and decontamination processes is also investigated. A Web of Science analysis reveals a substantial surge in research activity after 2015, largely driven by global crises such as the Syrian Civil War, the COVID-19 pandemic and rising geopolitical tensions. The paper emphasizes the multidisciplinary approach to CBRN detection, incorporating fields such as analytical chemistry, nanoscience, and engineering.

KEYWORDS: CBRN agents, detection, identification, spectrometry, Web of Science

1. Introduction

In the contemporary geopolitical landscape, the identification and detection of CBRN agents has become a matter of paramount importance considering the growing number of global threats. Advancements in technology, the emergence of bioterrorism, and the ongoing development of sophisticated weaponry have underscored the imperative for innovative methods to safeguard civilian and military populations. This multidisciplinary field integrates analytical chemistry, remote sensing, and biosensors to address the challenges posed by CBRN substances. Recent studies demonstrate an increasing reliance on advanced technologies, including for:

- Chemical agents: ion mobility spectrometry, hyperspectral imaging, and nanomaterials, to enhance detection capabilities in a variety of environments. Examples of detection techniques include the following: Gas chromatography-mass spectrometry (GC-MS) for detection of chemical warfare agents (Niessen, 2001), ion mobility spectrometry (IMS) for detecting toxic gases (Eiceman & Karpas, 2005), surface-enhanced Raman spectroscopy (SERS) (Hakonen et al., 2025) for molecular identification, and chemical hot aerosol research tool (CHART) system for detector evaluation against toxic chemical aerosols (Duran et al., 2024).

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●Biological agents: biosensors for pathogen identification (Turner, 2000), polymerase chain reaction (PCR) for detecting DNA of biological threats (Mullis & Faloona, 1987), and immunoassays for toxin detection (Knoll, 2010).

●Radiological agents: include Geiger counters for radiation level detection, scintillation detectors for radioactive isotope identification, and dosimeters for personal radiation exposure monitoring.

●Nuclear agents: gamma-ray spectroscopy for identifying nuclear materials, neutron detection systems for fissile materials, and remote sensing techniques for nuclear fallout mapping.

As research progresses, it is becoming progressively evident that science and innovation play pivotal roles in strengthening global security against CBRN threats. By leveraging such advanced technologies as mid-infrared spectrometry and molecular diagnostics, researchers are achieving more precise and efficient detection capabilities. The ability to continue in this endeavor depends on fostering interdisciplinary collaborations and an unwavering commitment to advancing technological solutions tailored to meet today's challenges (Whitesides, 2003).

The development of sophisticated sensors, including miniaturized and highly sensitive variants, has significantly improved the detection capabilities for CBRN agents. These sensors can identify trace amounts of hazardous substances, making them instrumental in the effectiveness of reconnaissance missions (Rosi & Mirkin, 2005). Notable examples of such technologies include mass spectrometry and microfluidics, which provide rapid and precise identification. The advent of remote sensing and unmanned aerial vehicles (UAVs) has profoundly impacted the realm of CBRN detection. The employment of UAVs, equipped with advanced sensors, facilitates remote detection and monitoring of CBRN threats, thereby reducing risk to personnel and enabling access to challenging environments (Fischer & Kakoulli, 2006). This approach facilitates real-time surveillance and data collection over wide areas, proving invaluable in both military and civilian applications. Nanotechnology is being explored for its potential in both detection and decontamination processes. The use of nanoscale materials has the potential to increase the sensitivity and selectivity of sensors, facilitating the detection of low concentrations of CBRN agents (Whitesides, 2003). In addition, nanomaterials can be used in decontamination efforts by providing efficient neutralization of hazardous materials. These advances represent a multidisciplinary approach in recent research, integrating fields such as artificial intelligence, materials science, and robotics to improve the detection and identification of CBRN agents.

2. Methodology

In January of 2025, a comprehensive search was conducted using the Web of Science (WoS) online literature database. This search strategy, which was implemented with the objective of identifying relevant publications, involved the utilization of search terms including "CBRN agents" in the "All Fields" section, along with "identification" and "detection" in the same section. The search was conducted with the intention of locating documents pertaining to CBRN studies that incorporated the terms "CBRN agents", "identification", and "detection" within their titles, abstracts, or keywords. It is notable that no restrictions were imposed on the years of publication during the search process. The publication counts of these documents were also recorded, revealing a total of 52 publications.

3. Results

Figure no. 1 includes data of publications and citations over the years from Web of Science, which represent research trends from 2006 to 2025. General interest in publications remained low and sporadic between 2006 and 2014. Starting in 2015, there was an increase in the number of publications, peaking around 2024. This suggests growing interest and research activity in the field of CBRN agent identification and detection in recent years. Citations follow a delayed but related pattern to publication. There's a noticeable rise in citations after 2016, reaching a peak between 2018 and 2023. For 2025, the observed citations are 11, indicative of the temporal dynamics inherent in the citation process, wherein recent publications require a sufficient interval to accrue citations. Correlation between publications and citations align strongly after 2015, suggesting that the increasing number of papers is contributing meaningful to the academic discourse. Peaks in publications (e.g. 2024) often correspond to higher citation activity in subsequent years, showing an impactful contribution to the field. This data could reflect the growing importance of CBRN related research in response to global challenges like bioterrorism or chemical treats.

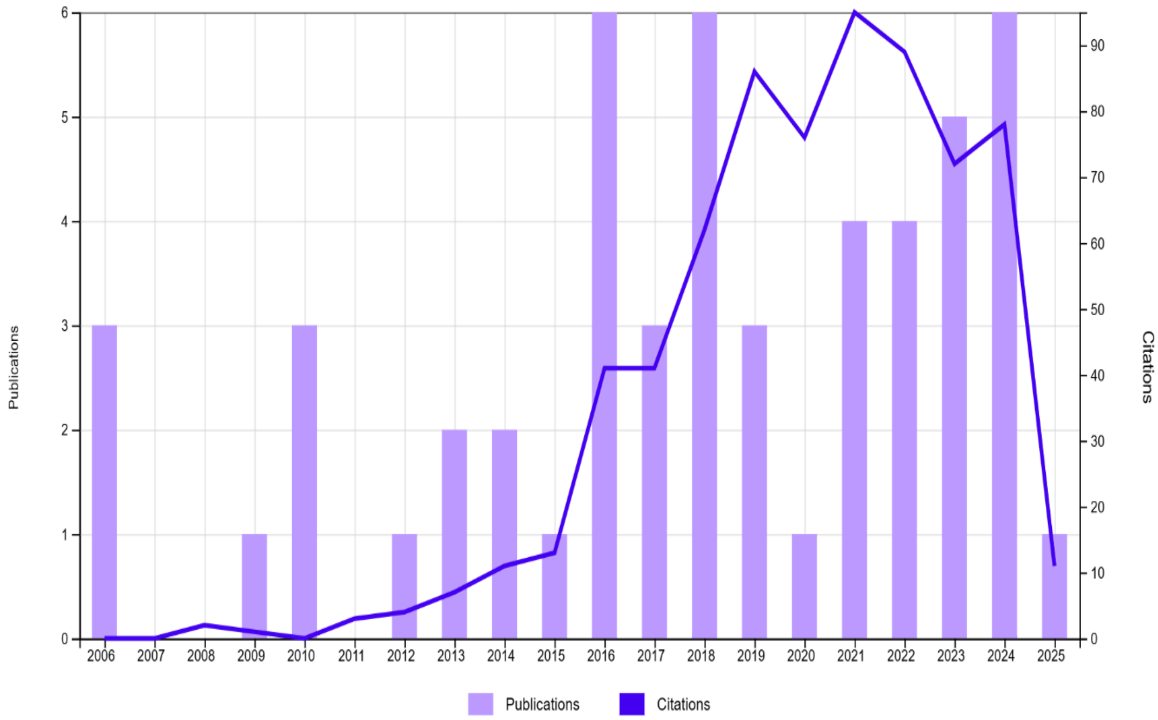

Figure no. 1: *Research trends in CBRN agent detection and identification from WOS (2006-2025)* (Source: https://www.webofscience.com/wos/woscc/citation-report/a77bd118-4a13-4829-8226-40ef9700a839-014a6ef86c)

Figure no. 2 is a tree map visualization of the first 10 research trends categories from WOS, showing different disciplines and their relative frequencies: Chemistry Analytical, Biochemical Research Methods, Nanoscience/Nanotechnology, Optics, Engineering Electrical & Electronic, Instruments & Instrumentation, Materials Science Multidisciplinary, Physics Applied, Spectroscopy.

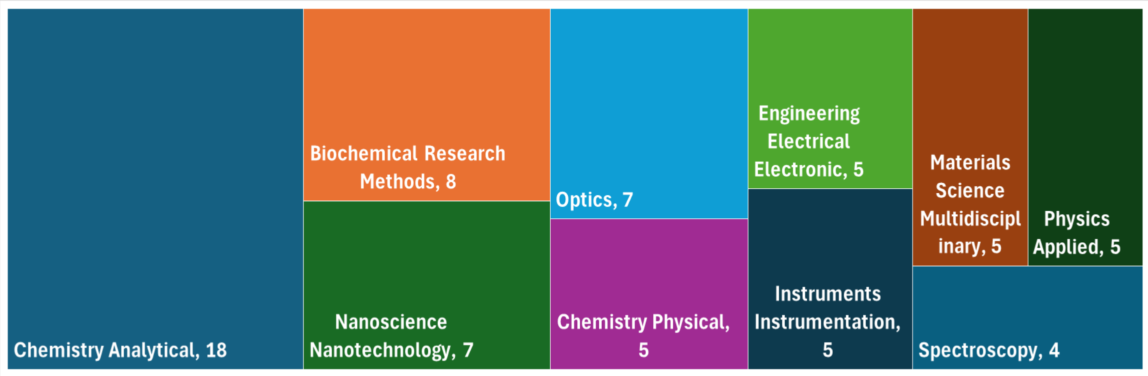

Figure no. 2: *Research Field Distribution of top 10 numerical results: A Web of Science Analysis (2006-2025)*

(Source: Authors' computation with data from Web of Science)

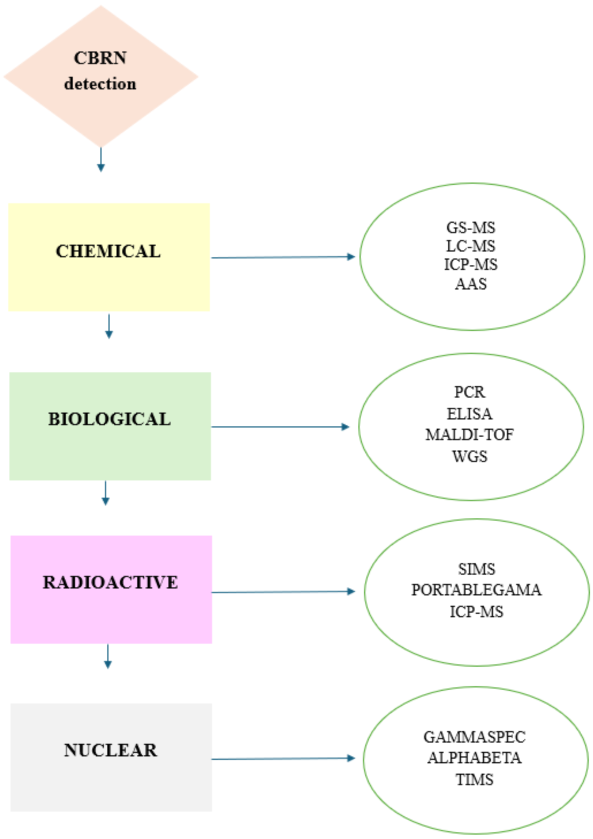

Figure no. 3: *CBRN detection and identification method*
(Source: original figure)

4. Discussion

In Figure no. 1, the observed trends in interest and activity surrounding the detection and identification of low-activity CBRN agents between 2006 and 2014 can be attributed to a few factors. One possibility is that CBRN threats did not occupy a prominent position on the global agenda during this period. Alternatively, it is possible that the prevailing methods and technologies were deemed sufficient, and thus, did not warrant significant investment.

Another potential explanation relates to funding and policy priorities. It is conceivable that resources were allocated to other areas, resulting in a comparatively limited research output in the field of CBRN detection and identification. Because of the lack of advanced technology, before the widespread adoption of machine learning, advanced sensors and automated detection systems, CBRN research faced technical limitations.

When the interest starts to grow, till 2015 to 2020, global events, such as the Syrian Civil War (involving chemical weapon usage) and growing fears of bioterrorism, may have spurred governments and researchers to invest more in this area. Also, the new tools like portable detection devices, AI for pattern recognition and genomic sequencing likely fueled more research opportunities. The efforts by global organizations like NATO, OPCW (Organization for the Prohibition of Chemical Weapons) and WHO might have raised awareness about the importance of CBRN preparedness.

The peak of research activity, from 2021 to 2024, has different factors that driving the surge: COVID-19 Pandemic (2020-2022), the pandemic likely highlighted the need for robust detection systems for biological threats, sparking broader interest in pathogen detection. The rising geopolitical tensions (e.g. Ukraine conflict, tensions in Asia) likely raised concerns about chemical and nuclear agents and governments and militaries may have allocated more resources toward dual-use technologies for CBRN and public health applications.

New publications from 2024 and 2025 haven't had enough time to accumulate significant citation yet due to the lag in the academic citation cycle.

The interplay between global crises and scientific research is evident. Peaks in activity often align with periods of heightened risk or awareness (e.g. pandemics, wars). The alignment of citations with publications suggests a focus on practical, impactful research that is well-received by the academic and defense communities.

In Figure no. 2, the most significant publication category is "Chemistry Analytical" with 18 occurrences and the second most prominent category is "Biochemical Research Methods" with 8 occurrences. This indicates that the research focus is heavily centered on analytical chemistry and the importance of biochemical techniques, possibly in applications like radiological detection, forensic analysis, or the study of biological interactions with chemical substances. Nanoscience/Nanotechnology (7 occurrences) and Optics (7 occurrences) indicate growing interdisciplinary research, possibly involving nanoscale materials and optical methods in chemical analysis. Optical techniques such as spectroscopy, imaging, or laser-based detection could play a crucial role in analytical applications. Engineering Electrical & Electronic (5 occurrences) and Instruments & Instrumentation (5 occurrences) suggest the importance of electronic and instrumental techniques in the field. This could relate to the development of advanced spectroscopic instruments, sensors, or electronic detection systems in analytical chemistry and forensic applications. Materials Science Multidisciplinary (5 occurrences) and Physics Applied (5 occurrences) demonstrate an interdisciplinary approach, possibly exploring material characterization techniques, nuclear forensics, or radiation detection technologies. Spectroscopy (4 occurrences) emphasizes the use of spectral analysis techniques in chemical and material identification. This aligns with the reliance on methods like mass spectrometry, gamma spectroscopy, and alpha-beta detection in radiological and nuclear forensic studies.

In Figure no. 3 the most prevalent analytical tools are represented include gas chromatography-mass spectrometry (GC-MS) (Niessen, 2001), atomic absorption spectroscopy (AAS) (Broekaert, 2006), inductively coupled plasma mass spectrometry (ICP-MS) (Houk, 1981), X-ray fluorescence (XRF) (Beckhoff et al., 2007), and ion chromatography (IC) (Bandosz, 2005). This suggests a strong emphasis on methods for detecting, identifying, and quantifying chemical substances, potentially linked to environmental monitoring, forensic applications, or materials analysis. The employment of mass spectrometry in CBRN-related analyses is a testament to its efficiency in screening and library-based identification. The identification of a target compound is further enhanced by Single Ion Monitoring (SIM) mode, which amplifies detection sensitivity, enabling the identification of trace concentrations. While GC-MS boasts a high degree of versatility, other techniques may be more suitable depending on the specific chemical properties of the compound in question (Plamboeck et al., 2016). Liquid Chromatography-Mass Spectrometry (LC-MS) has emerged as a routine, cost-effective method for high-throughput analysis over the past two decades. LC-MS is particularly advantageous for analyzing larger, less volatile molecules, which may be challenging for GC-MS. It also offers direct analysis of aqueous samples and avoids the need for derivatization required by GC-MS (Ardrey, 2003; Niessen, 2006). In the realm of analytical chemistry, the detection of inorganic substances entails the employment of sophisticated methodologies. Among these, Atomic Absorption Spectrometry and XRF stand as exemplary techniques, demonstrating remarkable efficacy in ascertaining the aggregate metal composition of a given sample. While these methodologies may not facilitate the identification of compounds, they furnish indispensable insights concerning elemental toxicity. Variants of these technologies, such as Atomic Emission Detectors integrated with GC systems, are useful for detecting compounds containing specific elements, such as derivatives of lewisite. Ion Chromatography has been identified as a particularly effective method for analyzing ionogenic substances, which are not compatible with conventional GC or LC-MS methods (Unden, 1992). During the preliminary stages of an incident, rapid screening can be conducted using portable devices such as Fourier Transform Infrared Spectroscopy (FTIR) or Raman spectroscopy. These instruments are efficient for single component analysis but are limited when dealing with complex mixtures. To achieve more comprehensive analyses, the deployment of mobile laboratories equipped with GC-MS is recommended (Plamboeck et al., 2016). For forensic investigations, laboratories prioritize definitive identification of the agents involved, often incorporating chemical attribution techniques to determine the origin of the substances. This stage demands a high degree of accuracy and reliability, as it forms a critical part of legal and investigative processes (de Zeeuw, 2004).

The detection of clandestine release of biological agents poses significant challenges. The initial indication of infection in humans or animals often manifests as symptoms, though these symptoms tend to emerge only after an incubation period, during which the infected individuals may have traversed considerable distances from the site of the release. Consequently, such scenarios can result in a substantial volume of clinical samples, potentially necessitating international collaboration and comprehensive screening efforts to ascertain the location of the release and identify the responsible parties. In instances where a potential biological release has been forewarned, or a specific crime scene has been identified – such as a laboratory or powder release, it is imperative to collect and analyze environmental samples (Lim et al., 2005; Ederveen, 2010). For unknown samples, the primary objective is identification, while for known agents, emphasis may shift to quantification and high-throughput analysis. Established identification methods have been reviewed to ascertain their potential benefit from standardization, harmonization, or the adoption of best practices. The most efficacious identification assays are characterized by their sensitivity, specificity, capacity to detect minimal concentrations of target agents without interference from background materials, reproducibility, and reliability. For confirmation, mobile laboratories equipped with immunological assays and PCR capabilities can be utilized (Plamboeck et al., 2016). Forensic investigations prioritize definitive identification of biological agents and frequently incorporate biological forensics analyses to attribute the source of potential acts of bioterrorism, biocrime, hoaxes, or accidental releases. Genotyping and whole genome sequencing are two such techniques, the selection of which depends on the genetic variance of specific bacterial strains and the laboratory's resources. Genotyping typically involves PCR steps, a well-established technique in laboratories (Sabat et al., 2013; Vogler et al., 2016). Post-incident monitoring frequently utilizes ELISA and real-time PCR methods for detecting biological agents. Confirmation of viable bacteria necessitates culturing on agar, often augmented by molecular methods such as DNA sequencing or MALDI-TOF (matrix-assisted laser desorption ionization-time of flight) analysis. The advent of next-generation DNA sequencing (NGS) has remarkably augmented the capacity to analyze extensive datasets, facilitating the detection of even low-frequency impurities such as pathogenic microorganisms (Lim et al., 2005; Fykse, 2015).

For analysis of radio-nuclear substances after the immediate aftermath of an incident, expeditious analytical methodologies that require minimal sample preparation are paramount for substantiating on-site measurements. These methods primarily rely on portable gamma spectrometry and include high-resolution gamma spectrometry as well as gross alpha and beta counting techniques. These approaches are widely employed by laboratories engaged in environmental monitoring. However, to ensure comprehensive and precise identification of the involved radiological or nuclear (RN) substance, these rapid methods must be complemented by nuclide-specific techniques for alpha and beta emitters. While these advanced methods boast greater sensitivity than gamma spectrometry, they are typically time-consuming and technically demanding. The employment of both rapid and nuclide-specific techniques is equally applicable during the post-incident monitoring phase (Plamboeck et al., 2016). Forensic investigations necessitate specialized techniques to ascertain the origin of the substance. These methods are intricate, time-consuming, and require highly skilled personnel. Common forensic techniques include Thermo-Ionization Mass Spectrometry (TIMS), Inductively Coupled Plasma Mass Spectrometry (ICP-MS), and Secondary Ion Mass Spectrometry (SIMS) (Wiser & Schwieters, 2005). In instances where a sample is identified as exclusively radiological, thereby excluding the potential for biological or chemical hazards, a systematic approach can be adopted. The initial step involves screening to confirm in situ measurements, utilizing gamma spectrometry and gross alpha and beta counting. Subsequent steps include the division of the sample for either non-destructive analysis – such as gamma spectrometry, imaging, and microanalysis (e.g., SEM, TEM, SIMS) – or RN-specific analysis for assessing health and environmental impacts. The non-destructive analysis is followed by destructive techniques, including alpha spectrometry, TIMS, ICP-MS, and beta liquid scintillation, depending on the investigative needs (Tamborini et al., 2002).

5. Conclusion

The rapid evolution of technologies for detecting and identifying CBRN agents has significantly enhanced global security measures. This research underscores the integration of advanced methodologies, including ion mobility spectrometry, hyperspectral imaging, and biosensors. These methodologies have led to a paradigm shift in the accuracy and efficiency of detection systems. The increasing adoption of unmanned aerial vehicles (UAVs) and miniaturized portable devices further emphasizes the shift towards real-time monitoring and response capabilities.

The multidisciplinary approach, incorporating analytical chemistry, nanoscience, and engineering, has contributed to substantial progress in the field. The role of nanotechnology in improving sensor sensitivity and decontamination methods remains a key focus for future advancements.

A Web of Science analysis reveals a marked increase in research interest since 2015, largely driven by global crises, including bioterrorism threats, the emergence of the novel Coronavirus (SARS-CoV-2), and geopolitical instabilities. This trend underscores the importance of continuous investment in research and development to address emerging CBRN challenges effectively.

Maintaining technological superiority in the face of evolving threats will require collaboration across scientific disciplines and international cooperation. By leveraging innovation and interdisciplinary research, the scientific and defense communities can enhance preparedness and response strategies, ensuring robust protection against CBRN hazards.

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