CHALLENGES AND GAPS IN BIOTERRORISM'S DETECTION AND INVESTIGATION

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INTRODUCTION

Any accidental or natural release of a pathogen or toxin in a population can deeply disrupt a community or country as demonstrated by the latest COVID-19 and avian influenza epidemics or more local outbreaks such as cholera, dengue or anthrax (Madhav, 2017; Rahman et al., 2020; Samsudin et al., 2024). A similar scale event qualifying as bioterrorism would create an even greater disruption since the intentional release of the biological agent or toxin would be carried out for the purpose of harming or killing animals or plants with the intent to intimidate or coerce a government or civilian population to further political or social objectives as defined by INTERPOL in its Bioterrorism incident pre-planning and response guide (2018).

While fortunately few bioterrorism incidents are reported across the globe, those which have been successful have had deep and often lasting impact on nations and populations. With a total of 5 deaths, 17 injured, almost 8 years of investigation and around $320 million dollars spent in decontamination, the 2001 anthrax attack in the USA illustrate perfectly how an incident that had a limited number of casualties has far reaching consequences, including the psychological impact on the community. Another example is the deliberate spread of broom-witch disease in Brazilian cocoa plantations in the early 1990s. This event completely transformed the social, economic and political fabrics of the Bahia state and beyond (Trevisan, 2019). Even without going so far as spreading the agent, the investigation of bioterrorism threats monopolizes precious resources at national and sometimes international level, as happened in 2005 when the New Zealand government organized 'Operation Waiheke' in response to a letter sent to their Ministry of Agriculture and Forestry claiming the deliberate release of Foot and Mouth virus on Waiheke Island. While this incident was a hoax, its investigation and management required setting up of a coordinated incident management system, as well as an operations group supported by logistics and intelligence groups (Mackereth & Stone, 2006).

As technology, threat actors and even climate change are increasing the risk of disease emergence and re-emergence, as well as the accessibility and the opportunities to weaponize biological agents, it is crucial for nations to strengthen their ability to efficiently prevent, prepare for and respond to bioterrorism incidents. This paper explores specific challenges about detecting and examining evidence in suspected or confirmed bioterrorism events to identify gaps and discuss opportunities for LEA and the larger community to improve the detection and investigation of bioterrorism events. It does not specifically address aspects relating to biosecurity measures, incident response and prosecution.

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METHODS (DESIGN/METHODS/APPROACH)

This desk-based study is based on current literature and INTERPOL's experience working with its membership in the area of bioterrorism prevention, preparedness and response. Google scholar (219,229,812 papers as of 24 June, 2024) and PubMed databases (over 37 million bibliographical references as of 24 June, 2024) were searched using the following keywords: Bioterrorism, Biothreat, Biocrime, Agrocrime, and Agroterrorism in combination with "crime scene management" or "microbial forensics" for papers published in the past 25 years.

DISCUSSION (FINDINGS)

Challenges of Bioterrorism Detection

Early detection of bioterrorism is key to mitigating its impact through the establishment of timely measures aimed at reducing the effectiveness of such an attack, avoiding subsequent attacks and averting the potentially catastrophic nature of mass pathogen release (Shea & Lister 2003). Detection is the unspecific demonstration of increased concentration of microorganisms in a particular environment, whereas identification is the species determination of the detected microorganism (Parida, Dash & Shukla, 2020). Unlike other forms of terrorism, several factors inherent to the nature of biological substances – including the sensitivity, specificity and technology needed to detect such a diversity of substances present in minute quantities among the regular background – make the detection of bioterrorism more difficult. As harmful biological substances are naturally present in the environment, independently from any human activities, and since natural outbreaks occur every day in every part of the world, detection of a bioterrorism incident consists foremost in identifying unusual disease events.

The intentional release of a biological agent can constitute either a covert or an overt attack. Overt attacks are easier to detect since by definition they are recognizable by law enforcement or other responders, either through a threat, warning or intelligence, the discovery of a means of dispersal or other signature activity/apparatus, or the discovery of questionable or suspect materials (Bioterrorism incident pre-planning and response guide, 2018). Except in some exceptional cases where the affected people are presenting acute and clear symptoms, biological agents or toxins would not cause immediate harm and their impact would only be visible after an incubation period (Pohanka, 2019). The clinical manifestations and epidemiological pattern of the disease would differ according to the characteristics of the agent(s) or toxin(s) used in the attack, its mode of dispersal, the affected population and other environmental conditions. To make things more difficult, the early signs and symptoms of a disease are often non-specific and could be mistaken for other endemic diseases or ongoing outbreaks. Strong epidemiological surveillance is therefore needed to detect unusual epidemiological patterns or disease presentations in human, animal and plant populations (Bower et al., 2022).

Biological agents and toxins agents are more easily available to nefarious actors who would not hesitate to use them. During the Covid-19 pandemic, for example, violent extremist groups were calling for the SARS-CoV-2 virus to be deliberately spread and to infect religious or ethnic groups particularly deemed adverse (Salman & Gill, 2020). Biological agents and toxins are more present in nature for multiple reasons such as the emergence of pathogens, climate change, human activities impacting the environment and human-animal interactions. In addition, the development of technology has accelerated the identification of new agents or traits that could be used in bioterrorism. In addition, technology advances are creating ways to engineer simpler, cheaper or more efficient processes or new pathogen traits or toxins, thus posing biosecurity threats worldwide as described for peptide and protein toxins synthesis (Lee et al., 2022) or CRISPR-Cas9 (Stasi & Thongpravati, 2024; Kosal, 2020).

The democratization of knowledge of biotechnology and life science through the development of knowledge-sharing online tools and platforms has been accompanied by the simplification of processes and tools. Insufficient regulations or monitoring of these tools and platforms provide opportunities for threat actors to develop, acquire and misuse biological agents. This also means that the resources to plan a bioterrorist attack no longer require highly elaborated laboratory facilities, sophisticated technical expertise or extensive financial resources. Technology platforms such as DIYbiosphere could provide opportunities for malicious actors to develop new bioterrorism agents, production, dispersal or concealment methods (Harvin, 2024).

Another challenge of bioterrorism detection is the overall lack of awareness of indicators of bioterrorism-related activities, starting with the first responder communities, including law enforcement and fire/rescue responders. This pertains to the lack of systematic training on these particular indicators which can be traced to the following: 1) chemical and radiological terrorisms have been seen as being much more likely than bioterrorism; 2) covert biological incidents are more likely to be detected by health services than by first responders; 3) detection of bioterrorism requires specific awareness in the absence of suitable equipment.

While many countries have established dedicated Chemical, Biological, Radiological and Nuclear (CBRN) units, most are mainly focusing on the prevention of, detection of and response to biological incidents of natural or accidental origin and/or eventually CBRN warfare. This means that their first responders' awareness to bioterrorism indicators is limited as well. Limited awareness of indicators of deliberate release of biological agents or toxins is not restricted to first responders and specialized units. This is true for human health, veterinary and plant protection professionals. Since many disease presentations share initial signs and symptoms, health professionals, with reason, are trained to look for common illnesses before thinking of 'exotic' ones, thus potentially delaying the detection of these diseases that are indicative of a deliberate introduction.

The lack of awareness at national level can be explained by the recent recognition of the issue by international instances governing health services. For example, the fifty-fifth World Health Assembly in 2002 proposed to develop international guidance and technical information to deal with deliberate use of biological agents, but the first training material was distributed in 2022 (*https://apps.who.int/gb/ebwha/pdf_files/WHA55/ewha5516.pdf*; *https://openwho.org/channels/cbde*). In the veterinary space, the World Organisation for Animal Health (WOAH) established its biological threat reduction strategy in 2015 and their first guidelines on biological threat indicators were published in 2018 (*https://www.woah.org/en/document/en_final_biothreat_reduction_strategy_oct2015/*; *https://rr-africa.woah.org/app/uploads/2024/10/SUSPIC3.pdf*). As far as plant health is concerned, despite a position paper published in 2007 by the European and Mediterranean Plant Protection Organization, there is currently no international guidance endorsed in that regard (*https://www.eppo.int/RESOURCES/position_papers/council_bioterrorism*; *https://www.ippc.int/en/about/core-activities/capacity-development/guides-and-training-materials/*).

Many of these health services may not be able to distinguish the early signs of a bioterrorist event from natural and accidental contamination or infection because in most instances one must look beyond symptoms to identify intentionality (Perlin, 2008) or detect unusual epidemiological patterns through the analysis of health database or specific criteria. But once identified, whom to report them to and how to do so? In many countries, there is no established operational process in the health sector to report suspected bioterrorism or deliberate biological incidents to trigger an early multi-agency investigation.

An essential part of detection of bioterrorism falls onto the intelligence community to try to detect incidents before an attack unfolds or to prevent recurrence. This aspect of detection requires a good understanding of the global bioterrorism threat landscapes, whether in terms of threat actors, capabilities, motivation or possible targets. Monitoring these various aspects and understanding their possible presentation in the context of the constant evolution of biotechnology, science and emerging diseases require specialized expertise and input that is not always available to national intelligence teams.

As illustrated for example in the analysis of the June 2018 Cologne Ricin Plot (Flade, 2018), bioterrorism is likely to involve transnational components. Therefore, cross-border intelligence sharing should also form an essential part of bioterrorism detection. This implies the development of established cooperation channels and partnerships, as well as a dedicated international database consolidating relevant information on all development stages of attacks across the world to provide the most accurate picture and information to countries worldwide. So far, most of the efforts have been geared up towards gathering epidemiological intelligence through various sources and less towards building the analysis necessary to detect unusual events that would be indicative of biological attacks or weapons development.

As described above, multiple actors are involved in various aspects of monitoring and data collection regarding different aspects of bioterrorism incident. But in many countries, those various stakeholders have no dedicated information system to store and structure this information in a useable way. Often there is no defined criteria, clear reporting mechanisms or guidelines for information sharing or outreach whether at national level or across border outside of the partnerships established with international organisations.

Current Status of Bioterrorism Detection

Bioterrorism detection combines bioterrorism activity monitoring, carried out by the security sector, and biological incident surveillance which is mostly under the responsibility of the health sector (Wenger, P. N., Halperin, W., & Ziga, E., 2008). Biological incident surveillance can be conducted in a passive or an active manner and both have their pros and cons in terms of cost/benefit perception, but in both cases it is based on a set of indicators or criteria (Wenger et al., 2008). The development of event-based surveillance is a major step for bioterrorism detection as it is meant to complement the classic indicator-based surveillance systems to: 1) detect rare and new events that are not specifically included in indicator-based surveillance or 2) quickly capture information about events that are a potential risk to health in a non-traditional approach to early warning applicable across human, animal and environmental health (Crawley et al., 2024), both specificities being expected in a covert bioterrorist attack. The application of AI-based technology for multi-dimensional open-source public health surveillance data analysis is opening the door to increased bioterrorism detection through the identification of variations in local and regional disease pattern, in modelled outbreak behaviour, or the detection of specific misinformation and disinformation patterns (Maclntyre, et al., 2023).

In any case, biological incident surveillance relies either on the detection of signs and symptoms in a human, animal or plan population, or on the detection of biological agents and toxins in the environment. The latter can be performed on a permanent basis at pre-identified detection points, such as critical infrastructures, major public events, high level visits or hubs (e.g. sewage systems, airports, mail sorting facilities, etc.), where an operator collects samples from contaminated environment or real-time stand-off detection. Stand-off detection has the advantage of minimizing the operator and equipment exposure to contamination (Coluccelli et al., 2023), but that solution is still largely in the research and development stage in the biological field. The continuous detection or monitoring of biological agents requires arrays of different sensors to cover multiple biological agents because most detection schemes are specific for a particular biological agent (Parida et al., 2020). This implies the dedication of financial, technical and human resources that are not readily available to many countries.

When a CBRN attack has occurred in a location where no permanent detection is in place, field detection can be deployed. However, where some radiological and chemical substances can be detected in real-time with specific equipment such as Geiger counters and Fourier Transform Infrared (FITR) or Raman spectroscopy devices, there is no field detection equipment that can provide an instant read of the potential presence of a dangerous biological agent (Kaszeta, 2023). Biological detection in the field still relies fully on the collection and preparation of an appropriate sample that will then be applied, most likely to a lateral flow assay or taken for molecular analysis (PCR or RT-PCR) to a laboratory, method that will take at least 15 minutes to process. Most lateral flow assays can process a very low number of agents at once (usually 1-5) requiring repetition of the operation and spending material that can be present in minute quantity already for a result that may not provide any indication and will have in any case to be confirmed in a laboratory. Moreover, presumptive testing results will have direct consequences on operational decisions (such as zoning, public order disruption, communication, etc.) that could in turn require the deployment of unnecessary resources and raise unwarranted alarm should the test turn out to be a false positive.

Table 1. *Differences Between Field Detection and Lab Identification*

	Field detection	**Laboratory identification**
Methods	Immunoassays (usually lateral flow)	Immunology Molecular biology Microbiology/Microscopy Spectrometry Chromatography Biochemistry/Enzymology
Characteristics	Presumptive Fast information On the spot Relatively limited equipment required Potentially contaminated environment Non-optimized procedures Limited methods available Limited to some agents and toxins	Confirmatory Time-consuming (sample preparation, etc.) Sophisticated equipment Controlled/safe environment Standardized/optimized procedures Many methods available Different laboratories for different agents and toxins or expertise

Whether considering environmental or field detection, these detection systems need to exhibit high sensitivity because biological agents and toxins are effective in very low quantities and the environmental background is complex and rapidly changing (Fatah, et al. 2001). The technology also needs to ensure rapidity, reliability, and specificity so as to quickly narrow down the correct etiological agent from other similar substances (Lim, Simpson, Kearns, & Kramer, 2005). In the late 1990s, most of the Research and development on detection of biological weapons involved nucleic acid or antibody-based probes combined with optical, most often fluorescence, transduction, or it involved adapting separation-based technology like mass spectrometry (Institute of Medicine (US) Committee on R&D Needs for Improving Civilian Medical Response to Chemical and Biological Terrorism Incidents, 1999). Since then, the same technologies have been further developed with the introduction of new materials, such as nanoparticles or quantum dots, of new techniques or methods to develop or improve biosensors and bioassays for biological agents and toxins detection. (Duriez, Armengaud, Fenaille & Ezan, 2016; Pohanka, 2019; Pohanka, 2023). However, to date, the number of agents detected, their availability for multiplex detection and their sensitivity remain limited for field detection (Kaszeta, 2023).

Challenges in Collection and Examination of Bio-Contaminated Evidence

Some countries have built strong approaches to detect and examine bio-contaminated evidence (Budowle, 2003). Given the resources and expertise needed to investigate such complex events, these approaches usually involve strong partnerships and coordination between agencies. However, many countries are still looking for guidance in that domain and the scientific literature on the topic of biological crime scene management remains scarce. Indeed, most of the recent literature on bioterrorism and forensics focuses on microbial forensics (Table 1), but provides little information on biological crime scene management and processing.

Table 2. *Number of Entries in Literature in the Past 25 Years Addressing Crime Scene Management and Microbial Forensics in the Field of Biological Threats*

Keywords	Number of papers retrieved (crime scene management/microbial forensics)	
	PubMed	Google Scholar
Bioterrorism	191 (0/50)	53,900* (52/1,130*)
Biothreat	683 (0/3)	11,100* (2/309)
Biocrime	6,613 (0/48)	2,020* (3/444)
Agrocrime	3 (0/0)	59 (0/3)
Agroterrorism	43 (0/1)	3100* (12/81)

*approximate numbers

While in many countries the legal basis for interagency coordination and cooperation is well established for disaster management, it rarely covers the investigation aspects linked to the accidental or deliberate release of biological agents, even under terrorism or CBRN misuse (DeVries, 2023). In absence of legal texts, the investigation of such incidents relies mostly on subpoenas allowing law enforcement to enrol the support of external expertise. However, these *ad hoc* solutions do not account for the degree of intricacy involved in the investigation of an incident involving the release of a harmful biological substance, as described in the lessons learnt from the 2001 Anthrax attacks in the USA (Butler 2002). Indeed, once a suspicious biological incident occurs, the criminal investigation requires new roles and responsibilities to be undertaken in addition to the regular incident response. This often leads to shifts in the incident command structure and additional coordination with more specialized units or services that varies also depending on the type of incident and the step of the investigation process. In absence of proper understanding of each other roles and constraints, coordination issues may arise that can jeopardize biological incident investigations, as well as compromise safety and security of the responders and the public.

Unlike for conventional scenes, several steps will take place to ensure the safety of the responders and mitigate the risk of accidental spread of the biological material into the population and the environment when processing a contaminated crime scene (Figure 1). Most of these steps though will require the support from other agencies, often with no law enforcement mandate or background. Ensuring that all responders involved in these different steps can perform their task safely in a manner that allows crime scene preservation and operations is challenging in itself (Zuidberg, van Woerkom, de Bruin, Stoel, & de Puit, 2014).

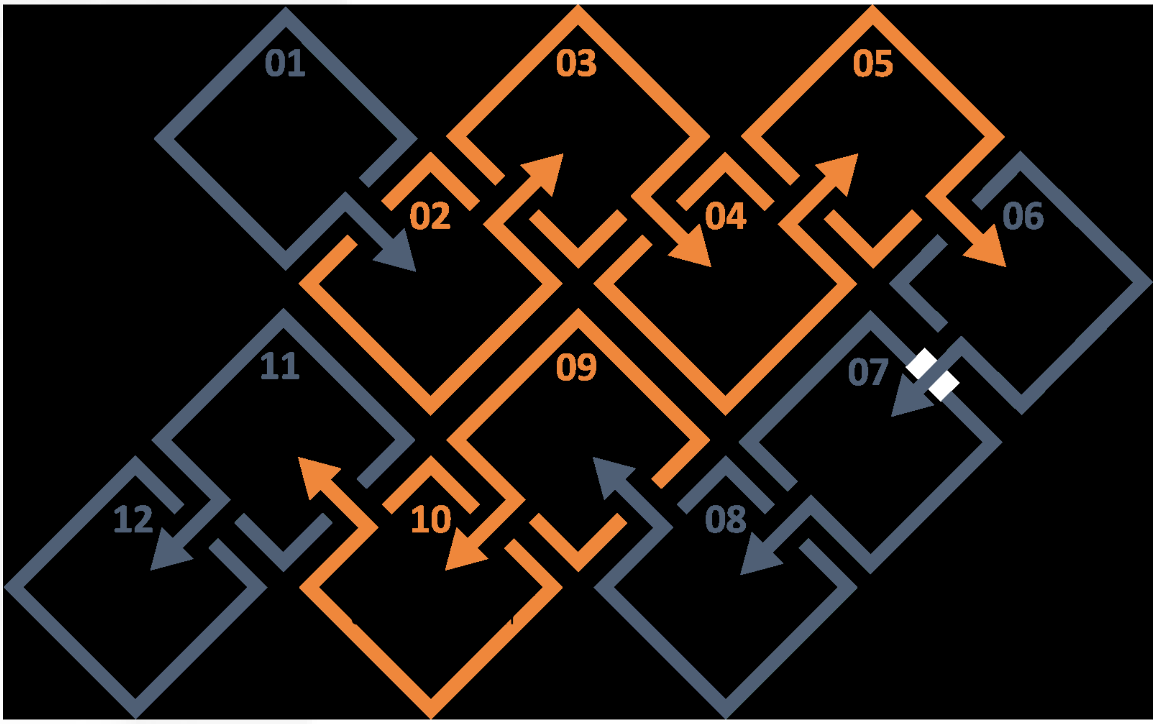

Figure 1. *Additional Steps Required to Safely Manage a Crime Scene Contaminated with Biological Materials Compared to a Conventional Crime Scene (Blue)*

Even before law enforcement officers can perform the scene reconnaissance, deployment of specific support units that will set up decontamination corridors and use specific detection equipment in a contaminated environment to carry out the CBRN hazard assessment can delay crime scene operations for a while and thus compromise some of the evidence. Technical challenges, such as logistics, equipment and carrying operations in a biological contaminated environment, also add to this coordination issues.

Integrity and preservation of evidence can be especially challenging in a biological incident as there could be many agencies involved within the incident scene (e.g. fire fighters, paramedics, military, CBRN teams, police, and environmental services) before it can be processed as a crime scene. For example, in many countries the CBRN hazard assessment is carried by firefighter or military units. While supporting the elaboration of a risk management strategy, the essential step of CBRN hazard assessment will determine which personal protective equipment (PPE) the investigative and supporting teams will be wearing to access the crime scene. This in turn will deeply impact the working conditions and forensics strategy to be applied on the scene (in the so-called hot zone).

Even without air supply limitations, the stress generated by the investigation of a high-profile bioterrorism event, the mental strain created by the work in a contaminated environment and the physical impact of operating in a PPE are limiting the time any team can spend in the hot zone. This will have to be considered, together with the information collected by the reconnaissance team and the available human and material resources for processing the scene, when establishing the forensics strategy.

Each forensic strategy will be unique as each scene is, but also because each country has a defined set of resources and capabilities for handling it. Applying the guiding principles of prioritisation of evidence to be collected will also be influenced by the capabilities of evidence examination both on-site and off-site. Considering the biological agent present on the scene and the effect of diverse types of decontaminants on materials and traces that would need to be exploited (Zuidberg, 2014), evidence decontamination may not be feasible and contaminated evidence will have to be examined.

While it is very tempting to process the maximum pieces of evidence in the hot zone to avoid taking the contamination elsewhere, several elements must be considered: operational context, quality of the work carried out in a non-controlled environment, equipment to be brought into the hot zone (and its fate or decontamination), as well as the feasibility of the examination. Another approach would be to carry out a maximum of the examination in a mobile laboratory equipped to handle biologically contaminated evidence. However, mobile labs also have their own limitation (size, equipment, technology available, decontamination protocols, etc.). Thus, the forensics strategy will have to balance those various constraints, as well as those of the specialized facilities where the necessary analyses can be carried out for the biological samples (Schmedes & Budowle, 2019) and for traditional evidence contaminated by a biological agent (Kaszeta, 2018). Once the strategy is established, forensics personnel trained in working in contaminated environment can enter the scene to process it, but several questions will need to be answered to properly collect, segregate and transport evidence. The first one pertains to the type of evidence and the analyses that can be carried out on-site. The type of evidence will determine: 1) whether traditional or microbial forensics have to be undertaken, 2) whether it can be decontaminated without damaging key elements (traces, digital information, etc.), 3) what analyses can be performed and under which conditions. These in turn will condition the fate of this evidence, as displayed in the simplified decision-making tree (Figure 2).

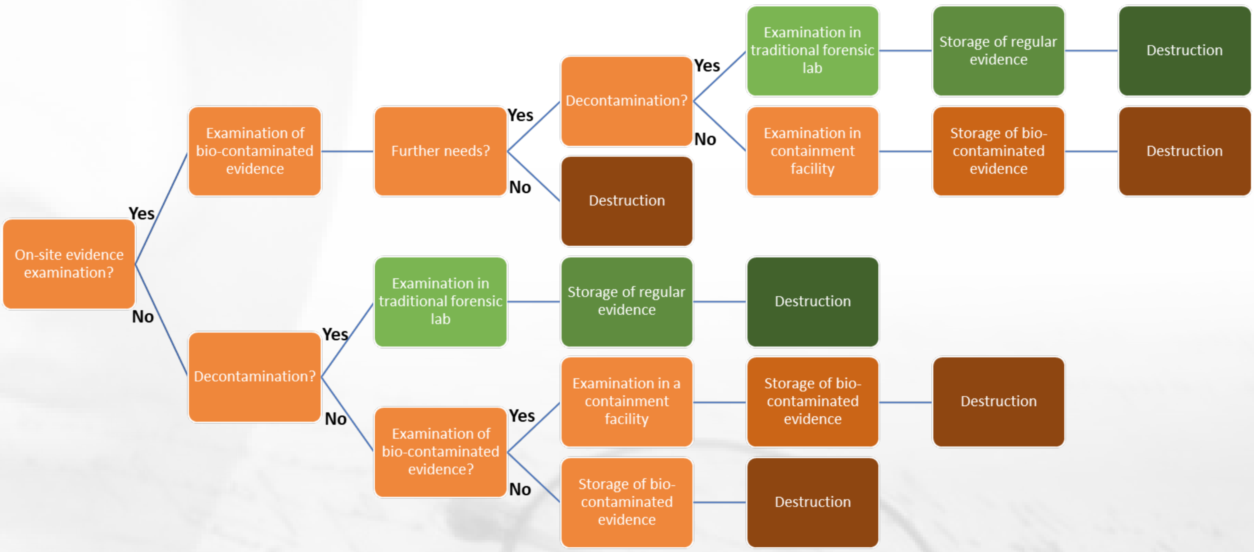

Figure 2. *Decision-Making Tree for Evidence Examination Depending on Technical Feasibility and Contamination Status (Orange: Bio-Contaminated Evidence, Green: Decontaminated Evidence)*

The identification of the biological agent or toxin involved in the attack is essential to establish proper countermeasures and mitigate the impact of the incident. However, in addition to ensuring the safety of the populations and the environment, additional analysis of the biological agent samples will be required to link the perpetrator to the attack and ascertain the deliberate nature of the incident. Microbial forensics is the scientific discipline dedicated to analyzing evidence from a deliberate release for attribution purposes. It combines the practices of epidemiology with the characterization of microbial and microbial-related evidence to assist in determining the specific source of the sample, as individualizing as possible, and/or the methods, means, processes and locations involved to determine the identity of the perpetrator(s) of an attack (Schmedes & Budowle, 2019). As highlighted in Table 2, such a complex discipline requires the use of various technology and disciplines that are not necessarily used or available in routine high containment or forensic laboratories. Therefore, elements that need to be considered when packaging biological samples is the destination of each sample evidence and acceptance criteria (or constraints) of the facility that will receive these pieces of evidence.

Table 3. *Technologies and Disciplines Involved in Microbiological Forensics*

Technologies	**Disciplines**
Advanced microscopy	Bacteriology
Chromatography	Biochemistry
Evolving, nascent technologies	Bioinformatics
Flow-cytometry	Genomics
High-throughput sequencing	Metabolomics
Hyperspectral imaging	Molecular Biology
Identification of indicators of engineering	Mycology
Mass spectrometry	Phytopathology
Metagenomics	Population genetics
Non-biologic tools (e.g. nanotechnologies)	Proteomics
Sensitive signature detection and characterization	Statistical analysis and confidence estimations
Synthetic biology	Virology

As discussed above, the processing of traditional evidence contaminated by a biological agent will first depend on whether they need to or can be decontaminated and what decontamination protocol can be applied. The effects of decontamination agents should be considered to avoid any damage to physical evidence, such as DNA and latent prints (Wilkinson et al, 2020). If proper resources and protocols are available, some evidence can be processed without decontamination, for example for some fingerprints or digital devices. For evidence that can be decontaminated, the application of specific decontamination protocols would be required to ensure the safety of the personnel performing regular forensics examination. As for the evidence that cannot be decontaminated, their examination will depend on the facilities where they are to be handled and process, the equipment and technologies that will be available in this high-containment areas, as well as the feasibility of the examination protocols.

Another aspect that should not be neglected is the question of accessing and manipulating in high-containment laboratories. Because of their inherent constraints and operations, some of these facilities would be unable to accept emergency work from an external entity to be carried out on their premises. In addition to their capacity to host certain types of biological agents, all these facilities have strict access and training requirements for personal allowed inside (Joseph, 2021). These safety requirements would supersede operational powers granted to law enforcement, for example through subpoenas. Bio-containment facilities operating procedures could also limit to some extent the possibility to store safely and securely any bio-contaminated evidence.

Concerning manipulations in high-containment facilities, while forensic science technicians are qualified to perform traditional forensics, they do not usually develop skills to perform their tasks in a high-containment laboratories. Conversely, laboratory technicians who are routinely operating in high-containment laboratories are perfectly versed in the inner running of such facilities. However, they are usually not trained in traditional forensics techniques. Working in a facility that was not meant to undertake traditional forensics in many cases will require to adapt forensics procedures to constraints specific to the high-containment facility. In addition to answering the who and how will the work be carried out in a non-forensic, high-containment laboratory, it is important to define how chain of custody and secured evidence storage will be maintained in these facilities.

Good Practices in the Collection and Examination of Bio-Contaminated Evidence

Interagency preparedness and cooperation require to first properly identify the resources and partnership needed to carry out safely and efficiently criminal investigation of biological incidents, from detection to prosecution. This will allow to ensure that the necessary conventions and agreements (or memorandum of understanding) are in place to facilitate joint activities and provide a framework for efficient cooperation between all the agencies involved. Often overlooked, magistrates in charge of the prosecution of such crimes should be fully aware of the processes and constraints to better anticipate the difficulties and limitations linked to this kind of investigation (*https://unicri.it/Publication/Prosecutor-Guide-Chemical-Biological-Crimes*).

Having the properly trained personnel and deploying the necessary resources to respond to a bioterrorism crime scene requires a thorough mapping of human, financial, equipment and facilities available at national level, as well as the identification of partners within and outside the countries that can support law enforcement crime scene processing in each of its phases. All these partners should have some level of awareness of the biological threats and be involved in joint planning and preparedness activities for biological incident investigation.

Once a cooperation framework and joint planning has been established, it becomes easier to elaborate joint Standard Operating Procedures (SOPs) and undertake joint training and exercises. These joint activities are essential in building trust and understanding between agencies that usually have different constraints, operating framework and intervention goals. But they also contribute to rehearse procedures and hone skills and mechanisms that are not frequently used, as well as to test and improve plans and procedures for various scenarios (Reutter et al., 2010). Those interagency simulation exercises can be small or large in scale but should always be carefully planned to maximize their benefits (*https://www.woah.org/app/uploads/2021/03/simulation-exercises-veng-revised-1st-edition.pdf*). They can also be used to maintain laboratory proficiency both for sample processing and results reporting (Worbs et al., 2015).

Having access to scientific reachback capable of understanding and advising on both safety and sampling is invaluable in the processing of a bio-contaminated crime scene. Scientific advisors should be as diverse as the biological field is to cover human, animal and plant pathogens, as well as toxins. They should have a good understanding of the responsibilities and needs of forensics specialists to best guide them on the type and quantity of samples to be collected. Reaching back to the laboratories that will be conducting microbial forensics can also contribute to providing the best samples and preserve them for optimal analyses.

Given the diversity in biological agents and toxins and technologies needed in microbial forensics, as well as the constraints linked to undertaking traditional forensics in high-containment environment, it is essential to develop laboratory networks that can be mobilised for the prompt examination of bio-contaminated evidence. Some of these laboratories would likely also be involved in the detection of bioterrorism events (Villanueva, Schweitzer, Odle & Aden, 2019). The development of a laboratory network, such as the US Laboratory Response Network for biological threats (Villanueva, et al., 2019) or the French Biotox-Piratox, offers opportunities to ensure flexibility and optimum use of national analytical capabilities (Thibault, Forcet, Lachenaud & Vidal, 2009). However, the network itself cannot be limited to the mapping of national capabilities: it must also provide the use of standardized reagents, standard-driven protocols, and training, including proficiency testing. Where national capacities are lacking, they can be compensated through regional or international networks or agreements (Nisii et al., 2009).

Existing Support from International Partners

Several international entities are providing global support to their membership about bioterrorism detection and/or evidence collection and examination. Support in this area includes information exchange on suspicious activities or events, as well as capacity building and incident support.

In the area of information exchange regarding suspicious biological incidents and bioterrorism prevention, several international bodies have developed intelligence sharing platforms to give opportunities to countries to provide and receive information. For example, from the animal health perspective, WOAH has developed the World Animal Health Information System (WAHIS) and WAHIS-Wild to track emerging and re-emerging domestic and wild animals on the basis of information confirmed by veterinary authorities (Fanelli et al., 2022). On the other end of the spectrum of the human-animal interface, the World Health Organization (WHO) runs the Epidemic Intelligence from Open Sources (EIOS) system to detect unusual or unexpected signals at various geographic levels (Togami et al., 2022). In the security arena, building from its outreach and work with its 196 countries, INTERPOL – with the support of its partners – is strengthening the global monitoring and detection of bioterrorism incidents through the development of BioTracker (*https://www.interpol.int/Crimes/Terrorism/Bioterrorism/Police-Data-Management-and-Analysis-Bioterrorism/ProjectSheet_BIOTRACKER_EN_JUNE2023.pdf*). It supports INTERPOL member countries through a data-sharing platform focusing on biological threats and incidents which includes an early warning component.

Beyond information collection and sharing, international organizations have been developing resources in support to national authorities to strengthen early detection of bioterrorist events and safe processing of bio-contaminated evidence. In the area of disease surveillance, for example, WHO and WOAH have long developed guidelines and tools, including listed diseases (*https://www.woah.org/en/what-we-do/standards/codes-and-manuals/terrestrial-code-online-access/?id=169&L=1&htmfile=chapitre_oie_listed_disease.htm*, *https://www.woah.org/en/what-we-do/standards/codes-and-manuals/aquatic-code-online-access/?id=169&L=1&htmfile=chapitre_diseases_listed.htm*) or priority pathogens (Jesudason, 2024), for early warning of disease outbreak. In the past years, they have expanded the scope of some of these resources to include deliberate release of biological agents and toxins, as exemplified by WOAH's development of a biological threat reduction programme in 2015 (https://www.woah.org/en/document/en_final_biothreat_reduction_strategy_oct2015/) or WHO launching in 2022 a massive open online course on "Chemical and Biological Deliberate Event" for health professionals (*https://openwho.org/channels/cbde*).

The same applies to intergovernmental agencies in the security arenas. In 2023, the Organization for the Prohibition of Chemical Weapons (OPCW) has a result of its biotoxins analysis process and has reviewed and expended its list of priority toxins, which now includes both low molecular and high molecular weight toxins (*https://www.opcw.org/documents/2023/04/sabrep123/analysis-biotoxins-report-scientific-advisory-boards-temporary-working*). The subsequent report highlights the importance for field detection and the potential value of strengthening early clinical diagnosis of biotoxin exposure and the need to determine whether exposure is due to deliberate use, rather than natural exposure. In 2024, INTERPOL has undertaken a full review of its list of biological agents and toxins of concerns for animal and human populations to ensure it remains relevant for the global law enforcement communities. This list, which is made available to the law enforcement community, can support the development of national and regional strategies to prevent, prepare for and respond to bioterrorism incidents targeting human and animal populations.

Several of the aforementioned intergovernmental organizations have also developed tools or frameworks to assess different aspects at the interface of bioterrorism surveillance and investigations. For example, some of the indicators of the WHO Joint External Evaluation or the WOAH Performance of Veterinary Services Pathway can identify capabilities and gaps related to public health and veterinary surveillance and epidemiological surveillance (Babigumira et al., 2023). Conversely, the Biothreat Detection Module of FAO's Surveillance Evaluation Tool was co-developed with WOAH and INTERPOL with the specific purpose to help countries assess their capacities to detect agroterrorism and agrocrime (Vasconcelos et al., 2021). With the launch in 2023 of its Global Biosecurity Enhancement Programme for Law Enforcement, INTERPOL developed, with the support of a group of expert, its Biosecurity Country Needs and Capability Assessment Framework (*https://www.interpol.int/content/download/21008/file/23COM003018-01%20CBRNE_BioT_Global%20Biosecurity_Porject%20sheet_2023-09_EN%2005%20HR%20%281%29.pdf*). This framework focuses on the interagency capacities, resources and partnerships needed, from a law enforcement perspective, to efficiently prevent, prepare and respond to suspected deliberate biological incidents, including the detection and investigation of bioterrorism.

INTERPOL is also contributing to the establishment of safer and more robust approaches for the investigation and processing of bio-contaminated evidence at national, regional and international levels. This is mostly done through capacity building activities undertaken with the support of national experts and organized as part of national training or co-organized with other intergovernmental organizations such as the WOAH, the United Nations Office for Counter Terrorism or the United Nations Office for Disarmament Affairs (*https://www.interpol.int/Crimes/Terrorism/Bioterrorism/BioTerrorism-Expertise*). While the mandate of some of those partner entities focuses on the investigation into the alleged use of biological agents and toxins by state actors (e.g. the United Nation Secretary-General's Mechanism for the investigation of alleged use of biological and chemical weapons or the OPCW), their work contributes to strengthen national expertise and international networks required to investigate bioterrorism.

In addition to strengthening prevention, detection of and preparedness for bioterrorism attacks, some of the international organization aforementioned, as well as regional organizations, also offer support to their membership in response to the deliberate release of a biological agent or toxin (Babigumira et al., 2023). For example, while WHO does not have a mandate to lead nor to participate in investigations in response to a potential deliberate event, they may collaborate with and support other entities and mechanisms, or deploy staff and resources to affected countries through their Global Outbreak Alert and Response Network (*https://goarn.who.int/*). WOAH and the Food and Agriculture Agency of the United Nations (FAO) would play a similar role should animal and/or plant health be targeted (*https://www.woah.org/en/what-we-offer/emergency-preparedness/interagency-cooperation-for-emergency-management/*; *https://www.fao.org/animal-health/our-programmes/emergency-management-centre-(emc)/en*).

Potential Solutions and Recommendations

International conventions do not require states to have legislation criminalizing the deliberate dissemination of biological agents against human, animal and plant populations. For many states, this is covered by some more general legislation without addressing the specificities of biological agents dispersal. Therefore, national legislation should be updated to provide better protection and prosecution of such acts (DeVries, 2023). In parallel, national law enforcement agencies need to ensure the proper level of awareness of their officials about the existing legal frameworks relative to biosecurity and the misuse of biological agents in their country.

To efficiently support cooperation between law enforcement and other relevant agencies, such as human, animal, plant and health agencies and regulatory authorities, interagency agreements should be formalized and provide a framework for the sharing of bioterrorism and biocrime information at national level. These agreements should also make provision for the early and sustained involvement of all relevant stakeholders to interagency prevention, preparedness and response activity in the area of bioterrorism, and include clear triggers and indicators for action and investigation with clearly defined roles and responsibilities as part of a 'One Health' approach to deliberate biological incidents.

Bioterrorism detection could be strengthened through awareness raising and training on triggers and indicators of bioterrorism in all stakeholders. However, this would have to be supported by the establishment of systems defining clear criteria and processes for the reporting of deliberate or suspicious events. In this regard, the development of additional guidance and resources from international organizations would be beneficial, particularly in plant health.

Existing resources developed by regional and international partners for generic purposes or for the very purpose of identifying gaps in prevention, preparedness and/or response to deliberate biological events are a good starting point to identify priority area for improvement (Babigumira et al., 2023). Similarly, priority biological agents and/or toxins lists from international organizations can support the prioritization of surveillance efforts at national level based on a clearly defined purpose and the application of strong and fit for purpose criteria (Pillai et al., 2023).

Both environmental and field detection are still quite limited compared to other CBRN substances. Considering the development of detection technology significantly depends on industry and academia, public-private partnerships should be considered to speed up innovation in this area in particular for rapid, sensitive, specific and cheaper field detection.

Intelligence units' expertise and tools should be strengthened to expand the scope of intelligence collection for a comprehensive analytical approach. Promoting international information sharing, including through INTERPOL BioTracker, represents a unique opportunity for member countries to contribute to the detection and early warning of biological incidents through an integrated intelligence collection and analysis, and thus provide a better understanding of the global bioterrorism threat landscape. Intelligence sharing between relevant international organizations should be promoted and facilitated through formalized cooperation agreements. The preparedness phase is essential for the establishment of interagency agreements for the safe biological crime scene management and forensic planning. These agreements should foster interagency cooperation, joint planning, joint SOPs, joint training and joint exercising (Green, M. S., LeDuc, J., Cohen, D., & Franz, D. R., 2019). They should also cater for the establishment of a comprehensive network of laboratories for evidence examination (microbial and traditional forensics in a 'One Health' perspective).

More guidance, research and resources should be developed on biological crime scene management, as well as safe and efficient examination of bio-contaminated evidence. Experience sharing in that area through various fora would be beneficial for forensics team developing expertise or looking for solutions to specific issues in the examination of traditional evidence contaminated by different types of biological agents or toxins.

CONCLUSION (ORIGINALITY/VALUE)

While some scientific literature exists on bioterrorism forensics, recent studies mostly focus on microbial forensics. This paper focuses on the institutional limitations and gaps in the detection of bioterrorism incidents, measures for the safe and efficient processing of the evidence collected in such investigations, as well as discussing opportunities to address those gaps.

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