Preliminary communication

A COMPACT, AI-POWERED SYSTEM FOR RAPID DECONTAMINATION DURING CBRNE INCIDENTS

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Abstract: Effective decontamination is critical in emergency response, yet traditional systems require extensive infrastructure, specialized personnel and significant logistical support, limiting their practicality in urgent scenarios. This Work-in-Progress (WiP) paper presents: i) the Fast Deployable Mass Decontamination system (FDMD), a novel decontamination tunnel designed for rapid deployment, operational flexibility and ease of use in various emergency response environments, and ii) the DECON Body Pose Estimation Tool (DBPET), a camera-based AI-driven image-analysis system that tracks body posture in real-time, integrated with the FDMD to ensure optimal decontamination coverage. Utilizing integrated speakers, the DBPET provides automated, step-by-step instructions to guide individuals and minimize body posture error based on international standards. Additionally, its multilingual support enhances accessibility, enabling clear communication in high-stress environments. FDMD incorporates three interchangeable sets of sprinklers, supporting both wet and dry decontamination methods based on the nature of the contamination. The system features a lightweight, modular structure that enables quick assembly with minimal training requirements, while minimizing its storage in a large suitcase. This paper examines the decontamination process and systems and outlines the FDMD's and DBPET's design, key technological components, initial experimental validation efforts and expected impact and benefits. Preliminary assessments focus on deployment speed, body posture efficiency and operational scalability. Future work will expand on performance testing, field trials and integration with other technological tools under development (e.g. Digital Triage Tag) and within emergency response frameworks. By addressing current decontamination challenges, FDMD integrated with the DBPET aim to provide an efficient, cost-effective, rapidly deployable and adaptable solution for first responders (FRs), experts and non-experts managing CBRNE incidents.

Keywords: Mass Decontamination, Body Pose Estimation, CBRNE incident, Emergency Response, Crisis Management

1. INTRODUCTION

Disasters, both natural and human-made, have shaped the course of history. From ancient plagues and natural catastrophes to the modern complexity of Chemical, Biological, Radiological, Nuclear and

Explosive (CBRNE) threats, humanity has continually adapted its response to crisis. Over time, disaster management has evolved, recognizing the need for effective strategies to minimize loss of life and infrastructure (Sendai Framework for Disaster Risk Reduction: 2015-2030, 2015).

The Disaster Management Cycle consists of four key phases: mitigation, preparedness, response and recovery (Coppola, 2020). In the context of CBRNE incidents, the importance of these phases becomes even more pronounced, as those present unique challenges due to the complex and hazardous nature of the materials involved, requiring the implementation of specialized strategies in each disaster management phase (Turmus and Hostiuc, 2023), (U.S. Department of Education, 2007).

During response, proper decontamination is essential for protecting victims and emergency personnel. Decontamination serves a dual purpose by neutralizing or removing harmful contaminant agents from affected individuals and by preventing cross-contamination and the spread of contamination to other areas and people (Lake et al., 2013). Despite being a phase of critical importance, current decontamination methods often face significant challenges, including the need for rapid deployment, resource limitations and effectiveness of existing systems in handling a wide range of CBRNE threats (Calder and Bland, 2015). Time is crucial in CBRNE events, often determining the effectiveness of response efforts. FRs operate under intense pressure to swiftly contain the source, mitigate risks and prevent cross-contamination, as delays can exacerbate exposure and complicate decontamination procedures (Hai-Long et al., 2015). The *proposed solution*, a novel decontamination system with enhanced capabilities, aims to address these challenges by providing a more efficient, scalable and effective approach. By integrating advanced technologies such as a DBPET, the system ensures real-time tracking of body posture, optimizing decontamination coverage, minimizing human error and overcoming the limitations of current methods, while improving overall response and recovery efforts. This innovation enhances response times, offering faster and safer decontamination in both low and high-risk events.

2. LITERATURE OVERVIEW AND STATE OF THE ART

Decontamination is vital in CBRNE response, mitigating health risks and secondary contamination, while also reducing the burden on medical infrastructure. The selection of the appropriate method depends on the contaminant type, operational context and required level of protection for affected individuals and FRs. Methods range from simple physical removal to more sophisticated ultrasonic procedures, each with specific benefits and limitations (International Atomic Energy Agency, 2023). This study focuses on physical removal, wet and dry decontamination techniques, both of which are central to mass casualty decontamination. These protocols generally follow six operational steps to ensure systematic and effective treatment of exposed individuals (Madigan, 2023), (Lake et al., 2013). Depending on the scenario, wet or dry methods may be employed, offering operational flexibility based on environmental constraints and contamination type (Chilcott et al., 2018). The selection of decontaminant agents is also critical to decontamination effectiveness (National Institute of Justice, 2001).

In recent years, the focus has shifted toward systems that combine operational efficiency with responder and victim safety. A critical insight from field exercises highlights the importance of privacy, clear communication and trust-building to ensure cooperation and reduce psychological distress during mass decontamination (Carter et al., 2012).

Decontamination systems are broadly categorized into fixed and portable types, as defined by ANSI/ISEA 113-2013. Fixed systems, often installed at critical infrastructures, offer robust, high-throughput capabilities but suffer from limited mobility. Portable systems, on the other hand, enable rapid deployment at the point of need, nevertheless are often limited in capacity and protection features. Table 1 summarizes their comparative strengths and limitations.

Table 1: Strengths and limitations of fixed and portable decontamination systems.

Fixed Decontamination Systems		*Portable Decontamination Systems*	
Strengths	*Limitations*	*Strengths*	*Limitations*
High efficiency usage in permanent or semi-permanent locations	Requires infrastructure, often limiting mobility	Mobile and adaptable to diverse environments	Lower capacity and efficiency than fixed systems
Integration with larger facility operations	Expensive installation and maintenance	Rapid deployment, reducing contamination spread quickly	Requires continuous monitoring and operation to maintain efficiency
Consistent and reliable for long-term use	Limited flexibility for deployment in varied environments	Cost-effective solution	May require additional resources, increasing operational costs for prolonged use
High capacity for large-scale decontamination	Requires significant space, less suitable for tight or remote spaces	Suitable for incidents in unpredictable locations	Vulnerable to environmental factors

Based on evaluations from the U.S. Department of Homeland Security (Homeland Security, 2007), which emphasize operational agility and system adaptability under field conditions, this study proposes a novel, portable system that retains mobility, while incorporating enhanced features traditionally associated with fixed installations.

Considering these evaluations, the system under development is designed as a lightweight, portable decontamination unit that combines the mobility advantages of portable systems with key operational features typically found in fixed installations. A major innovation lies in its dual capability, enabling both wet and dry decontamination methods, allowing adaptation to a wide range of contamination scenarios, environmental conditions and logistical constraints. The system also incorporates an AI-powered body posture monitoring and correction mechanism, which provides real-time audiovisual feedback to guide individuals through the correct decontamination sequence. This intelligent feature reduces the need for direct supervision, ensures optimal exposure to decontamination agents and enhances procedural consistency. By adopting this hybrid and modular approach, the system addresses critical operational needs while maximizing speed, effectiveness and adaptability in various CBRNE environments.

3. THE PROPOSED CONCEPT

3.1 SYSTEM OVERVIEW

The proposed solution, the "Fast Deployable Mass Decontamination" system (FDMD), an innovative and portable decontamination tunnel, is designed to provide rapid, efficient and scalable decontamination for both large and small-scale CBRNE incidents. Contrary to traditional fixed or bulky inflatable units, FDMD is a self-contained, low-cost system that deploys quickly across various environments without the burden of maintaining large infrastructure. Its compact, suitcase-sized design allows easy transport in standard vehicles, enabling flexible pre-positioning and use even in confined spaces, where larger systems are impractical. A major advantage is its dual capability design, featuring three interchangeable sprinkler sets for wet or dry decontamination plus optional water-only rinsing. To further streamline the decontamination process, a camera-based DECON Body Pose Estimation Tool (DBPET) is utilized to track body posture to ensure that people maintain the correct pose inside the decontamination tunnel (Chilcott et al., 2018). They are continuously guided using automated, multilingual, step-by-step visual and audio instructions, enabling clear guidance even in high-stress situations. The guidelines integrate international decontamination protocols in CBRNE incidents. The tunnel also interfaces via the DBPET with digital triage and emergency response systems, logging sensor information and statistics around the process and decontamination status for efficient resource allocation.

The system has advanced from conceptual and preliminary design to the detailed design stage, and is currently in the Prototype 1 development phase. Simulations of water and decontaminant flow, have confirmed the system's structural stability, dual wet/dry decontamination capability, and integration with the DBPET system, forming the basis for upcoming field trials.

3.2 SYSTEM STRUCTURAL COMPONENTS

The system (FDMD and DBPET) is comprised of a set of interconnected subsystems (Table 2) designed to ensure efficient operation. Its modular architecture facilitates rapid and simple assembly and disassembly, optimizing transport and storage.

Table 2: Key Structural Components of the System.

Structural Components	*Description*
Frame and Enclosure	The inflatable frame and stretched-wall enclosure is constructed from lightweight, durable and cost-effective materials, ensuring ease of transport and rapid deployment, even in high-pressure environments. The weather-resistant tunnel enclosure is also easy to clean and maintain, making it suitable for diverse operational conditions.
Inflation System	An integrated inflatable system is connected to the tunnel. It consists of a pressurized gas cylinder (e.g., mixed CO_2 and N_2 cylinder), that can inflate the frame though a nut valve by pulling a manual pull toggle. The gas cylinder can be replaced easily after use.

Decontamination Mechanism	The tunnel employs a multi-method decontamination system with three sprinkler sets, each comprising five full cone spray nozzles connected via pipelines. Strategically positioned for full-body coverage, the nozzles deliver uniform spray using a 60°-90° angle, ensuring head-to-toe reach. One central nozzle at the arc's top targets the upper body, while two on each side provide overlapping coverage. Decontaminants are delivered through an integrated piping network linked to motorized valves and sources like pressurized cylinders or tanks. For rinsing, the system connects easily to standard taps or external pumps.
Control	A centralized user-friendly control panel with simple buttons and led indicators is incorporated. It allows operators to adjust and monitor the decontamination stage. The control system is connected directly to the Jetson device of the DBPET to allow operators to monitor (through led lights) the body posture of the affected individuals inside the tunnel.
Monitoring System	FDMD features a wide range of sensors, allowing the continuous monitoring of the device. A pressure sensor is incorporated into the inflatable structure constantly monitoring its status and detecting any leaks. The device's location will be continuously transmitted to the central management system, either via the GPS module or directly through the Jetson device. The system utilizes infrared sensors at the entrance and exit of the tunnel, and cross-references their signals with the DBPET's algorithm, to accurately monitor the decontamination throughput rate.
Waste and Drainage Management System	The system is equipped with an external drainage connection, featuring a hole for piping that can connect FDMD to an external collection tank. This allows the system to effectively collect used chemicals and wastewater, preventing recontamination. Pumps are utilized to transfer the waste to the external tank. The system's design ensures easy integration with existing waste management infrastructure.
Power Supply	The system's power requirements are met through standard electric power sources. It features plug connection to simple home electric plugs or connection to external batteries, power banks or small generators.
User Interface (UI)	The UI system enhances safety and usability through integrated visual and audio guidance. Victims receive posture instructions via wall-mounted images and multilingual audio prompts. Cameras embedded in the FDMD continuously monitor posture using the DBPET Algorithm, which provides real-time audio feedback for optimal positioning.
DECON Body Pose Estimation Tool	DBPET is a self-contained and portable system that is comprised of a central processing unit, a camera, a speaker, a microphone, a Wi-Fi adapter, infrared sensors, and a small external battery. A Jetson Development kit is used to connect all peripheral devices and provide the required computational power.

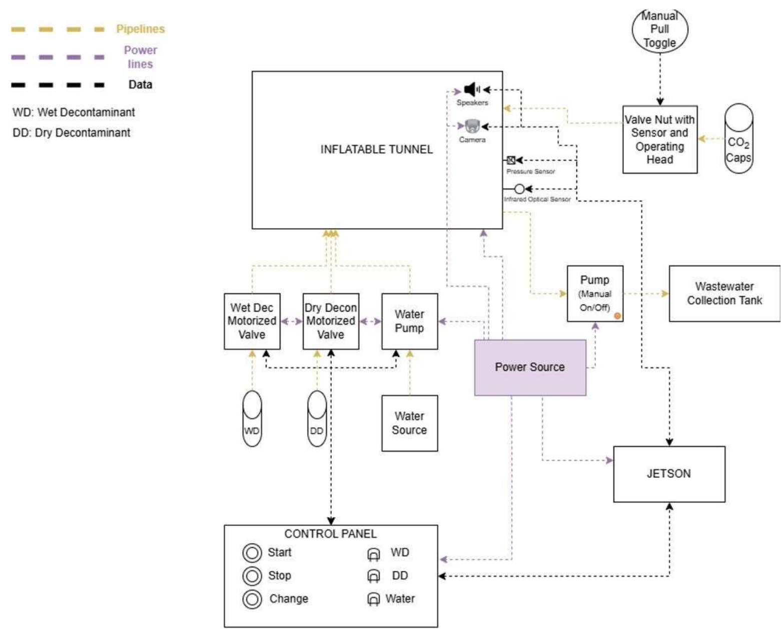

Figure 1: Structural diagram of the system.

3.3 SYSTEM WORKFLOW

The integrated operation of the FDMD and the DBPET enables an end-to-end, semi-automated and standardized decontamination process for CBRNE incidents. While the FDMD provides a rapidly deployable, compact physical infrastructure for effective wet or dry decontamination, the DBPET enhances the procedure by offering real-time, AI-driven audiovisual guidance to ensure correct body positioning according to international decontamination protocols. Together, they form a unified system designed to maximize operational efficiency, precision and accessibility under emergency conditions. The overall system workflow can be described through the following stages, based on the DBPET's operation.

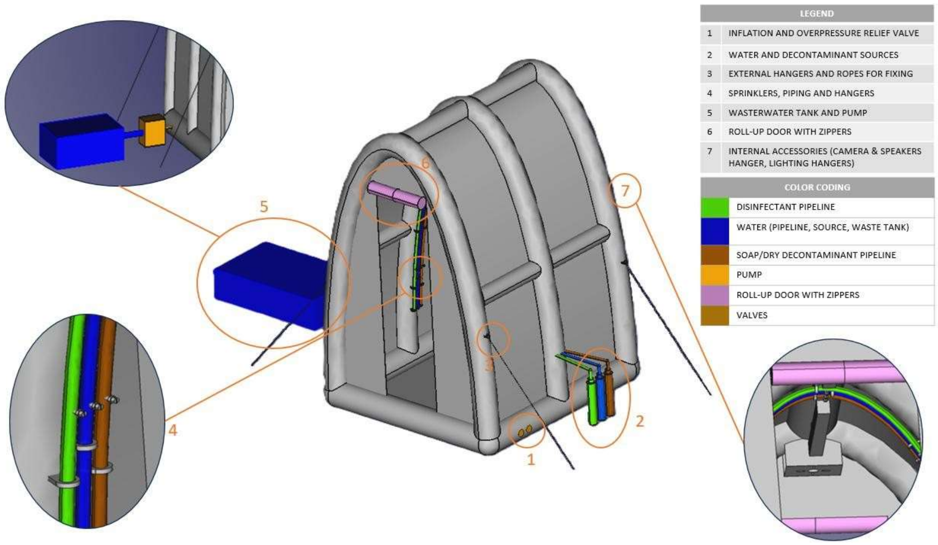

Figure 2: FDMD Preliminary CAD design.

3.3.1 INITIALIZATION

Upon deployment, the FDMD structure is assembled and connected to the necessary power and water sources, requiring minimal setup time (target < 15mins). Simultaneously, DBPET's main processing unit is activated, performing an automated recognition and verification of all connected devices, including cameras, speakers and local processing nodes. External operators can then select the desired language for the human-tool interaction from at least five available options, ensuring multilingual support for diverse populations. As users approach the decontamination line, they are detected by the system’s camera and directed toward predefined marked positions within the FDMD tunnel, where spraying nozzles are installed. Visual signs strategically placed inside the decontamination infrastructure, coupled with body-part-specific audio instructions from the speakers, assist the users in assuming their initial pose for the decontamination procedure.

3.3.2 POSE REFINEMENT

The computer vision-based AI model processes the camera feed to calculate the joints’ 3D positions, with a benchmarked accuracy of at least 90%, and a comparison between them and a scale-adjusted pose derived from international protocols (Lake et al., 2013) is conducted. Based on the detected deviations, the tool delivers further audio instructions targeted on specific body parts, achieving real-time pose refinement. Through the refinement rounds, the tool continuously evaluates and iteratively provides guidelines for the user’s posture adjustment, until the deviation falls below a predefined accuracy threshold. This threshold is determined through extensive testing to ensure compliance with decontamination protocols, while maintaining operational efficiency. At this point, we would like to highlight that the image processing of the camera's feed is performed exclusively on the main processing unit, ensuring privacy and security standards. All data are processed directly on the device (Jetson) and then discarded, with no visual information transmitted externally, guaranteeing full compliance with GDPR and relevant data protection regulations. Access is controlled via secure authentication, and any personally identifiable information is anonymized or not retained, maintaining confidentiality and data integrity throughout operation.

3.3.3 DECONTAMINATION

Once the pose refinement is successfully completed, the tool instructs the user via the speakers to maintain the corrected pose, while the external operator initiates the decontamination spraying process. In case the user systematically fails to maintain the required pose, an audio notification prompts the operator to temporarily halt the spraying process, and a new refinement round is initialized until completion.

3.3.4 SECONDARY EXTERNAL DEVICES

After the completion of the decontamination steps, the user proceeds to the designated exit of the FDMD, where a motion sensor records their departure. The validation of the number of individuals exiting the infrastructure using the motion sensor and the AI-based model's detections ensures safety and compliance with the international protocols. Using the Wi-Fi USB adapter, the tool can optionally connect to a local network or hotspot to transmit non-personal operational data, such as the number of decontaminated individuals, average refinement rounds, average decontamination time, and status updates and other measurements from the decontamination line, if linked to an external monitoring infrastructure. The DBPET is engineered to operate as a standalone, automated and adaptive system, with at least 6 hours of power autonomy on its battery, facilitating precise and standardized decontamination procedures, while ensuring user compliance and process integrity.

3.4 DEPLOYMENT SCENARIOS AND APPLICATIONS

This section explores example deployment scenarios, highlighting the system’s flexibility and effectiveness in diverse environments. The following scenarios illustrate the wide range of applications and operational benefits of the system.

Table 3: Deployment scenarios detailed descriptions.

Scenario 1: Large-Scale Emergency Response
Description: In large-scale contamination scenarios, such as a hazardous chemical spill in a train station, multiple FDMD units can be swiftly deployed at key access and exit points to manage affected individuals. Their compact design, rapid setup and ease of use allow FRs or security staff to operate them with minimal training, limiting contamination spread during the early stages of response. FDMDs provide immediate decontamination before fixed installations are available and can later support secondary roles. Each unit integrates the DBPET system, powered by an embedded Jetson device, which guides users through body pose detection and multilingual instructions. Real-time communication with the central management platform ensures coordinated oversight, situational awareness and optimized resource deployment. This interconnected approach strengthens the overall responsiveness and effectiveness of mass decontamination operations. *Key features:* Multiple units for coverage, Centralized monitoring *Benefits:* Scalability, Central Monitoring, Quick Operation
Scenario 2: Urban Environment: High-Density/Confined Spaces
Description: In confined, high-density environments like an office during emergency evacuation, FDMD units can be quickly deployed near exits or in hallways to enable immediate decontamination. Compatible with standard water taps and power outlets, and operable by non-experts with minimal training, the system ensures rapid setup. Integrated DBPET delivers multilingual, step-by-step pose guidance, to correctly perform the process. By supporting decontamination at exit points, it limits contamination spread while preserving evacuation flow. Its compact form and plug-and-play design make it ideal for space-constrained, time-critical scenarios. *Key features:* Compact units, rapid setup in tight spaces *Benefits:* Compact, Rapid Deployment, Minimal Disruption
Scenario 3: Pre-Positioning for Rapid Response
Description: Pre-positioning FDMD in high-risk zones such as hospitals, airports or industrial facilities ensures immediate availability in case of an emergency. These units can be placed in strategic locations, such as near entry/exit points, to allow for fast decontamination when needed. Since the system requires only basic user training, any trained security officer or emergency responder can quickly deploy it, significantly reducing response time during a chemical spill, biological threat or other contamination events. Regular checks ensure the system is always operational and ready for use, ensuring swift, effective response without delays. *Key features:* Cost-effective units pre-positioned for quick activation *Benefits:* Proactive Readiness, Strategic Placement, Minimal Training

4. IMPACT AND BENEFITS

The system provides measurable benefits across operational, societal, technological, and environmental domains. The following Table 4 summarizes the system's core advantages, highlighting how its innovative design improves efficiency, safety and sustainability while maintaining operational flexibility in diverse emergency scenarios.

Table 4: Impact and benefits summary.

Impact Area	*Key benefits*
Economic	Cost-efficient compared with traditional fixed and portable units; minimal operator training in contrast with existing inflatable systems; no permanent infrastructure required
Operational	Lightweight design (can be carried by a single person); rapid deployment and operation by a single operator; modular and scalable; coordinated multi-unit response; dry and wet decontamination capabilities
Societal	Improved public safety; reduced health risks (Homeland Security, 2014); preserves user dignity through enclosed decontamination (Carter and Amlôt, 2016); multi-language AI guidance
Technological	AI-driven posture guidance (DBPET); modular sprinkler sets; pull-through inflation; multi-sensor monitoring; streamlined compared with traditional portable units lacking integrated automation
Environmental	Minimal infrastructure; low power consumption; eco-friendly agents; reduced vehicle emissions; more sustainable than large-scale fixed or heavy portable systems

5. FUTURE WORK

Following the current development and testing phases of the system, several areas for future enhancement have been identified to further strengthen its operational effectiveness, resilience and adaptability in diverse CBRNE scenarios. A primary objective is the continuous optimization of the FDMD unit's hardware design to reduce weight and improve modularity, thereby enhancing portability and deployment speed in challenging environments. Investigations will also focus on expanding the system’s compatibility with alternative power and water sources, including the potential integration of battery-powered operation and mobile water tanks, to increase autonomy in field conditions. Regarding system monitoring and control, future iterations will emphasize the advancement of centralized management features, enabling enhanced real- time supervision and predictive maintenance capabilities.

Following the development of the DBPET’s core functionalities, several enhancements are planned to focus on automation, security and integration. Ensuring encrypted communication and protection against unauthorized access is a top priority to reinforce network and data security. An NFC reader will be installed at the FDMD exit to enable instant triage and decontamination status updates via smartwatch tagging, supporting better coordination (Athanasiadis et al., 2022). The spraying valves will be connected to the DBPET through dedicated cabling, allowing automated control of the decontamination cycle. A maintenance protocol will be developed to support long-term reliability and train responders on proper hardware handling. Additionally, AI models such as real-time sentiment detection are being considered to monitor stress levels and trigger alerts for improved situational awareness. A dynamic LED posture guide panel will also be considered, displaying various body postures and highlighting the correct one using color-coded lights. Synced with the Jetson device and DBPET, it will help users maintain correct positioning throughout the cycle, improving compliance and clarity without relying solely on audio. These upgrades aim to enhance automation, operational autonomy and user experience. Together, these enhancements will elevate DBPET into a fully integrated, intelligent system that supports both operational efficiency and responder well-being in high-stress scenarios.

To verify and validate the system, a structured testing roadmap has been defined. The programme will evaluate both technical performance and operational effectiveness including different key metrics. Table 5 presents the verification, evaluation and validation roadmap.

Table 5: Planned testing activities.

Test Activity	*Planned Period*	*Key Performance Indicators (KPIs)*
Laboratory Test Series 1	Sept - Oct 2025	Deployment time, space requirements, initial AI monitoring performance
Usability Tests	Feb 2026	Training requirements, workflow efficiency, user compliance
Integration Tests	Mar 2026	Connectivity, automation functionality, control accuracy
Laboratory Test Series 2	May - Jun 2026	Flow rate distribution, decontamination efficiency, AI detection accuracy
Full-Scale Trial 1	Aug 2026	Real-world deployment time, operator compliance, system robustness
Full-Scale Trial 2	Oct 2026	All metrics combined; readiness for and TRL6 advancement

6. CONCLUSION

This paper introduced *"A Compact, AI-Powered System for Rapid Decontamination During CBRNE Incidents"*, focusing on the FDMD system and the DBPET. Designed for rapid and scalable decontamination, the system integrates AI-driven automation and user support, enabling non-expert users to perform effective decontamination without specialized training. The FDMD system's modular design ensures quick deployment, while DBPET optimizes the process through real-time monitoring and multilingual guidance. Future enhancements will focus on increased automation, cybersecurity and resource optimization, with potential integration of wearable triage systems for improved coordination. This approach significantly advances mobile decontamination technology, supporting FRs and enhancing CBRNE incident management.

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