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Decontaminants Used After Biorisk Material Decontamination: Environmental Impact and the Role of Drones in Detection and Remediation of Resistance in Ecosystems

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ABSTRACT

In our rapidly evolving world, the confluence of challenges and opportunities in decontamination, ecological resilience, and cutting-edge technology has become a focal point of concern and innovation. This review explores the interplay between these elements, with profound implications for human safety and environmental equilibrium. Post-decontamination treatment is pivotal in countering Chemical, Biological, Radiological, and Nuclear (CBRN) hazards. Thorough contamination elimination is imperative for risk management. The emergence and proliferation of resistance within ecosystems present a complex challenge. Resistance mechanisms can thwart decontamination agents, affecting environmental restoration, human health, and ecological resilience. Drone technology heralds a transformative era in environmental monitoring. Drones with advanced sensors and data capabilities provide access to remote, hazardous, and inaccessible ecological areas. Real-time data empowers researchers to adapt to evolving conditions, including resistance dynamics. Drones also serve as tools for targeted remediation in contaminated areas, optimizing resource allocation and minimizing disruption. Case studies highlight their efficacy in ecological restoration. Integrating drones into post-decontamination protocols is a paradigm shift. Real-time data, facilitated by drones, bridges the gap between ecological understanding and strategic action. In conclusion, safeguarding our world is a collective responsibility. Drones symbolize our commitment to harmonizing human needs with the environment. This review illuminates a path forward, celebrating our capacity to protect, preserve, and prosper, not just for ourselves but for the world we inhabit. It emphasizes the imperative to save our planet, forging a sustainable future where humanity and nature thrive in harmonious coexistence.

Keywords: Decontamination, resistance, drone technology, environmental monitoring, ecological resilience

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1 Introduction

In an era characterized by rapid technological advancements and an increasingly interconnected global community, the management of biorisk materials and the consequences of their inadvertent release or misuse have emerged as critical concerns for both public health and environmental preservation [1]. The process of decontamination, which seeks to mitigate the hazards posed by these materials, represents a pivotal component in safeguarding human health and ecological integrity [2]. However, it is imperative to recognize that the efficacy of decontamination procedures is not without collateral ramifications, particularly regarding their environmental implications [3].

Concurrently, the advent of drone technology has opened new vistas in environmental monitoring and remediation. Drones, equipped with advanced sensor arrays and remote sensing capabilities, offer an unprecedented opportunity to scrutinize the aftermath of decontamination efforts with precision, allowing for real-time data collection and decision-making [4]. Their integration into biorisk material management holds immense potential in addressing the ecological consequences of post-decontamination decontaminants and in developing targeted strategies for resistance detection and remediation. As traversing the intricate terrain of post-decontamination decontaminants, environmental impacts, and the pivotal role of drones, this review endeavors to elucidate the complexities surrounding these issues [5]. Through a synthesis of existing literature, analysis of case studies, and exploration of future research directions, this review seeks to provide a comprehensive understanding of the challenges and opportunities that lie at the intersection of decontamination, environmental stewardship, and the preservation of ecosystem resilience. In so doing, it underscores the imperativeness of adopting a holistic approach that harmonizes human safety with environmental sustainability in the context of biorisk material management [6].

This review aims to delve into the intricate and multifaceted nexus between post-decontamination decontaminants, their influence on the environment, and the evolving challenges posed by the emergence of resistance in ecosystems. While the immediate objective of decontamination is to render biorisk materials innocuous, the inherent properties of decontaminants and their interaction with environmental matrices often engender unforeseen ecological perturbations [7]. In parallel, the phenomenon of resistance, long studied within the realm of antimicrobial resistance, is increasingly manifesting itself in ecological settings post-decontamination, eliciting concerns about the resilience of ecosystems and their capacity to rebound from anthropogenic perturbations [8].

2 Post-Decontamination Decontaminants: Agents and Their Environmental Implications

The effective mitigation of biorisk materials necessitates not only the initial decontamination procedures but also the subsequent application of post-decontamination decontaminants [9]. These agents, designed to neutralize residual contamination and ensure the complete eradication of hazardous materials, play a pivotal role in the safety and security of both human populations and the environment [10,11].

2.1 Types of Post-Decontamination Decontaminants

Post-decontamination decontaminants encompass a spectrum of chemical, biological, and physical agents, each tailored to the specific nature of the biorisk material and the environment in which decontamination occurs. These agents are diverse, ranging from oxidizing chemicals and biocides to enzymatic compounds and radiation-based methods. The choice of decontaminant is contingent upon factors such as the type of hazardous material, the contamination level, and the intended decontamination site [12].

• Chemical Decontaminants: Chemical agents, exemplified by oxidizing agents like hydrogen peroxide or chlorine-based compounds, are extensively used in post-decontamination processes. They are prized for their ability to react with and neutralize biological agents and toxins. However, the indiscriminate use of such chemicals can have profound effects on surrounding ecosystems. Runoff from decontamination efforts can contaminate soils and water bodies, leading to adverse ecological consequences [13].

• Biological Agents: Biological decontaminants employ living organisms, such as enzymes or bacteria, to break down or metabolize biorisk materials. While biodegradation is a promising approach, the introduction of non-native organisms into ecosystems may disrupt natural microbial communities, potentially leading to ecological imbalances.

• Radiation-Based Decontamination: Radiation-based methods, including gamma irradiation and electron beam treatment, utilize ionizing radiation to eradicate contaminants. While highly effective, these methods can induce chemical changes in soils and other materials, altering their physicochemical properties and potentially affecting soil fertility and microbial activity [9].

2.2 Environmental Implications

The use of post-decontamination decontaminants, although indispensable for safeguarding human health, engenders a series of environmental implications that demand careful consideration. These implications encompass soil and water contamination, alteration of microbial communities, and disruption of ecosystems [14].

• Soil Contamination: Residues of decontamination agents can persist in soil matrices long after their application, potentially leading to soil pollution. The accumulation of such residues may alter soil chemistry, affecting nutrient availability and soil pH, which, in turn, can influence plant growth and overall ecosystem health.

• Water Contamination: Runoff from decontamination efforts can transport decontaminants into nearby water bodies, raising concerns about water quality. Contaminants can adversely affect aquatic ecosystems, disrupting aquatic life and posing risks to human water resources [15].

• Microbial Community Shifts: The introduction of decontamination agents into soil and water environments can induce shifts in microbial communities. These shifts may favor the development of resistance mechanisms among microorganisms, a phenomenon that can impact ecosystem functioning and resilience.

• Ecosystem Disruption: The cumulative effect of post-decontamination decontaminants on soil, water, and microbial communities can lead to broader ecosystem disruptions. These disruptions may manifest as changes in species composition, habitat degradation, and alterations in trophic dynamics.

Apparently, it becomes evident that post-decontamination decontaminants are not without their ecological consequences. It is imperative to recognize the intricate interplay between human safety and environmental stewardship, seeking a balance that minimizes adverse impacts on ecosystems while ensuring the effective neutralization of biorisk materials [16].

2.3 The Imperative of Post-Decontamination Treatment

The utilization of post-decontamination decontaminants arises from the critical necessity to ensure that residual contamination, often imperceptible to the naked eye, is thoroughly eliminated following initial decontamination procedures [17]. The need for post-decontamination treatment is underscored by several factors:

- Residual Threats: Even the most meticulous initial decontamination processes may leave behind minute traces of biorisk materials. These residual contaminants, although at reduced concentrations, continue to pose a potential threat to human health and the environment. The persistence of such contaminants can result from their adherence to surfaces, penetration into porous materials, or subsurface infiltration into soils [18].

- Persistence of Biological Agents: Biological agents, including microorganisms and their toxins, exhibit tenacity in adverse environmental conditions. Residual spores, for instance, can remain viable for extended periods, posing a latent danger if not effectively neutralized. Consequently, post-decontamination decontaminants are designed to target these lingering threats, preventing their resurgence [19].

- Preventing Recontamination: In scenarios where decontaminated areas are intended for subsequent use, the prevention of recontamination is paramount. Post-decontamination treatment acts as a safeguard against the reintroduction of biorisk materials into spaces where they may pose risks to occupants or the broader environment [20].

- Environmental Resilience: While the focus of post-decontamination treatment is primarily on human safety, it is intrinsically tied to environmental resilience. By ensuring that residual contamination is eliminated, additionally mitigating the potential for ecological perturbations arising from low-level, persistent contamination should be made [21].

In sum, the imperative for post-decontamination treatment lies in its capacity to address residual contamination that lingers in the aftermath of decontamination efforts. This strategic approach safeguards against potential threats, bolsters environmental resilience, and upholds the overarching objective of biorisk material management—namely, the protection of human health and the environment [22].

3 Resistance in Ecosystems: A Growing Concern

In the complex milieu of post-decontamination scenarios, the emergence and proliferation of resistance in ecosystems have become a topic of escalating concern. Resistance, in this context, refers to the ability of microorganisms and other biological entities within ecosystems to withstand and adapt to the presence of post-decontamination decontaminants [23,24].

3.1 The Dynamics of Resistance

Resistance in ecosystems manifests as the capacity of resident organisms to endure and, in some instances, thrive in the presence of post-decontamination decontaminants that were originally intended to eradicate them. These resistant organisms may include bacteria, fungi, algae, or even higher-level organisms within the ecological hierarchy. The dynamics of resistance are shaped by several interrelated factors [25]:

• Selection Pressure: The application of post-decontamination decontaminants exerts a profound selection pressure on microbial populations. Those microorganisms possessing inherent or acquired resistance mechanisms gain a competitive advantage.

• Genetic Adaptation: Resistance can arise through genetic adaptation, involving mutations that confer protection against decontaminants. Genetic changes may occur spontaneously or be transferred horizontally among microbial communities, enabling the rapid dissemination of resistance traits [26].

• Co-Selection: The use of broad-spectrum decontaminants may co-select for resistance to antibiotics or other antimicrobial agents. This phenomenon is particularly concerning in environments where human and veterinary pharmaceuticals coexist with post-decontamination agents.

• Ecological Context: The ecological context plays a pivotal role in resistance dynamics. Environmental conditions, nutrient availability, and the presence of competing or symbiotic species all influence the prevalence and persistence of resistance [27].

3.2 Mechanisms of Resistance

Resistance in ecosystems arises through a spectrum of mechanisms, each conferring a degree of protection against post-decontamination decontaminants. These mechanisms may be intrinsic or acquired, stemming from the acquisition of resistance genes. Key mechanisms include [28]:

• Efflux Pumps: Microorganisms can employ efflux pumps to expel decontaminants from their cellular membranes, reducing their intracellular concentration.

• Enzymatic Degradation: Certain microorganisms produce enzymes capable of degrading decontaminants, rendering them ineffective.

• Biofilm Formation: Microbial communities often encase themselves in protective biofilms, shielding against decontaminant penetration.

• Genetic Resistance Elements: Resistance genes, including those encoding for antibiotic resistance, can be mobilized and disseminated among microorganisms via horizontal gene transfer mechanisms [27].

3.3 Implications of Resistance

Resistance in ecosystems carries significant implications for human health, environmental stability, and biorisk material management:

• Human Health Risks: Resistant microorganisms may persist in the environment, potentially encountering humans or animals. This may raise concerns about the transfer of resistance genes to pathogens, complicating diseases treatment.

• Ecological Resilience: Resistance can alter the composition and functioning of microbial communities, potentially reducing ecosystem resilience and adaptability to environmental changes.

- Long-Term Environmental Impact: The persistence of resistant organisms in the environment may have long-term repercussions, necessitating proactive strategies to mitigate resistance and protect ecosystem health.

The intricate terrain of resistance in ecosystems makes the picture clear that this phenomenon warrants comprehensive examination and proactive management strategies [27,28].

4 Monitoring and Managing Resistance

Effectively addressing resistance in ecosystems necessitates a multifaceted approach that encompasses monitoring, assessment, and adaptive management. This proactive stance is crucial to mitigate the potential consequences of resistance emergence. Several key considerations underpin these efforts [29]:

- Surveillance and Detection: Monitoring the presence and prevalence of resistance in ecosystems is paramount. Molecular techniques, metagenomics, and microbiome analysis offer valuable tools for identifying and quantifying resistance genes and resistant organisms within ecological niches.

- Environmental Risk Assessment: A comprehensive assessment of the environmental risks associated with resistance is indispensable. Such assessments evaluate the potential ecological consequences of resistance, helping to inform management strategies [30].

- Integrated Management: Addressing resistance in ecosystems necessitates an integrated approach that combines ecological restoration, targeted intervention, and responsible decontamination practices. Strategies may include the use of alternative decontamination agents, decontaminant-free zones, and promoting natural attenuation of contaminants.

- Adaptive Management: Given the dynamic nature of resistance and ecosystems, adaptive management strategies are essential. These strategies involve ongoing assessment and adjustment based on evolving data and ecological conditions.

- Drone-Based Monitoring: As technology advances, drones have emerged as powerful tools for real-time monitoring of resistance. Equipped with various sensors, including DNA sequencers and imaging devices, drones can provide valuable data for tracking resistance dynamics in remote or challenging-to-reach environments [31,32].

4.1 Defining Resistance in Ecosystems

Resistance in ecosystems is a multifaceted phenomenon that resonates deeply within the context of post-decontamination scenarios. At its core, resistance denotes the capacity of microorganisms and other biological entities residing within ecosystems to withstand and adapt to the presence of post-decontamination decontaminants, which were originally introduced with the intention of eradicating them. This intricate concept becomes especially pertinent in the wake of decontamination efforts, as it encapsulates the resilience of life forms in the face of chemical, biological, or physical agents designed to curtail their existence. The relevance of resistance in ecosystems emerges from the profound interplay between human interventions, such as decontamination, and the inherent adaptability of organisms to environmental pressures. This adaptability encompasses a spectrum of mechanisms that empower microorganisms and other species to endure the challenges posed by decontaminants. In doing so, these resilient organisms can persist and, in some instances, proliferate, despite the initial intent of rendering them inert [33].

4.2 Decontaminants and the Genesis of Resistance

The use of decontaminants, which constitute an integral component of post-decontamination protocols, may inadvertently precipitate the emergence of resistance in ecosystems. The pathways through which this occurs are complex and multifaceted, reflecting the dynamic nature of microbial communities and ecological systems [34]:

- Selection Pressure: The application of decontaminants creates a potent selection pressure within ecosystems. In essence, it initiates a competitive landscape in which organisms possessing innate or acquired resistance mechanisms gain a distinct advantage. This selection pressure often results from the elimination of susceptible individuals, allowing resistant counterparts to thrive and perpetuate their genetic traits.

- Genetic Adaptation: Resistance can manifest through genetic adaptation, driven by mutations that confer protection against decontaminants. These genetic changes may occur spontaneously within microbial populations or be facilitated by horizontal gene transfer mechanisms, which facilitate the rapid dissemination of resistance traits among microbial communities.

- Co-Selection: Particularly concerning is the phenomenon of co-selection, where the use of decontaminants with broad-spectrum antimicrobial properties inadvertently selects for resistance to other classes of antimicrobial agents, including antibiotics. This co-selection scenario can exacerbate the spread of resistance within ecosystems, compounding the challenge of managing resistant organisms.

- Ecological Dynamics: Resistance dynamics within ecosystems are intricately intertwined with the ecological context. Factors such as environmental conditions, nutrient availability, and the presence of competing or symbiotic species significantly influence the prevalence and persistence of resistance. Consequently, the emergence and propagation of resistance within ecosystems are influenced by a complex web of ecological variables.

Navigating the intricate landscape of resistance in ecosystems, it becomes evident that this phenomenon transcends traditional disciplinary boundaries, necessitating interdisciplinary research and management approaches. A comprehensive understanding of resistance dynamics, their underlying mechanisms, and their ecological consequences is paramount to mitigating the potential risks associated with resistance in the aftermath of decontamination efforts [35,36].

5 The Role of Drones in Resistance Management

The integration of drones into resistance management strategies represents a promising avenue for enhancing our understanding and response to resistance in ecosystems. Drones offer several advantages [37]:

- Real-Time Data Collection: Drones equipped with advanced sensors can collect real-time data on resistance markers, microbial communities, and environmental conditions. This data aids in assessing the extent and dynamics of resistance.

• Remote Sensing: Drones can access remote or hazardous areas, providing valuable insights into resistance in otherwise inaccessible environments, such as post-decontamination sites or contaminated natural reserves.

• Adaptive Sampling: Drones can be programmed to adaptively sample based on detected resistance markers, allowing for targeted sampling and analysis in areas of concern.

• Early Warning Systems: By continuously monitoring resistance markers, drones can serve as early warning systems, alerting stakeholders to emerging resistance trends and facilitating timely intervention.

Resistance in ecosystems represents a multifaceted challenge with far-reaching implications for human health and environmental stability [7]. Grappling with this phenomenon, proactive strategies, including the innovative use of drones, hold promise in enhancing our capacity to detect, monitor, and manage resistance in post-decontamination scenarios.

6 Drones in Environmental Monitoring: Pioneering Precision in Post-Decontamination Assessment

6.1 The Pivotal Role of Drones in Environmental Monitoring

In the realm of post-decontamination assessment and environmental monitoring, the introduction of Unmanned Aerial Vehicles (UAVs), commonly referred to as drones, has marked a transformative paradigm shift. These aerial platforms, equipped with an array of advanced sensors and instrumentation, have emerged as indispensable tools for acquiring real-time data in dynamic and often challenging ecological settings. Their capacity to navigate diverse terrains, access remote or hazardous areas, and capture high-resolution imagery has propelled them to the forefront of environmental monitoring practices [38].

The pivotal role played by drones in environmental monitoring cannot be overstated. Their agility and versatility enable them to execute tasks that were once logistically cumbersome or prohibitively expensive. Moreover, their capacity to collect data in situ, at the heart of environmental processes, affords researchers and environmental managers a level of precision and immediacy previously unattainable. This capacity for real-time data acquisition, paired with their ability to venture into otherwise inaccessible domains, positions drones as instrumental assets in assessing the impact of post-decontamination decontaminants on ecosystems [39].

6.2 Advantages of Drone-Based Assessment in Post-Decontamination Scenarios

The advantages inherent in employing drones to evaluate the impact of post-decontamination decontaminants on ecosystems are manifold and extend across several critical dimensions [8]:

1. Remote Sensing Capabilities: Drones can access remote or challenging terrains, such as contaminated sites or fragile ecosystems, without the need for on-site human presence. This attribute is invaluable in post-decontamination assessments where safety or accessibility may be compromised.

2. Real-Time Data Acquisition: Perhaps their most distinguishing feature, drones provide real-time data, enabling researchers to capture the dynamic nuances of ecological responses immediately after

decontamination efforts. This immediacy is invaluable for assessing the immediate impact of decontaminants.

3. High-Resolution Imaging: Equipped with advanced cameras and imaging systems, drones capture high-resolution imagery, facilitating the precise identification of changes in vegetation, soil conditions, or aquatic ecosystems. This capability enhances the detection of subtle alterations resulting from post-decontamination interventions.

4. Adaptive Sampling: Drones can be programmed to adaptively sample specific areas of concern, focusing data collection efforts where resistance markers, ecological shifts, or contamination hotspots are detected. This targeted approach optimizes resource utilization and data relevance.

5. Improved Safety and Cost-Efficiency: By reducing the need for physical access to hazardous or challenging environments, drones enhance safety for human personnel while minimizing logistical costs associated with extensive fieldwork.

6. Multimodal Sensor Integration: Drones can integrate a diverse range of sensors, including DNA sequencers, spectrometers, and thermal imaging cameras. This multifaceted sensor integration enables comprehensive data collection, allowing for a holistic assessment of environmental changes.

In essence, drones have transcended the realm of technological novelty to become indispensable allies in the pursuit of understanding and mitigating the impact of post-decontamination decontaminants on ecosystems. Their capacity to bridge the gap between human safety and ecological preservation through precise, real-time data acquisition underscores their transformative potential in post-decontamination assessments [40,41]. Figure 1 shows a drone design concept used in post-decontamination.

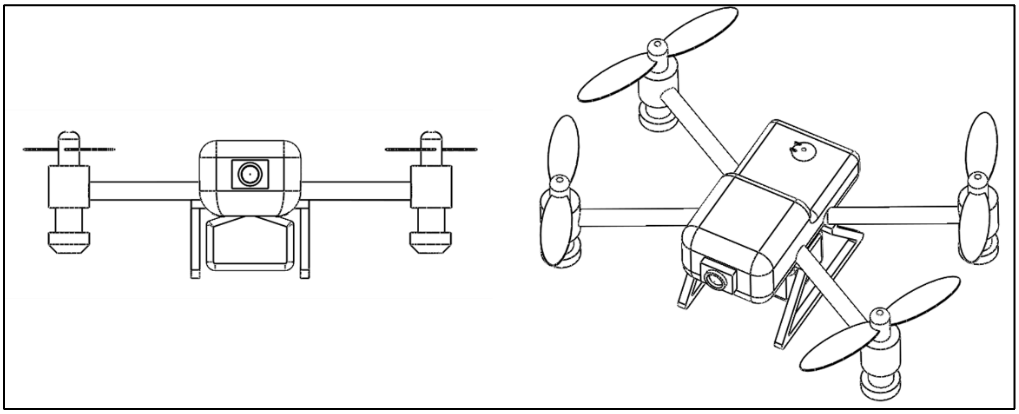

Figure 1: Drone design concept used in post-decontamination.

7 Drone-Based Resistance Detection: Navigating Resistance Frontiers with Precision

7.1 Harnessing Drones for Resistance Detection in Ecosystems

The deployment of drones as instruments of ecological exploration extends beyond their capabilities in environmental monitoring. These aerial platforms have emerged as instrumental allies in the endeavor to detect and scrutinize resistance within ecosystems. The utilization of drones for resistance detection represents an innovative and transformative approach that holds immense promise in our quest to comprehend the complexities of resistance dynamics in the aftermath of decontamination efforts.

Drones, with their real-time data acquisition capacity, can be employed to survey environments for signs of resistance, encompassing changes in microbial populations, genetic adaptations, and shifts in microbial community structures. Their ability to access remote or otherwise challenging ecological niches empowers researchers to venture into areas where resistance may be lurking, providing critical insights into the resilience of ecosystems following decontamination interventions [42,43].

7.2 Sensor Technologies and Data Analysis Methods in Resistance Monitoring

The efficacy of drone-based resistance detection relies heavily on sensor technologies and data analysis methods designed to decipher subtle ecological shifts. Drones can be equipped with an array of sensors tailored to detect resistance markers, assess microbial community dynamics, and capture environmental variables. These sensors may include [44,45]:

- DNA Sequencers: DNA sequencers onboard drones can analyze environmental samples to identify specific resistance genes or mutations. This approach offers unparalleled precision in detecting genetic adaptations linked to resistance [46].

- Spectrometers: Spectrometers enable drones to collect spectral data from ecosystems, revealing changes in vegetation, soil properties, or water quality. Such changes may serve as indirect indicators of resistance-related ecological shifts.

- Thermal Imaging Cameras: Thermal imaging cameras can identify temperature variations in ecosystems, potentially indicating the presence of resistance-associated microbial activity. Elevated temperatures, for instance, may signify the metabolic activity of resistant microorganisms [47].

Data analysis methods in resistance monitoring encompass a spectrum of computational techniques, including bioinformatics, machine learning, and ecological modeling [7]. These methods enable researchers to analyze and interpret the voluminous datasets collected by drones, facilitating the identification of resistance patterns, ecological responses, and correlations with environmental parameters. While exploring the potential of drones for resistance detection, it becomes evident that their integration into resistance monitoring protocols enhances our capacity to discern and understand the intricacies of resistance dynamics within ecosystems [37,48].

8 Remediation Strategies with Drones: Precision in Ecological Restoration

8.1 Drones as Catalysts for Targeted Remediation

Drones, with their capacity for real-time data acquisition and agile maneuverability, extend their transformative influence beyond resistance detection into the realm of targeted ecological remediation. The potential of drones for precision-based interventions in contaminated areas is a testament to their versatility and utility in the preservation of ecosystem health. In contaminated environments, drones can serve as aerial delivery platforms for remediation agents, such as bioremediation microorganisms, enzymes, or specific chemicals [49,50]. By precisely delivering these agents to areas where resistance is detected or contamination persists, drones minimize unnecessary dispersion of remediation resources, thus optimizing their effectiveness. This targeted approach minimizes ecological disruption and maximizes the chances of successful remediation [42,51].

8.2 Case Studies and Drone-Assisted Ecological Restoration

The application of drones in ecological restoration and remediation efforts is exemplified by numerous case studies across various ecosystems. These case studies offer valuable insights into the tangible benefits of drone-assisted restoration [52,53]:

- Riparian Zone Restoration: Drones have been used to reseed native vegetation along riverbanks and wetlands. By dropping seed pods or spraying seeds precisely in areas needing restoration, drones enhance biodiversity and improve habitat quality.
- Contaminated Site Remediation: In contaminated industrial sites, drones have played pivotal roles in the delivery of remediation agents, such as bioremediation microbes or chemical treatments, to specific areas of concern. This approach accelerates the restoration process and minimizes the spread of contaminants.
- Invasive Species Management: Drones have been utilized to identify and manage invasive plant species in sensitive ecosystems. They can disperse herbicides or deploy targeted treatments to control invasive species' spread while minimizing harm to native flora.

These case studies underscore the potential of drones not only as tools for data collection and analysis but also as instruments of ecological healing and rejuvenation. By integrating drones into post-decontamination and restoration protocols, enhancing our ability to address the ecological repercussions of contamination and resistance while fostering ecosystem recovery and resilience [40,54].

9 Integrating Drone Technology: Enabling Adaptive Management

The integration of drone technology into post-decontamination protocols represents a paradigm shift in the realm of biorisk material management. It offers a dynamic approach that aligns human safety with environmental stewardship. By incorporating drones, we bridge the gap between data collection and decision-making, empowering adaptive management strategies that respond to real-time ecological insights. The role of real-time data, facilitated by drones, is central to the concept of adaptive management. Decision-makers are empowered to respond promptly to ecological changes, resistance trends, or unexpected challenges arising from post-decontamination scenarios [40,51]. This agility allows for the dynamic adjustment of remediation strategies, allocation of resources, and implementation of ecological restoration measures. In essence, the integration of drone technology not only enhances our capacity for data collection and ecological understanding but also instills agility and adaptability into the heart of post-decontamination protocols [55,56]. It embodies a holistic approach that recognizes the intricate interplay between human safety, environmental preservation, and the preservation of ecosystem health. As we continue to navigate the evolving landscape of biorisk material management, the role of drones remains pivotal, offering a beacon of hope for the harmonious coexistence of humanity and nature in an era of increasing technological advancement [57,58].

10 Conclusion: Forging a Sustainable Path Forward

The confluence of post-decontamination decontaminants, resistance in ecosystems, and the transformative potential of drones has illuminated the intricate terrain of biorisk material management and environmental stewardship. In our pursuit of a sustainable path forward, several key takeaways emerge:

1. Environmental Guardianship: Biorisk material management extends beyond human safety; it embodies our responsibility as environmental stewards. Recognizing the potential ecological

consequences of decontaminants and the emergence of resistance underscores the urgency of harmonizing human interests with those of the environment.

2. Precision and Agility: Drones epitomize precision and agility in post-decontamination scenarios. Their real-time data acquisition capacity empowers us to make informed, adaptive decisions that mitigate ecological harm and promote resilience.

3. Interdisciplinary Collaboration: Effective management of resistance and environmental consequences requires interdisciplinary collaboration. Experts from fields spanning microbiology, ecology, technology, and policy must collaborate to navigate this complex landscape.

4. Innovation and Adaptation: The evolving landscape of biorisk material management demands innovation and adaptation. The integration of drones exemplifies our capacity to harness cutting-edge technology for the greater good of humanity and the environment.

5. Holistic Perspective: A holistic perspective, one that encompasses human safety, environmental health, and ecological resilience, is paramount. As we advance in our understanding of resistance and environmental dynamics, this perspective guides our decision-making.

In our collective journey through the realms of decontamination, resistance, and the innovative application of drone technology, we have unraveled the profound interconnectedness of human endeavors with the delicate ecosystems that cradle our existence. The path forward is illuminated by a stark yet compelling realization: we bear a shared imperative to safeguard our world. At the intersection of science, technology, and environmental stewardship, we find the blueprint for a sustainable future. Our responsibility extends beyond the preservation of human safety; it encompasses the protection of the intricate web of life that thrives alongside us. Resistance in ecosystems, often sparked by the very interventions intended to protect us, underscores the need for vigilance and ecological mindfulness.

The role of drones, as our emissaries into the unknown, symbolizes our unwavering commitment to harmonize the interests of humanity with those of the environment. Their ability to collect real-time data, pinpoint resistance, facilitate restoration, and guide adaptive management signifies a transformative force that we must embrace and wield responsibly. As we conclude this exploration, let us not forget the imperative to save the world—one ecosystem, one habitat, one species at a time. The world we share is an irreplaceable tapestry of life, intricately woven by the forces of evolution, time, and nature's wisdom. It is our privilege and duty to act as its guardians, ensuring that the delicate threads of biodiversity remain unbroken, the ecosystems resilient, and the planet habitable for generations to come. In the face of evolving challenges and advancing science, let us remain steadfast in our commitment to protect, preserve, and prosper together. The fate of our world is intertwined with our choices, and it is within our power to chart a course towards a sustainable, harmonious coexistence—one that saves not only ourselves but the remarkable world we call home.

11 Declarations

11.1 Acknowledgements

Authors have conflict of interest to declare. We would like to thank Fatma ALTINTAŞ for her kind interest in our study.

11.2 Authors' Contributions

Ahmet Koluman: Wrote the paper, build the concept and made the research.

Atakan Konukbay: Designed the concept, added the CBRN approaches, edited the language and corrected the proof.

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