ADVANTAGES, RISKS AND DUAL-USE CHALLENGES OF NANOTECHNOLOGY IN CBRN'S BIOLOGICAL SCENARIOS

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ABSTRACT

Purpose: CBRN (Chemical, Biological, Radiological, and Nuclear) threats, particularly biological agents, are inherently volatile and difficult to control. Their early detection, identification, mitigation and neutralization, specifically of those that are novel, engineered, or intentionally released, represent a major challenge. Nanotechnology offers promising, new tools and approaches to address these issues, with applications ranging from highly sensitive and selective detection platforms to smart materials and devices for identification, protection and mitigation, as well as advanced decontamination methods and technologies that could strengthen the preparedness and response in CBRN settings.

Design/Methods/Approach: A comprehensive scientific literature review was conducted using systematic content analysis and comparative assessment, emphasizing the advantages, risks, and dual-use implications of nanotechnology in the context of CBRN security.

Findings: The use of nanotechnology in CBRN systems can significantly improve the early threat detection, agent identification, treatment, environmental monitoring, safety and functionality of personal protective equipment, filtration systems, etc. Nonetheless, the same features that make these prevalent technologies beneficial, also, raise ethical dilemmas and safety concerns about their potential misuse. The engineered nanomaterials, for instance, could potentially be repurposed for hostile applications, including targeted delivery of biological toxins or gene-editing agents. Therefore, the implementation of nanotechnology in CBRN landscape must be balanced with responsible oversight and ethical considerations.

Originality/Value: The paper provides a multidisciplinary and integrative perspective of nanotechnology applications in CBRN scenarios, synthesizing the most notable and important scientific reports and discussions regarding the emerging capabilities, associated risks, and the need for strategic planning for the safe and ethical use of advanced materials and nanotechnology in CBRN.

Keywords: CBRN threats; preparedness and response; nanotechnology; advantages, risks and dual-use challenges.

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INTRODUCTION

Chemical, Biological, Radiological, and Nuclear (CBRN) agents include a broad spectrum of hazardous substances, organisms and materials, like toxic chemicals, infectious pathogens, radioactive, and nuclear materials, with the potential to cause devastating and catastrophic consequences in human, animal, and plant populations, environment, and infrastructure. The history of their use is extensive, complex and shaped by numerous pivotal events (Robertson & Robertson, 1995). For instance, the large-scale deployment of chemical agents during World War I encouraged international community to adopt the 1925 Geneva Protocol, which prohibited their use in warfare (UN, 1925). Both **ancient** and modern misuse of biological agents served as the basis for signing the Biological Weapons Convention in 1972, intended to ban their development and improvement of their delivery systems, production, and stockpiling (UN, 1972). Moreover, the bombing of Japan at the end of World War II, stressed the harrowing potential of nuclear weapons, and led to drafting and adoption of few agreements, including the Treaty on the Non-Proliferation of Nuclear Weapons (UN, 1968).

Although CBRN agents can be detrimental, they can also have legitimate and beneficial applications. Certain chemical agents are employed in various industrial areas and medicine, while some nerve agents have been investigated for therapeutic purposes. Biological agents are used both in medicine and research, such as development of vaccines from deteriorated or inactivated pathogens. Finally, radiological materials are widely utilized in medicine for diagnosis and treatment of cancer as well as in various industrial processes, while nuclear materials are also used in diagnosis and for imaging, as well as for electricity generation in nuclear power plants (NRC, 2007; WHO, 2004; WNA, 2025).

Whether they arise from natural events, accidental release, or intentional use or misuse, CBRN agents have unique properties and modes of action that require specialized detection, prevention and response strategies. Their complexity and potential impact on societies make their containment specially challenging at every phase, from the initial signs of their presence to the complete clearance at the location, while often involving coordinated efforts across multiple disciplines and agencies (WHO, 2004). Namely, their rapid and accurate identification and detection are usually difficult due to their varied properties, the possibility of mixed contamination, being invisible and odorless, or causing delayed health effects (IFRCRCS, 2023). Even when modern detection systems are used, field conditions can reduce their speed and accuracy. Neutralization and mitigation of these agents require methods that are sufficient to inactivate or destroy them and, simultaneously, be safe for people, infrastructure, and the environment. Another problem is decontamination with no single solution for all types of agents, while the choice of method is determined by the surface of agent, surrounding conditions, and available resources (WHO, 2004). Ultimately, the success of the entire process depends not only on good preparation, training, and the ability to align technical decisions with operational realities, but also on the use of advanced technologies.

COUNTERING BIOTHREATS, NANOTECHNOLOGY AS A NOVEL SOLUTION

Among various CBRN threats, biological agents or biological threats (biothreats) that include bacteria, viruses, fungi, and toxins derived from diverse living organisms, are extremely insidious due to their stealth, adaptability, routes of exposure (inhalation, ingestion, or direct contact), disruptive potential, and other diverse features that make them particularly suitable to weaponization (Roffey, Lantorp, Tegnell & Elgh, 2002; Oliveira, Mason-Buck, Ballard, Branicki & Amorim, 2020). The devastating impact of these agents has been demonstrated throughout history. Historical 20th-century state-run bioweapons programs in Japan, the Soviet Union, and elsewhere, as well as relatively small-scale event, 2001 anthrax attacks in the U.S., are genuine reminders of their destructive potential (Christopher, Cieslak, Pavlin & Eitzen, 1997; Inglesby et al., 2022). Furthermore, the recent global outbreak of coronavirus, the COVID-19 pandemic, has further stressed how even naturally occurring biothreats can rapidly reform economies, governance, and public trust in a short time (Nicola et al., 2020).

From a public health and security perspective, their small size, potential for rapid and silent transmissibility, and ability to replicate within a host make biothreats difficult to detect and control. Additionally, their capacity to remain undetected for prolonged periods and to trigger epidemic or pandemic outbreaks, chronic health problems, and mass casualties complicates countermeasures both technically and strategically (Roffey et al., 2002).

The traditional detection methods are widely accepted, time-tested approaches that rely on well-understood biological, chemical, and physical principles. Among them the most commonly used are: cell culture, assays based on biochemical and immunological recognition, biomolecular techniques like polymerase chain reaction, animal lethality assay, or physical methods such as gas-liquid chromatography, high-performance liquid chromatography, thin-layer chromatography, capillary electrophoresis, smear microscopy with a sputum sample, and others (Drakulić et al., 2013; Drakulić et al., 2015; Joksić et al., 2017; Todorović et al., 2019; Miletić Vukajlović et al., 2020; Todorović, Bobić & Drakulić, 2023; Gligorov et al., 2023; Todorović et al., 2024; Valenta Šobot et al., 2024). These approaches have been the standards for decades, however they are usually expensive, laboratory-based, time-consuming, complex, with abysmal specificity, require purified samples and specialized equipment and trained personnel, or they are not well suited for emerging or engineered pathogens (Parida, Dash & Shukla, 2020). Moreover, the conventional methods for decontamination and prevention are primarily based on the use of physical and chemical agents. While effective in many cases, the physical methods like sterilization via heat, the application of powerful UV radiation, and chemical decontamination through the use of broad spectrum disinfectants including chlorine-based solutions (e.g., sodium hypochlorite), formaldehyde, or hydrogen peroxide, are generally corrosive, toxic to living populations, and require significant time and labor for large-scale application, making them difficult to use for rapid response in a biological incident (CDC, 2023).

In recent years, thus, the efforts in the field of biothreats detection, identification, neutralization and decontamination technologies have been made to overcome the shortcomings of traditional methods by providing unprecedented speed, sensitivity, and portability. The modern CBRN defense methods employ a broad range of various analytical and physical solutions. For instance, those for detection and identification, like advanced analytical techniques, mass and ion mobility spectrometry, are utilized for rapid and precise recognition of the agents (Perida et al., 2020; Todorović et al., 2023; Todorović et al., 2024). The Advanced Oxidation Processes that use the powerful oxidants like ozone are efficient in neutralization of contaminants, while the Laser Decontamination is used for vaporization of the harmful substances from surfaces (Saravanan et al., 2022; Laserax, 2025). Moreover, the additional strategic disciplines and trends that stand out in CBRN defense systems and that could accelerate the response time against the threats and moderate their adverse effects are: artificial intelligence, internet of things, remote sensing, advanced materials, and nanotechnology (Pantić et al., 2022).

Nanotechnology, a multidisciplinary field, refers to the design, manufacture, manipulation, and application of materials, structures, devices, and systems with structural features on the nanoscale (1 to 100 nm) (De Luca, Nagy & Macario, 2023) and spherical surface area-to-volume ratio exceeding 60 m^{2}cm^{-3} (Mekuye & Abera, 2023). Nanomaterials (NMs) can be classified according to **origin** (natural, or artificial), **structural configuration**/composition (organic, inorganic, carbon-based, and composite), **dimensionality** (0-3 dimensions (D)), **pore sizes** (micro-, meso-, and macroporous), **solubility** (dispersed, or aggregated), **phase** (single-phased, or multi-phased), potential toxicity (fiber-like, persistent granular, and CMAR (carcinogenic, mutagenic, asthmagenic, or reproductive toxin)), and others (Mekuye & Abera, 2023; Kurul, Turkmen, Cetin & Topkaya, 2025). They exhibit unique and distinct morphological and physicochemical properties including smaller size, lighter weight, distinct magnetic properties, enhanced stability, mechanical strength and surface reactivity, higher specificity in molecular interactions, altered permeability, and improved electrical and heat conductivity that make them differ fundamentally from bulk materials, single atoms, and molecules. Their characteristics arise from quantum effects, enlarged surface area-to-volume ratio, and presence of interphase domains that make the application of these materials highly versatile, and applicable in numerous sectors of science and technology, and well suited for the CBRN biological landscape (Guidotti, Ranghieri & Rossodivita, 2009). As dimensions of nanoscale materials are similar to those of cells, genetic molecules, microorganisms, and tissues, they are transforming drug delivery systems, enabling targeted therapies that increase treatment effectiveness while minimizing adverse side effects. By providing innovative, interdisciplinary solutions and strategies to complex health challenges, they simultaneously advance diagnostic imaging, biosensing, tissue repair processes and regenerative medicine (Agrahari et al., 2016; Kargazar & Mozafari, 2018). While in the light of CBRN protection, nanotechnology also provides state-of-the-art multidisciplinary tools for the detection, neutralization, and decontamination of hazardous agents. Nanoscale materials can be incorporated into protective clothes, filters, sensors, decontamination agents, where they enhance the sensitivity of detection systems, improve the efficiency of neutralization strategies, and facilitate rapid, targeted decontamination of polluted locations, thereby strengthening preparedness and response capabilities in both military and civilian contexts (De Luca, Chiodo, Macario, Siciliano & Nagy, 2021; De Luca et al., 2023). Moreover, in the environmental science, nanotechnology is shown to be useful for pollution remediation, detection of environmental contaminants at unprecedented sensitivity levels, facilitating early warning systems for public health and safety (De Luca, Macario, Siciliano & Nagy et al., 2022). While providing numerous advantages, the rapid development of nanotechnology also raises substantial concerns related to safety, ethical consideration, and regulatory issues, including the potential toxicity of nanoparticles (NPs) (Todorovic et al., 2024), their impact on the environment, and the risks associated with their dual-use applications (Shajar et al., 2023).

Nanotechnology-based technologies for biothreat detection: real-time diagnostics, nanobiosensors

In CBRN detection, the real-time diagnostics has a pivotal role. Nanotechnology has widely been used in design of portable real-time diagnostic tools that are rapid, highly sensitive and suitable for early detection of hazardous agents directly in the field (Lai et al., 2024; Mishra et al., 2025). A variety of nanosensors are exploited, including nanobiosensors, optical nanosensors, carbon-based nanosensors, and others for detection of biomarkers, biological agents/threats present at extremely low concentrations (Diez-Pascual, 2021; Lai et al., 2024; Mishra et al., 2025).

Nanobiosensors, or biosensors based on nanotechnology, are advanced analytical devices in nanometers scale that combine a biological recognition element with a physical or chemical transducer to quantify analytes like pathogens, biomolecules, or environmental sources with a high sensitivity and specificity (Chaturvedi, Tripathi & Ranjan, 2025; Mishra et al., 2025). The principle of nanobiosensor operation relies on the binding of a specific biological agent (analyte) to the recognition element (cell-based, tissue-based, or a molecule like an enzyme, DNA strand, or antibody) that induces measurable change of NMs, which is subsequently converted into a detectable optical, electrochemical, electrical, and other forms of signal (Sainz-Urruela, Vera-López, San Andrés & Díez-Pascual, 2021). The high surface area of NMs allows greater immobilization of receptors to the sensor which enables a higher density of sensing elements within a confined space and more efficient binding interactions with the target analyte that generate stronger and more reliable signal (Ahmadi, Warkiani, Rabiee, Iravani & Rabiee, 2023; Mirzadeh-Rafie et al., 2023). The detection of targets is straight from the sample, rapid, real-time, accurate, reversible, and non-destructive, while the small size of these devices make them suitable for field-based sensors (Rowland, Brown, Delehanty & Medintz, 2016) and especially valuable in CBRN events, including detection of contaminants, and pathogens, and disease markers in bodily fluids like sweat, saliva, urine, and blood, as well as disease monitoring (Mishra et al., 2025). Different NMs have been used for nanobiosensors to achieve better performance and enhance their applicability in CBRN scenarios. For instance, among metallic NPs most widely used are gold NPs (AuNPs), due to their good biocompatibility, high surface-to-volume ratio, unique optical properties, excellent conductivity, catalytic capabilities, and selectivity properties, as well as ability to easily form stable conjugates with biomolecules, which enable highly sensitive colorimetric or plasmonic detection of biothreats (Bilge & Sinag, 2025). AuNPs are used for detection of DNA of *Brucella species* with assay run in a short time (up to 10 min) within pg/μL detection limits (Sattarahmady, Tondro, Gholchin & Heli, 2015). While altering the surface with various molecules including other DNA sequences, antibodies, etc., these systems can be easily improved for detection of other bacterial DNA, viruses and specific toxins (Shyu, Shyu, Liu, & Tang, 2002; Guarise, Pasquato, De Filippis & Scrimin, 2006; Uzawa et al., 2008; Jannetto et al., 2010; Veigas et al., 2010). When incorporated into lateral flow immunoassays, the superparamagnetic AuNPs can be used for rapid detection of *Bacillus anthracis* spores, ricin, and others (Shyu, et al., 2002; Wang et al., 2015). These NPs are also integrated into advanced detection platforms, like surface enhanced Raman spectroscopy (SERS), inductively coupled plasma mass spectrometry (Zhang, Anderson, Huarng & Alocilja, 2011), quartz crystal microbalance, evanescent field-coupled waveguide-mode sensors (Saha, Agasti, Kim, Li & Rotello, 2012; Arcos Rosero, Bueno Barbezan, Daruich de Souza & Chuery Martins Rostelato, 2024; Karnwal et al., 2024), and localized surface plasmon resonance (LSPR) (Jin et al., 2009; Zhu, Du & Fu, 2009; Kleo, Kapp, Ascher & Lisdat, 2011; Gopinath, Awazu, Fujimaki, Shimizu & Shima, 2013), where they overall improve sensitivity and specificity of analyte detection (Chen et al., 2025; Shakir, Mirzakhil, Ulfat, Atif & Mansoor, 2025). Moreover, NPs synthesized from noble metals like palladium, platinum, and silver, or rare earth metals such as europium, gadolinium, and terbium, are also highly effective in immunoassay development (Algar et al., 2011). Among them, silver NPs (AgNPs) that exhibit antimicrobial properties demonstrate a significant potential for theranostic applications, where they can be employed for both identifying and treating infectious diseases (Rowland et al., 2016).

Optical nanosensors are fast, highly sensitive analytical devices for detection of various agents in CBRN scenarios, including biological like bacteria, viruses, and toxins. Among them, quantum dots (QDs), quantum-confined semiconducting nanocrystals with intrinsic photoluminescence (PL), stand out as precise and reliable for real-time, multiplexed monitoring of various target analytes present in low concentrations. When functionalized with target-specific probes, QDs convert binding events into bright, easily detectable fluorescent signals, making them highly effective for sensitive detection applications (Rowland et al., 2016; Lai et al., 2024). For instance, antibody-labeled QDs are engineered to recognize proteins of toxins and viruses, including ricin and *S. typhi* (Goldman et al., 2004; Yang & Li, 2005; Gemmill et al., 2013), and also have been applied for simultaneous monitoring of cholera, ricin, SEB, and shiga toxin (Goldman et al., 2004). Moreover, antibody-labeled QDs can serve as fluorescent tags in combination with laboratory techniques such as agglutination and flocculation assays or flow cytometry (Wang & Morris, 2005; Zahavy, Heleg-Shabtai, Zafrani, Marciano & Yitzhaki, 2010). While QDs functionalized with aptamers, synthetic DNA capture elements, are shown sufficient in detection of bacteria, viruses, and toxins (Kiel, Holwitt, Parker, Vivekananda & Franz, 2004; Roh, & Jo, 2011).

When integrated into field-deployable platforms, such as Förster resonance energy transfer (FRET), SERS, and LSPR, QDs-based nanosensors provide rapid and high specificity results (Rowland et al., 2016). For example, several QD-based FRET sensors are successful in detection of botulinum neurotoxin (BoNT) (Sapsford et al., 2011; Lee et al., 2015), among other targets. Various biosynthetic QDs (BQDs) are also used for the creation of advanced highly sensitive electrochemical biosensors that use techniques like differential pulse voltammetry, electrochemical impedance spectroscopy, and electrochemiluminescence (Yao, Yan, Tang, Deng & Li, 2013; Wang et al., 2020; Pham et al., 2021; Yemets, Plokhovska, Pushkarova, Krasylenko & Blume, 2022; Lai et al., 2024). Recently, QDs have been widely and successfully exploited for sensitive detection and inhibition of SARS-CoV-2, largely due to low toxicity, cost-effective synthesis, strong PL, and ease of functionalization with metallic NPs. These properties enabled fluorescence-based imaging of viral interactions, point-of-care diagnostics, and single-molecule tracking (Roh & Jo, 2011; Huang et al., 2020; Nasrollahzadeh et al., 2020; Singh et al., 2020; Ahmadi et al., 2023).

Carbon-based nanomaterials (CNMs), including carbon nanotubes (CNTs), fullerenes, graphene and its derivatives, nanodiamonds, and other nanosized carbon allotropes, in recent years are showing a promising potential in CBRN defense due to their unique properties such as biocompatibility, low toxicity, exceptionally large surface areas, superior electrical conductivity, mechanical strength, and ability to be functionalized (Diez-Pascual, 2021; Sainz-Urruela et al., 2021; Ahmadi et al., 2023). The identification of an analyte can be achieved by the simple visualization of aggregates formed upon binding, which is shown as successful method for the detection of *Bacillus anthracis* (Wang et al., 2006). Furthermore, CNTs are used as substrates for fluorescence-based assays in viral detection, e.g. a composite of CNTs, AuNPs, and QDs has been developed to recognize influenza virus (Lee et al., 2015). In this system, CNTs combined with AuNPs are functionalized with influenza antibodies, which are recognized by antibody-conjugated QDs that allow binding of the viral particles. The resulting PL signal enables detection of the virus across an exceptionally wide concentration range (Lee et al., 2015). CNMs can also be used as efficient quenching agents, as demonstrated with fluorophore-labeled single-stranded DNA. When attached to the surface of fullerene (including C60 fullerene) clusters, CNMs undergo PL quenching from the fluorophore, while upon hybridization with complementary DNA, the DNA-fluorophore complex is released from the C60 surface and the PL signal is restored (Li, Zhang, Luo & Sun, 2011). Additionally, CNMs have been successfully integrated into electrochemical sensing platforms (Singh et al., 2013; Singh, Sharma, Hong & Jang, 2014), like in the work of Das and coworkers (2011) in which a CNMs/nanoscale zirconia composite deposited on an indium-tin-oxide electrode enabled detection of an analyte through electrochemical impedance changes due to surface modifications (Das et al., 2011). Moreover, several fast and cost-effective diagnostic tests with significant sensitivity and specificity that are based on NMs, particularly on CNTs and graphene derivatives, have lately emerged as a promising option for large-scale screening during COVID-19 pandemic (Mirzadeh-Rafie et al., 2023). These sensors target different biomarkers, including viral RNA, glycoproteins, and the spike (S) protein, and others. To achieve this, they rely on different detection strategies, such as immunoassays, SERS, or ultra-low-field nuclear magnetic resonance relaxometry, etc. While depending on the approach, the reported limits of detection vary extensively, ranging from ng to fg, or they are expressed as copies/mL to copies/μL, or in different manner (Mirzadeh-Rafie et al., 2023). It should be noted that CNMs are used not only in production of nanobiosensors, but also in other areas, such as filtration, protective materials, and others (Farmand et al., 2022).

Nanotechnology-based strategies for protection and decontamination: advanced protective clothes; photocatalytic decontamination nanomaterials

While nanotechnology has brought significant progress in detection of biothreats, its application in protection against and decontamination of harmful agents is as just as vital. The nanoscale materials are widely exploited in the development of nano-enhanced protective equipment, where their unique properties contribute to improved filtration efficiency, durability, and resistance to hazardous biological agents, as seen in advanced respirators and protective clothes (De Luca et al., 2023; Abedinloo, Parvari, Cheraghi & Assari, 2025). NMs with improved surface area and reactivity, including nanocatalysts and adsorbents, as well as reactive NPs, are also considered useful for applications in numerous environmental areas, such as water purification, air quality improvement, soil remediation, biodiversity conservation, and waste management (Prince et al., 2025).

Personal Protective Equipment (PPE) is shown effective in CBRN scenarios when it is selected properly, well maintained, and correctly used in all potential exposures, as it represents the first line of defense between individuals and potentially lethal biothreats (Abedinloo, Parvari, Cheraghi & Assari, 2025). In this domain, nanotechnology offers a transformative advancement by enabling the design and fabrication of advanced materials with enhanced filtration, antimicrobial activity, and barrier properties. Compared to traditional filter media, which primarily rely on mechanical interception, and which are often insufficient in capturing the smallest viral and bacterial particles, especially those in the sub-micrometer range, due to large gaps between the fibers (on average 10-30 μm), the *nanofibers*, form a complex, highly porous network with an extremely high surface-area-to-volume ratio and pore sizes at the nanoscale. PPE with nanofibers insures increased respiratory comfort, and high filtering properties as well as reduction of heat accumulation and fatigue of the wearer during long-term use (De Luca et al., 2023). The performances of nanofiber filters have been extensively studied during COVID-19 pandemic, as demonstrated in a study of Leung and Sun (2020). They tested electrostatically charged polyvinylidene fluoride (PVDF) nanofiber filters assembled in modules of 2, 4, and 6 layers, each containing 0.765 gm^{-2} of charged PVDF nanofibers and showed that these filters, whether charged or uncharged, can capture ambient aerosols ranging from 10 to 400 nm, including tiny droplets potentially containing SARS-Cov-2 particles (Leung & Sun, 2020). Besides nanofibers, other nanonstructures have been investigated and exploited to successfully block penetration and deactivate biological agents, as well as to ensure that PPE can be easily cleaned and reusable without losing their efficiency and safety, while still being environmentally friendly (De Luca et al., 2023). Among various types of nanoscale materials, the most used are NPs of Ag, copper (Cu), copper iodide, copper oxide (CuO), graphene, graphene oxide, and others (Lee et al., 2016; Abbasinia, Karimie, Haghighat & Mohammadfam, 2018; McCarthy, Gino, d'Entremont, Barari & Renouf, 2020). When incorporated into the fibrous matrix of masks and suits, these NPs provide strong antimicrobial properties by releasing ions that can disrupt the cellular membranes of bacteria and inhibit viral replication upon contact, effectively neutralizing the threat in high-risk environments where individuals may face exposure (De

Luca et al., 2023). In addition, smart, multifunctional protective materials coated with nanoscale hydrophobic layers that repel liquids, and prevent direct contact with contaminated aerosols or droplets are designed to be responsive to certain environmental signals, self-cleaned, and sterilized, which is essential for the safety of first responders and other personnel that are facing biothreats. Notable examples are PPE enhanced with graphene microfiber fabrics that are available on the market since the beginning of the COVID-19 pandemic (De Luca et al., 2023).

Hazardous agents are typically removed from the site by physical elimination, dissolution, or by their chemical and biological neutralization. Although effective, these traditional decontamination methods, often lacking selectivity, demand the massive use of water, diluents and/or aggressive chemicals (sodium hydroxide, hypochlorites, peroxides, and others), can damage materials, and may pose risks to human health and the environment (Bhadra, Abdulkareem & Al-Thani, 2019). In the contrast, new, more proficient and faster decontamination approaches based on nanotechnology, introduce engineered solid catalytic materials with acidic, basic, or redox properties, high specific surface area (ca. 1000 m^2g^{-1}) and adsorption capacities, that can accelerate the breakdown or capture of hazardous agents in air, water, soil and other surfaces under mild conditions like room temperature. Therefore, they are promising substitutes to conventional methods including thermal destruction, incineration, and other methods (Kumar, 2005). The key nano-based decontamination strategies utilize a variety of materials and approaches. Commonly employed materials are: zero-valent iron NPs; metal oxide NPs such as Ag, Cu, and titanium dioxide (TiO_2); as well as carbon-based materials including CNTs and graphene-based NPs (Rezania et al., 2024). Frequently applied methods encompass nano-adsorbents for contaminant removal, nanofiltration membranes for separation, and nanophotocatalysis, that generate reactive oxygen species (ROS) to rapidly break down organic contaminants, including microorganisms and toxins (Bhadra et al., 2019). Additional methods involve nano-biocides and antimicrobials which eliminate or inhibit the growth of pathogens, as well as nano-bioremediation, where NMs enhance the activity of microorganisms that break down pollutants or act as carriers to distribute microbes to contaminated sites (Ningthoujam et al., 2022). For example, upon the exposure to light, ultraviolet (UV) or visible light in some cases, TiO_2 photocatalyst provokes mass production of ROS that in return damage RNA, proteins, or other viral, bacterial or fungi particles, as well as specific toxins, leading to their inactivation and degradation (De Pasquale et al., 2020). As demonstrated in the study of Lu and coworkers (2022), a TiO_2-coated glass sheet inactivated 99.9% of SARS-CoV-2 in aerosols in a short time (within 20 min) (Lu et al., 2020). Additionally, metal-organic frameworks, including those in "nanosponge" form, are novel highly porous crystalline materials with high surface area, and diverse functionalities that trap and/or catalytically degrade a wide range of toxins and pathogens among other pollutants (Karmakar, Velasco & Li, 2022; Mishra et al., 2023).

Nanomedicine and therapeutic interventions: targeted therapy, drug delivery, tissue repair

Nanomedicine is fast-developing interdisciplinary field that combines nanotechnology with medical and pharmaceutical sciences, advancing detection, diagnosis, prevention, and treatment of diseases (Haleem, Javaid, Singh, Rab & Suman, 2023). It employs engineered nanoscale structures, devices, and systems that interact with biomolecules (proteins, DNA, cell membranes, etc.) to provide transformative solutions, approaches and strategies to healthcare, including applications relevant to CBRN defense, such as targeted therapy, drug delivery, tissue repair, and other (Haleem et al., 2023; Singh et al., 2024; Kurul et al., 2025). As sustainable and biocompatible alternatives to conventional methods, NMs and nanorobots have the potential to lower toxicity, improve patient safety and effectiveness of treatments (Singh et al., 2024).

Targeted therapy and drug delivery systems showed promising in the treatment of various diseases, including cancer, neurological disorders, cardiovascular, and infectious diseases, since they are more bioavailable, have negligible off-target side effects and optimal drug efficacy when compared to traditional therapeutic agents (Boppana et al., 2024). By binding or encapsulating versatile therapeutic agents like hydrophilic and hydrophobic drugs, small molecules, peptides, proteins, or nucleic acids in the bloodstream, these systems protect medications from enzymatic degradation and premature clearance, and selectively direct them to specific sites within the body. They can also be engineered to respond to external or internal stimuli such as pH, temperature, light, or magnetic fields, thereby enabling controlled release at the level of target cells, tissues, or organs (Emeihe, Nwankwo, Ajegbile, Olaboye, & Maha, 2024). These nanoscale engineered platforms can be classified in several ways, with most common grouping according to materials composition: **organic** (liposomes, polymeric NPs, dendrimers, micelles, exosomes/nanovesicles, etc.), **inorganic** (AuNPs, AgNPs, iron oxide NPs, silica NPs, QDs, and others), and **carbon-based systems** (CNTs, and graphene oxide, etc.) (Boppana et al., 2024; Emeihe et al., 2024; Tenchov et al., 2025). Each class possesses unique physicochemical properties that dictate its behavior, biocompatibility, and suitability for specific clinical applications. According to the mechanism by which NPs reach and accumulate at the target site, they can also be divided into passive or active targeting systems. Table 1 lists characteristics of passive and active targeting systems, each with distinct mechanisms, applications, advantages and limitations, as well as examples (Mok & Zhang, 2013; Barua & Mitragotri, 2014; Kumar, 2025; Clemons et al., 2018; Afrasiabi, Pourhajibagher, Raoofian, Tabarzad, & Bahador, 2020; Zhou, Krishnan, Jiang, Fang & Zhang, 2021; Singh et al., 2024; Tenchov et al., 2025, *https://insidetx.com/review/a-comprehensive-review-of-passive-and-active-nanoparticle-targeting-technics/*).

Alternative classification can further be made, such as classification by structural morphology (e.g., solid NPs, hollow vesicles, and spherical micelles), and design strategies (like hybrid (lipid-polymer hybrids, organic/inorganic core-shell systems, multifunctional composites, etc.) and natural-based (protein-based nanocarriers, polysaccharide-based nanocarriers, biomimetics, etc.)), each offering additional ways to describe the versatility of these systems (Patra et al., 2018; Egwu et al., 2024; Tenchov et al., 2025).

Traditional approaches for restoration or replacement of damaged tissue and organs, utilize grafts, scaffolds, or cell transplantation with lot of limitations, such as immune rejection, poor integration, or partial functional recovery. To address these issues, nanotechnology offers innovative solutions and approaches for tissue repair and regenerative medicine by creating biomimetic scaffolds that replace tissue functions; filling up the space until the damaged tissue is regenerated; acting as carriers for drugs and growth factors, and guiding stem cell behavior for tissue ingrowths (Peran et al., 2013). *Nanostructured scaffolds* are 3D frameworks that mimic the natural extracellular matrix and provide a supportive milieu for cell adhesion, proliferation, and differentiation while optimizing porosity, mechanical strength, and flexibility. When functionalized with bioactive molecules, they can further boost regenerative outcomes, and reduce fibrotic responses, improve antimicrobial activity, and even deliver local biochemical signals, creating an environment that resembles natural tissue. In contrast, nanosensors combined with scaffolds ensure real-time monitoring of the healing process, by detecting changes in pH, oxygen levels, or the expression of specific biomarkers, allowing dynamic adjustment of therapeutic interventions and improving overall treatment outcomes. Commonly used NMs for their designing are: electrospun nanofibers, hydrogel-based nanocomposites, and carbon-based (Liang, Hsiao & Chu, 2007; Arora et al., 2012; Barrett-Catton, Ross & Asuri, 2021; Hajishoreh et al., 2023). The use of nanocarriers in this field is mainly focused on delivery systems where they directly transport genetic material, drugs, growth factors or other biomolecules to injury site and release them in controlled manner (Dadfar et al., 2019; Gao et al., 2024). Importantly, stem cell nanotechnology, a synergistic platform, creates a multifunctional, precisely controlled regenerative microenvironment, supports targeted tissue repair, upgrades therapeutic efficacy, and the development of personalized regenerative strategies. This is accomplished by integrating stem cells capacity for self-renewal, differentiation into tissue-specific lineages, and secretion of regenerative factors, with nanoscale signals, functionalized NPs, and scaffold surface patterns, which guide stem cell behavior, enhance tissue integration and functional recovery. Studies have showed that mesenchymal stem cells on nanocomposite scaffolds can accelerate bone formation and mineralization, while induced pluripotent stem cells combined with conductive NMs promote cardiac repair. Similarly, neural stem cells guided by nanofiber scaffolds are able to enhance axonal regeneration, and NPs-enhanced hydrogels with stem cells stimulate angiogenesis and epithelialization in skin and wound healing (Arora et al., 2012; Samuel, Sundarraj & Sudarmani, 2023).

Table 1: *Characteristics of passive and active nano-drug delivery systems*

Approach	**Passive targeting**	**Active targeting**
Mechanism	Uses natural physiological or pathological processes (e.g., enhanced vascular permeability, leaky vasculature, or the enhanced permeability and retention effect)	Uses ligand-receptor interactions for specific binding
Nanocarrier modification	Usually unmodified or minimal	Functionalized with ligands (antibodies, peptides, aptamers, etc.)
Target specificity	Moderate, depends on tissue pathophysiology	High, directed by ligand-receptor recognition
Application	Liposomes or polymeric NPs that accumulate in organs commonly affected by toxins or pathogens (e.g., liver or lungs) due to enhanced permeability Solid lipid NPs for sustained delivery of antiviral drugs against aerosolized viruses Superparamagnetic iron oxide NPs for drug/gene/cell delivery	Antibody/aptamer-conjugated NPs designed to bind specifically to bacterial toxins, like BoNT Ligand-functionalized nanocarriers that recognize viral surface proteins (e.g., SARS-CoV-2 S protein) to deliver antiviral therapeutics directly to infected cells Nanocarriers with antidotes targeted to receptors expressed on cells exposed to chemical warfare agents
Advantages	Simple design, easier to produce	High precision, reduces off-target effects, controlled release possible
Limitations	Less specific, potential for systemic distribution	More complex design, higher cost, potential immunogenicity
Examples	NPs accumulating in tumors or inflamed tissue	Antibody-conjugated liposomes targeting specific cancer cells

Antimicrobial NMs and nanovaccines are rapidly developing and promising nanotechnology-based strategies for prevention and treatment of infection diseases. *Antimicrobial NMs* show great potential in direct interaction with pathogens through multiple mechanisms, including direct rapturing of microbial walls and membranes, interfering with DNA replication and protein synthesis, generating ROS, and controlling release of antimicrobial ions which not only inhibit microbial growth but also prevent the formation of persistent biofilms. Different NMs, including those based on zinc oxide, Ag, CuO, and carbon, are among the most extensively studied due to their chemical stability, ease of production, tunable physical properties, and compatibility with a wide range of biomedical materials and formulations. Moreover, polymer-based nanostructures offer the added advantage of tunable functionality and improved biocompatibility. These nanodrugs can be used independently or in combination with traditional drugs (Mondal, Chakraborty, Manna & Mandal, 2024). In contrast, *nanovaccines* exploit NPs as carriers of antigens that enhance the stability, and bioavailability of antigens. These systems provoke stronger and prolonged both innate and adaptive immune responses against bacterial and viral pathogens with minimal side effects compared with conventional formulations. They also enable co-delivery of adjuvants and multiple antigens within a single nanocarrier, improving vaccine efficacy (Das & Ali, 2021; Ross et al., 2024). Moreover, their versatility allows rapid adaptation to emerging pathogens, which is a critical advantage in the dynamic CBRN landscape (Manju et al., 2023).

Ethical, safety and misuse concerns: dual-use technology and weaponization, health and environmental risks

The widespread applications of nanotechnology across diverse fields like medicine, environmental remediation, consumer products, and CBRN defense, have brought transformative opportunities, but they simultaneously introduced complex ethical, safety, and misuse challenges. Although many forms of nanoscale engineered materials, nanosystems, or devices, are developed for beneficial applications, such as targeted drug delivery, regenerative medicine, precision imaging, and diagnostics, their unique properties make them suitable for deliberate misapplication. Their small size, high surface reactivity, and ability to cross biological barriers could be exploited for malicious purposes, including delivering toxic agents, creating novel biochemical weapons, or designing nanostructures that evade medical countermeasures (Kosal, 2010). For instance, nanostructures could be engineered into aerosolized delivery systems capable of dispersing toxins or pathogens with controlled release, enhanced stability and persistence in the environment (Snow & Giordano, 2019). They could also act as stealth coatings for existing threats, prolonging their circulating time and stability, as well reducing detectability by immune system, which could be used to camouflage the presence of harmful agents in malicious applications (Vignesh, Menaka, Amal, Selvakumar & Vasanth, 2025). Their capacity for controlled release and surface modification show potential for designing highly specific and potentially lethal nanocarriers and capsules, without distinguishing the line between therapeutic innovation and weaponization (Kosal, 2010). Such dual-use scenarios emphasize the necessity for robust ethical oversight in research and development, appropriate mitigation strategies and international security frameworks, so the potential of nanotechnology can be responsibly harnessed to benefit society, human health, and overall well-being (Kosal, 2010; Vaseashta, 2025; Vignesh et al., 2025).

Due to smaller size, higher surface-to-volume ratio and potential for bioaccumulation, NMs can interact with biological systems in ways that their larger-scale counterparts do not. This often leads to unpredictable behaviors and toxicological effects that require entirely new approaches of study. For this reason, various research methods have been applied to address the safety issues related to NMs application and misapplication, as well as environmental and human health concerns associated with their intentional or accidental release. Computer simulations, *in vitro* cell cultures models, and *in vivo* animal studies, have been used to uncover potential threats, investigate the mechanisms associated with NMs toxicity (like oxidative stress, apoptosis, inflammation, and organ-specific toxicity), and to evaluate potential risks from different exposure scenarios (Todorović et al., 2024; Vignesh et al., 2025).

Current solutions and strategies primarily involve risk management and the establishment of effective regulatory frameworks to minimize the potential of NMs on health and the environment. Various research institutions, organizations, and worldwide regulatory agencies, like the United States Food and Drug Administration (USFDA), European Medicines Agency (EMA), and Environmental Protection Agency (EPA) have proposed regulatory guidelines for assessing the NMs cyto/geno/immunotoxicity, pharmacokinetics, environmental impact, and necessities for labeling and reporting their side effects (Vignesh et al., 2025). The real and multifaceted risks of nanotechnology are complicated as current guidelines are still evolving and remaining regionally fragmented, rather than being globally synchronized. Therefore, strengthening international cooperation, harmonizing testing protocols, and ensuring transparent communication are essential to guide the responsible use of nanotechnology, protect human health and the environment, and prevent the exploitation of these innovations for hostile purposes.

CONCLUSION

The history of CBRN agents, particularly biological, illustrates both their legitimate applications and their potential for deliberate misuse. Although the use of certain agents has clearly been beneficial, their destructive capacity emphasizes the need for resilient regulatory frameworks and international cooperation to prevent abuse.

The rise of nanotechnology, including NMs, devices and nanosystems with specific properties, offers new possibilities for strengthening our defenses against biothreats. By improving detection and decontamination processes, medical interventions, enhancing protective technologies, and supporting overall public health preparedness, the innovations, approaches and strategies based on nanotechnology provide significant benefits across multiple domains. However, their dual-use nature requires careful evaluation, since the same properties that make them valuable for defense could also be exploited with malicious intent. A balanced multifaceted approach, which integrates safety, ethical considerations, and transparency, is essential to safeguard public health and security while simultaneously mitigating the risks of its misuse. To address the complex challenges and potential risks associated with biological agents and emerging nanotechnologies, the global collaboration between scientific communities, policymakers, and international organizations is crucial to developing effective and ethical solutions.

ACKNOWLEDGEMENTS

This paper was financially supported by the European Commission, grants 101214954 – GROUNDUP and 101217399 – SPARKUP, and Ministry of Science, Technological Development and Innovation of the Republic of Serbia, grant 451-03-136/2025-03/200017.

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