ADAPTIVE HAZARDOUS WASTE TREATMENT IN GAZA GENOCIDE ZONE USING NANOTECHNOLOGY AND BIOTECHNOLOGY: A LITERATURE REVIEW

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ABSTRACT

The Impact of the genocide in Gaza's zone faces serious challenges in the management of Hazardous and Toxic Materials waste due to infrastructure damage and territorial blockade. Post-genocide building debris contains toxic materials such as asbestos, heavy metals, and persistent organic compounds, which risk contaminating soil, water, and air and threatening the health of Gaza's 2.3 million residents. International regulations (the Basel Convention, Rotterdam, Stockholm) prohibit the cross-border movement of hazardous waste without consent, so Gaza must process its own hazardous waste according to the principles of environmentally sound management. Limited resources and infrastructure due to the blockade since 2007 have exacerbated the difficulties of handling waste. This literature review examines nanotechnology-based solutions and biotechnology to treat hazardous waste in Gaza. The study results show that nanotechnology (e.g., zero-valent iron nanoparticles, nano-axis activated carbon) effectively absorbs and neutralizes harmful pollutants. Meanwhile, biotechnology in the form of Bioremediation by microorganisms can decompose toxic organic compounds and extract heavy metals through bioleaching at low cost and is environmentally friendly. This combination of nano-bio strategies has the potential to be applied in Gaza to safely manage hazardous waste, mitigate health impacts, and meet international standards.

Keywords: Hazardous Waste; Gaza; Nanotechnology; Biotechnology; Bioremediation

1. INTRODUCTION

The protracted genocide zone in Gaza has led to massive infrastructure damage and hazardous waste dumps. Repeated military strikes (2008, 2012, 2014, 2021, 2023) destroyed thousands of buildings, producing millions of tons of debris and debris mixed with toxic materials (Hu et al., 2025). Figure 1 shows the condition of building ruins in Gaza after the genocide zone in 2024. Dust from bombed buildings is shown to contain asbestos, heavy metals (e.g., lead, mercury, cadmium), and toxic organic compounds (such as dioxins, polychlorinated biphenyls/PCBs) that are released into the environment (Chahar et al., 2023). The health risks from chronic exposure to these toxic substances are very high, including respiratory distress, cancer, and reproductive disorders (Al-mabhouh et al., 2021; Barakat et al., 2018).

Figure 1. The condition of building debris in Gaza after the genocide (February 2024)

Hazardous waste in Gaza from building material includes e-waste (e.g. leftover computers, televisions, refrigerators) that contain toxic heavy metals (Pb, Hg, Cd, etc.) and plastics with harmful additives (Khan et al., 2024), industrial chemical waste (example: 886 tons of pesticide waste from a destroyed fertilizer plant in 2021(Abuhamed et al., 2023), medical waste from damaged health facilities, as well as asbestos construction debris. If left unmanaged, these wastes pollute groundwater, air, and the food chain through bioaccumulation and biomagnification, thereby increasing cases of acute and chronic diseases (Manduca et al., 2017; Mears et al., 2022).

Blockades and international rules constrain the management of hazardous waste in Gaza. The blockade since 2007 has restricted the entry of equipment and technology, and has virtually closed off opportunities for hazardous waste exports outside Gaza (Abuhamed et al., 2023). Meanwhile, the *Basel Convention* prohibits the export of toxic waste to countries that refuse to accept it, requiring environmentally friendly waste treatment within the country(Kanamugire, 2017). The *Rotterdam Convention* sets up procedures for *Prior Informed Consent* (PIC) for trade in hazardous chemicals, preventing toxic dumping in developing countries without consent (Kanamugire, 2017). The *Stockholm Convention* requires reducing and eliminating persistent organic pollutants (POPs) such as PCBs and dioxins (Fiedler et al., 2019). Moreover, OECD Council Decision (1992) controls the shipment of hazardous waste between OECD member countries, prohibiting exports to non-OECD countries that do not have adequate management capacity (Erdiwansyah et al., 2022; Vigoya et al., 2020; Yoshioka & Era, 2021). These regulations (summarized in Table 1) prevent Gaza from discharging B3 waste outside; Gaza must build internal solutions according to standards *Environmental Sound Management* (Durham & Pizzino, 2019; Neill, 2012; Tal & Cohen, 2024) to protect public health and the global environment.

Table 1. International Regulations Related to Hazardous Waste and Their Implications

No	Global Environmental Agreement	Content
1	Basel Convention (1989)	Controlling the cross-border movement of hazardous waste requires environmentally friendly management in the country of origin. Gaza cannot export hazardous waste indiscriminately; it must be processed within the region.
2	Rotterdam Convention (1998)	Implement *Prior Informed Consent*/ PIC (preliminary approval) procedures for trade in hazardous chemicals and pesticides. Imports of hazardous materials into Gaza are closely monitored; the prevention of dumping of hazardous waste into Gaza by external parties.
3	Stockholm Convention (2001)	Protect health from POPs by limiting and eliminating their production, use, and storage. Gaza must manage and reduce POP compounds (e.g., PCBs, dioxins) in their waste.
4	OECD Council Decision (1992)	limited simplification procedures and prohibit exports to non-OECD countries without guarantees of safe management. Gaza (non-OECD) must not be a dumping destination for other countries' waste, nor can it send its waste abroad without special permission.

Source: (Durham & Pizzino, 2019; Fiedler et al., 2019).

With limited resources, Gaza needs innovative, cheap, and self-sufficient technology to treat hazardous waste locally. Technology, nanotechnology, and biotechnology emerged as potential solutions. Nanotechnology promises nanomaterials (1–100 nm) with a surface area and high reactivity to absorb or detoxify harmful pollutants (Chahar et al., 2023). Meanwhile, biotechnology offers a process, *bioremediation*, which uses microorganisms to destroy or stabilize toxic substances naturally (Khan et al., 2024). Both have been applied in various studies for hazardous waste treatment with promising results, including in wastewater contaminated with heavy metals, pesticides, and other toxic substances (Chahar et al., 2023).

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1 Hazardous Waste and Its Impact in Gaza

Hazardous waste includes any waste that has the potential to harm humans and the environment due to toxic, corrosive, explosive, or radioactive properties. In Gaza, the accumulation of hazardous waste has increased dramatically due to the genocide. In the May 2021 genocide alone, >370 thousand tons of debris were created in 11 days, of which *Unexploded Ordnance* (UXO) and hazardous components (asbestos, heavy metals) were identified at many of the wreckage sites (Abuhamed et al., 2023). Post-genocide electronic waste adds to the complexity, as it contains a mixture of metals (Pb, Hg, Cd, Cr) that are carcinogenic in nature, as well as organic compounds such as *polybrominated diphenyl ethers* (PBDE) of plastic that have similar persistent organic pollutants/POP properties (Al-Najar et al., 2015; Khan et al., 2024). These POP compounds can persist long in the environment, accumulate in biological tissues, and cause hormonal disorders, cancer, and teratogenic effects (Yavuz & Unal, 2025). The World Health Organization (WHO) report (2025) notes that heavy metal pollution in Gaza is associated with an increase in cases of deformed and premature babies in the last decade (Yavuz & Unal, 2025). Thus, hazardous waste in Gaza is an urgent health-environmental problem, where the population's chronic exposure to contaminants (through polluted water, inhaled dust, food chains) will have long-term impacts (Yavuz & Unal, 2025).

The international regulatory framework has established strict standards for hazardous waste management, as presented in Table 1. The Basel Convention focuses on preventing the transfer of hazardous wastes to places that cannot handle them, which implicitly requires Gaza to develop internal capacity. The Rotterdam Convention requires approval and exchange of information before hazardous materials are traded (Setiyono, 2024), ensuring that hazardous chemicals do not enter and exit Gaza without the knowledge of the relevant authorities. The Stockholm Convention calls for eliminating chemicals such as PCBs, organochlorine pesticides, and dioxins (Fiedler et al., 2019), which is appropriate given the findings of dioxins and PCBs in the debris and smoke of burning garbage in Gaza. In addition, OECD policies emphasize the collective responsibility of developed countries to ensure that hazardous waste is managed safely and not diverted to vulnerable areas. Gaza, although not a sovereign state that is a party to the agreement, is affected by this global norm, for example, in the difficulty of exporting hazardous waste out of the region due to legal and political restrictions. Thus, the policy literature emphasizes the urgency of local innovation in Gaza: waste treatment technology must be effective, in accordance with international standards, and can be run with limited resources.

2.2 Nanotechnology Approaches in Hazardous Waste

Nanotechnology refers to the manipulation of materials at the nanoscale (1–100 nm), where unique physicochemical properties emerge compared to their bulk counterparts. Its central features, such as high surface area-to-volume ratios, tunable surface chemistry, and enhanced catalytic activity, have positioned nanomaterials as promising tools for environmental remediation, particularly in the management of hazardous waste. Several nanotechnology-based mechanisms have been explored in the literature: (1) adsorption using nanosorbents to capture heavy metals and toxic organics; (2) photocatalysis through nanocatalysts (e.g., TiO_2 nanoparticles) for oxidative degradation of hazardous organics; (3) zero-valent iron nanoparticles (nZVI) for reductive dehalogenation of persistent pollutants; (4) nanostructured membranes and nanofiltration for efficient contaminant separation; and (5) nanosensors for the detection of pollutants at trace levels (Del Prado-Audelo et al., 2021; Jain et al., 2021).

In the context of hazardous waste management in Gaza, these technological options acquire urgent relevance. Gaza has faced prolonged genocide that has severely disrupted its waste management infrastructure, leading to the accumulation of hazardous waste from medical facilities, chemical residues, construction debris, and electronic sources. Such conditions have intensified risks of soil, groundwater, and coastal contamination (UNDP, 2024; Reuters, 2024). Nanotechnology applications could offer context-sensitive interventions: nanofiltration units for wastewater treatment, TiO_2-based photocatalysts for degrading toxic organics in medical waste, and nanosorbents for immobilizing heavy metals. However, field implementation in Gaza is constrained by limited access to raw materials, chronic energy shortages, security restrictions on equipment mobility, and the absence of large-scale treatment facilities. Literature therefore recommends modular, low-energy, and portable nanotechnology solutions, such as green-synthesized nanosorbents or solar-assisted photocatalytic reactors, that can be deployed in emergency or resource-limited conditions (Hooshmand et al., 2020; UNDP, 2024).

In summary, nanotechnology offers a suite of technical solutions for reducing hazardous contaminants through adsorption, degradation, and separation. Yet, in genocide-affected regions like Gaza, practical deployment requires adaptation to operational constraints, risk mitigation strategies, and the design of appropriate, low-cost technologies. Field-based pilot studies testing nanosorbent–photocatalytic hybrid systems or renewable-powered nanofiltration units represent critical pathways for bridging laboratory innovation with real-world applicability.

2.3 Biotechnology Approaches in Hazardous Waste

Biotechnology-based remediation leverages the capacity of living organisms or biological systems to detoxify, transform, or immobilize hazardous pollutants. Core mechanisms include biodegradation (mineralization of organic pollutants to CO_2 and H_2O), biotransformation (conversion into less toxic metabolites), biosorption (binding of heavy metals by living or dead biomass), bioaugmentation (addition of pollutant-degrading microbial strains), and phytoremediation (use of plants for pollutant uptake or stabilization) (Bala et al., 2022).

Recent advances highlight the use of engineered microbial consortia, where complementary metabolic pathways enable degradation of complex compounds; enzyme-based remediation (e.g., laccases, peroxidases) to catalyze oxidative breakdown of toxic organics; microalgae systems for nutrient removal and metal uptake; and hybrid approaches that couple biological treatment with adsorption or membrane processes for improved efficiency. Synthetic biology also expands the scope by engineering microbial tolerance to toxicity and broadening substrate specificity (Bala et al., 2022). Nevertheless, critical challenges remain, including biosafety concerns, monitoring of secondary metabolites, and longer treatment durations compared to physicochemical methods.

For hazardous waste in Gaza, biotechnology provides several operational advantages. First, *in situ* application minimizes the need to transport hazardous waste across insecure areas. Second, the adaptability of bio-based systems makes them suitable for resource-constrained environments, relying on simple reactors or locally available biomass as biosorbents. Third, biotechnology enables resource recovery, such as energy generation through anaerobic digestion or recovery of metals from waste streams. For example, medical waste could be pretreated (via autoclave, where available) and subsequently treated in bioreactors or algal photobioreactors to reduce organic load and pathogens. However, the Gaza context, marked by damaged facilities, prolonged electricity outages, and waste accumulation in temporary dumpsites, poses significant barriers to consistent biotechnological operations (UNDP, 2024).

Therefore, literature suggests modular and rapid-response biotechnological approaches: portable biofiltration units, biomass-derived biosorbents for metal removal, and microbial consortia adapted to extreme conditions. Yet, challenges include ensuring full pollutant degradation, minimizing toxic by-products, and developing simplified operational protocols that can be implemented with limited technical expertise. Integrating biotechnology with lightweight physicochemical methods (e.g., adsorption followed by biodegradation) and conducting pilot-scale demonstrations under field conditions are essential steps toward sustainable hazardous waste management in Gaza (Bala et al., 2022).

3. RESEARCH DESIGN METHOD

This research uses a systematic literature study design to explore hazardous waste treatment technologies suitable for Gaza. The research stages include:

(1) Secondary Data Collection – We collected Scopus-indexed scientific articles (2018–2025) that discuss nanotechnology and biotechnology in hazardous waste remediation, as well as reports from international institutions (UNEP, WHO) on the environmental conditions of Gaza. Sources are selected that are most relevant to the Gaza case: e.g., a case study of post-genocide waste (Al-Mabhouh et al., 2021), innovation in e-waste management in developing countries, and the development of nanomaterials for water filtration (Chahar et al., 2023).

(2) Critical Evaluation – Each technology is evaluated for its suitability to the Gaza context using the following criteria: *Effectiveness* (ability to remove/neutralize key pollutants such as heavy metals, POPs), *Affordability* (in terms of cost and availability of materials), *Operational simplicity* (can be run with minimal infrastructure and locally trained personnel), and *Regulatory Alignment* (does not generate new harmful by-products and supports compliance with Basel/Stockholm standards).

(3) Synthesis of Integrated Solutions – Based on the findings of the literature, the concept of a hazardous waste treatment system in Gaza was designed to combine nano and bio components. This concept includes the flow: segregation and pretreatment of waste (e.g. manual destruction of e-waste), bio-processes (microbial fermentation or bioleaching reactors for metal extraction and organic degradation), followed by nanoprocesses

(wastewater filtration with nanomembranes or the addition of nanoparticles to absorb toxic residues), and finally final storage (stabilization of residual hazardous solids in a cement or clay matrix to make them inert). The initial validation of the concept was carried out by comparing its hypothetical performance against the literature data, such as the efficiency of metal removal by bioleaching vs. water quality standards.

This method of literature study allows conclusions to be drawn based on the latest scientific evidence without conducting direct experiments in Gaza (which is difficult to do given the situation on the ground). However, to corroborate the findings, we also considered best practice reports from other regions facing similar constraints (blockades or facility limitations) as an analogy. With this approach, the research is expected to provide evidence-based recommendations for policymakers and the scientific community in Gaza.

4. RESULTS AND DISCUSSION

4.1 Nanotechnology-Based Solutions for Hazardous Waste Management in Gaza

The results show that nanotechnology can be adapted to address some of Gaza's main hazardous waste problems: heavy metals dissolved in wastewater, persistent organic contaminants, and stabilization of hazardous materials. Some concrete solutions include:

1. **Zero-Valent Iron Nanoparticles (nZVI) for Groundwater Remediation.**

   nZVI can be injected into wells or contaminated soil locations. These particles will reduce toxic metal ions such as Cr (VI) into a less harmful form (Cr (III)) and precipitate them as hydroxides, as well as break down chlorinated molecules into simple compounds. The advantages of nZVI are its high reactivity and wide range in soil pores, as its nano size allows for sound diffusion. Field studies outside Gaza showed that nZVI injections were able to reduce the concentration of TCE (trichloroethylene, an organochlorine compound) by >90% in 1 month (Chahar et al., 2023; Tal & Cohen, 2024). For Gaza, this technology can be applied to areas of former factories or destroyed pesticide warehouses, where the soil contains harmful chemical residues. The preparation of nZVI can be done locally by reducing Fe salts using borohydride or through the biosynthesis route using plant extracts, thereby reducing import dependence.

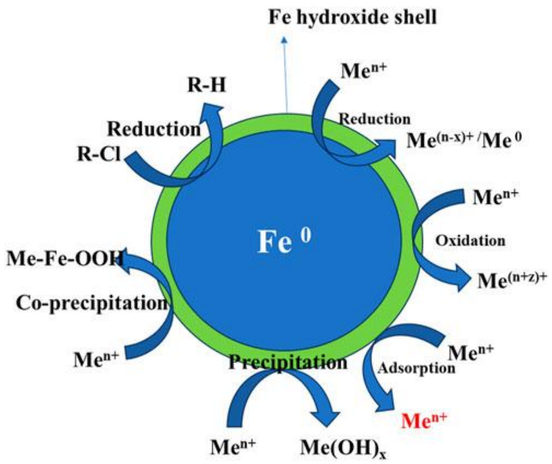

Figure 2. Various mechanisms in metal removal by zero-valent iron nanoparticles (nZVI) (Chahar et al., 2023)

Using Figure 2 above in the methodology confirms the variety of nanomaterial strategies we considered. By understanding the character of each type of nZVI, we can map out which type is best suited for applications in Gaza: for example, a type (C) stabilized nZVI may be more suitable because Gaza's groundwater contains high levels of ions (salinity), and the coating polymer can prevent the passivation of particles by chloride ions. The above method steps align with the structured secondary data-based qualitative research framework, so that the results and subsequent discussions presented can be scientifically accounted for.

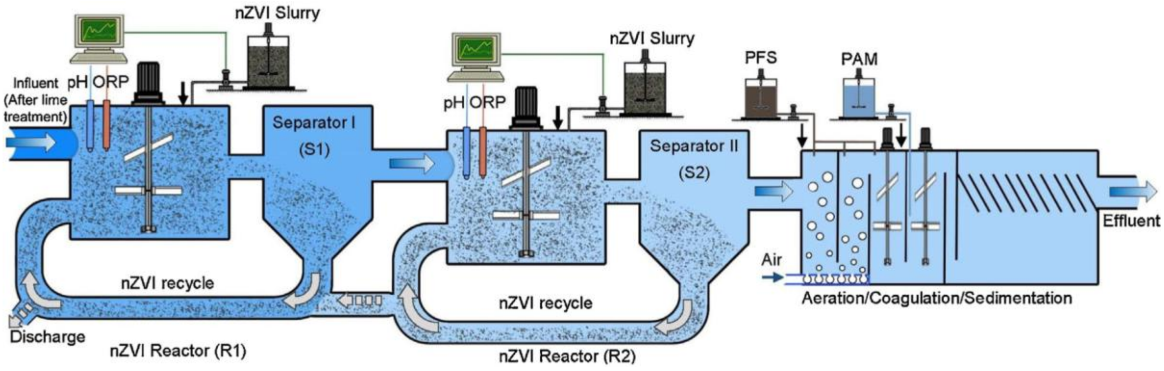

Figure 3. Systematic model series for hazardous wastewater treatment with nZVI (Pasinszki & Krebsz, 2020)

2. **Nano-Carbon and Zeolite for Heavy Metal Filtration**

Nano-carbon (including graphene oxide, reduced graphene oxide, carbon nanotubes, and nano-scale activated carbon/activated biochar) and zeolite (both natural and modified) are two types of high-performance adsorbents that have been extensively researched for treating heavy metal contamination in wastewater (Qasem et al., 2021). Nano-activated carbon has a very high adsorption capacity against metals such as Pb^{2+}, Cu^{2+}, and Hg^{2+} (Chahar et al., 2023). Both materials offer different but complementary capture mechanisms: nano-carbon generally relies on its enormous surface area, surface functions (oxide, carboxyl, hydroxyl) for complexation and electrostatic bonding, and the ability to be modified into composites (e.g., magnetization) to facilitate separation; while zeolite works through ion-exchange mechanisms in its porous aluminosilicate structure and can also be modified to increase its affinity for specific metal cations (Qasem et al., 2021).

In terms of adsorption performance, graphene oxide (GO) and nanostructured carbon-based materials exhibit very high adsorption capacities for metal ions such as Pb (II), Cd (II), Cr (VI), Ni (II), and Hg (II). The advantage of GO and CNT (Carbon Nanotubes) is the ease of functionalization (e.g., grafting of amino groups, sulfonates, or chelating agents) so that selectivity towards certain ions can be increased. Magnetic composites (e.g., GO-Fe_3O_4) allow the adsorbent to be removed using a magnetic field after the adsorption process, which supports the recovery and regeneration of adsorbents on a batch or fixed-bed scale. The literature also reports that adsorption kinetics in nano-carbon often follow the pseudo-second-order model (indicating the role of chemical interactions), while the Freundlich/Langmuir isotherm is used to model adsorption capacity depending on surface conditions and modifications (Melchor-Durán et al., 2024).

Zeolites, especially modified natural zeolites, offer a reliable and chemically stable ion-exchange mechanism. The advantages of zeolites include resistance to relatively harsh operating conditions, predictable ion exchange capacity based on the Si/Al ratio and pore structure, and generally lower raw material costs (for natural zeolites). Simple modifications, such as cation exchange ($Na^+ \rightarrow Ca^{2+}/Fe^{3+}$), acidification, or impregnation with metal oxides, often increase affinity for certain heavy metals and extend the working pH range. A comprehensive review concludes that zeolite is highly effective for the removal of Pb, Cd, and Ni and can be used in continuous filter configurations in water treatment plants (Pérez-Botella et al., 2022).

Practical applications often combine the strengths of both materials through zeolite–nano-carbon composites (e.g., GO/zeolite, magnetic GO/zeolite). This combination utilizes the surface area and functional capabilities of GO to capture specific forms of organo-metal complexes, while the zeolite framework provides ion-exchange capacity and structural stability to the filtration column. Studies show that composites often exhibit higher adsorption capacity, faster adsorption rates, and better performance over a wide pH range compared to single materials (Karnwal & Malik, 2024).

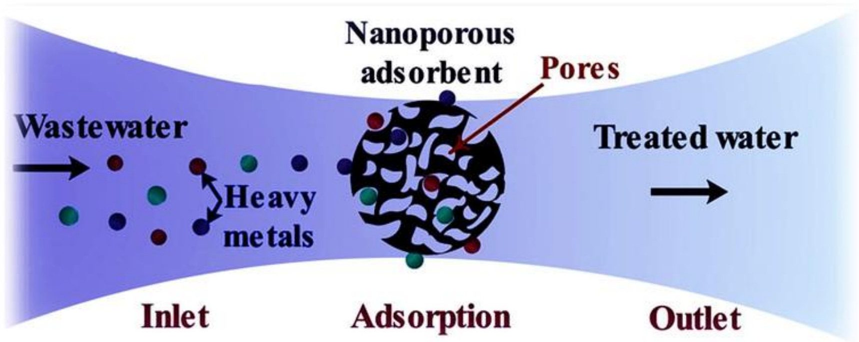

Figure 4. Heavy metal ions adsorption process (Qasem et al., 2021)

This is relevant for filtering well water or hospital wastewater in Gaza that may be contaminated with heavy metals (e.g., from the wreckage of electronic and medical equipment). Nano zeolite (porous aluminosilicate) can be commissioned in a simple filtration column: when water is drained, ammonium or heavy metal ions are exchanged for sodium/calcium ions in the zeolite, so the output water is clean of toxins. Real application: local communities can be provided with nanozeolite zeolite-based filter units to be installed in rainwater tanks, preventing the consumption of metal-contaminated water. Zeolite can be obtained from natural sources (volcanic rocks) that are refined and activated, making this technology relatively inexpensive.

3. Silver and Copper Nanoparticles for Disinfection and Inactivation of Hazardous Medical Waste

Medical waste and household wastewater in Gaza often contain pathogens and chemical residues. Silver nanoparticles (AgNP) are known to be potent antimicrobials; The addition of AgNP to liquid waste storage containers can prevent the growth of pathogenic microbes while oxidizing specific organic matter (Ghosh et al., 2022; Palani et al., 2023). AgNPs exhibit biocidal activity through a combination of mechanisms: the release of Ag^{+} ions that interact with microbial proteins and enzymes, the production of reactive oxygen species (ROS) that damage membranes and DNA, and the physical penetration of small particles that disrupt cellular structures. Therefore, AgNPs are effective against Gram-positive/negative bacteria, viruses, and some fungi, making them suitable for targeting pathogens found in medical waste such as blood, cultures, and contaminated equipment. Several technical reviews confirm the role of AgNPs in water and surface disinfection applications, while highlighting the variability of activity according to the size, shape, and stabilizing coating of the nanoparticles (Duman et al., 2024).

AgNPs with an average diameter of 15 nm have been effectively employed for bacterial sterilization in water treatment applications. These nanoparticles exhibit a strong antibacterial performance that increases proportionally with the applied dose, achieving up to 99.72% bacterial inhibition under optimized conditions. The optimal operational parameters were identified at a pH of 6, with a contact time of 20 minutes and an AgNP concentration of 0.01 mg/mL, demonstrating their high efficiency and rapid disinfection capability in aqueous environments (Rangaraju et al., 2024).

Similarly, copper oxide (CuO) nanoparticles can catalyze the decomposition of dyes and phenol in wastewater. The antimicrobial mechanism of CuNPs also involves the release of Cu^{2+} ions, induction of oxidative stress (ROS), and disruption of cell membranes and respiratory enzymes. Several studies comparing the effectiveness of Cu-based NPs and AgNPs report that under certain conditions, CuO NPs exhibit similar or higher activity against certain pathogens (including resistant strains) and are often more economical for large-scale applications such as waste treatment. Additionally, Ag+Cu combinations or composites (e.g., Ag–Cu) can produce synergistic effects, accelerating microbial inactivation and reducing the required metal dosage (Wozniak-Budych et al., 2023).

Although Gaza lacks water treatment infrastructure, the use of these nanomaterials at the point of use, for example, in jerry cans or water wells, can reduce the load of contaminants before the water is disposed of or reused. Of course, supervision is needed so that the concentration of nanoparticles used remains safe and does not cause a permanent residue in the environment.

4. Nano-Composites for Solidification of Hazardous Wastes

Nano-composites for the solidification/stabilization (S/S) process of hazardous waste combine a matrix phase (usually a cement, geopolymer, or polymer matrix) with dispersed nanomaterials (e.g., nano-SiO_2, nano-Al_2O_3, iron oxide nanoparticles, graphene/graphene oxide) to improve contaminant immobilization and the mechanical properties of the final product. The cement composite material can increase the strength of the stabilizer matrix so that the dangerous metals are "trapped" more firmly in it. Research shows that adding 1% nanosilica to cement mixtures can reduce heavy metal percolation by up to 70% compared to ordinary cement (Hemalatha et al., 2022).

Studies have demonstrated that adding graphene nanoplatelets or nano-silica into alkali-activated matrices improves compressive strength and reduces leaching of Pb, Cd, and Zn from municipal solid waste incineration residues (Su et al., 2025). Similarly, nano-titanate or nano-Fe oxides have shown enhanced durability and immobilization under harsh environmental conditions (Metaxa et al., 2021).

The concept is that Gaza's hazardous waste can be mixed with cement-nanosilica to form concrete blocks for non-structural construction projects (e.g., road barriers). This provides two benefits: waste is inertized and converted into building materials, supporting a simple circular economy in Gaza.

From the above results, it appears that nanotechnology can be applied in a modular and scalable. This means that the technology can be used from a household scale (such as simple nanofilters) to a limited area scale (nZVI injection at specific industrial sites). For Gaza, nanotechnology strategies need to be adapted to material access: for example, the production of nano-activated carbon can utilize local organic waste (wood chips, coconut shells/tamarinds) through thermal carbonization, reducing the need to import materials. Most importantly, any nanotechnology innovation must be ensured not to violate the provisions of *the Basel Convention* – especially when it comes to not generating new harmful "nanowaste". Until now, the scientific consensus has been that nanomaterials such as nZVI and carbon tend to be trapped in the soil or can be filtered after use so that the risk of their spread is controlled. However, monitoring is still necessary.

4.2 Biotechnology-Based Solutions for Hazardous Waste in Gaza

The literature search also shows that biotechnology – particularly the application of Bioremediation – is particularly relevant in Gaza, given the state of local resources. Some of the biotechnology solution alternatives identified include:

1. **E-waste bioleach**

   Given the large amount of e-waste from rubble (damaged electronic tools), the bioleaching technique is paramount. As already described, the bacteria *Acidithiobacillus* Sp. It can dissolve heavy metals from electronic fragments by oxidizing sulfide compounds and producing sulfuric acid. The advantage of bioleaching is that it can be done in a simple reactor (e.g., barrel or aerobic tub) without high energy. Case studies in India report that bioleaching using *Acidithiobacillus ferrooxidans* at 35°C for 10 days is able to extract 90-95% copper and zinc from circuit board powder (Annamalai & Gurumurthy, 2022).

   For Gaza, the application scenario is to collect the PCB pieces, soak them in an iron-oxidizing bacterial culture solution, and aerate slowly. The final solution contains dissolved metals (Fe, Cu, Zn), which can be further processed (e.g., precipitation/metal collected). Residual solids (resin, fiberglass, plastic) can be burned under control or further processed by plastic-eating fungi. This process is relatively inexpensive; The main need is nutrition for bacteria (e.g., sources of sulfur or iron that can be obtained from mining waste or sulfate fertilizers).

2. **Biosorption and Phytoremediation of Heavy Metals**

In addition to microbes, biosorption using dead biomass or hyperaccumulator plants is a low-tech solution. For example, agricultural waste from Gaza (straw, husks) can be processed into biosorbents through minimal chemical treatment (acidification to open pores). These biosorbents bind heavy metal ions through their carboxylate and hydroxyl groups. Research shows the biosorbent capacity of activated sawdust can reach >50 mg Pb^{2+} per gram, comparable to commercial activated carbon (Khan et al., 2024). Meanwhile, some plants such as *Vetiver grass* or *Populus* Sp. It is known to be able to absorb metals from the soil (phytoremediation).

Gaza could use the vacant land of the former genocide to plant hyperaccumulator plants as a long-term effort to suck heavy metals from ammunition-contaminated soil. Harvested plants, containing high metals, must then be secured. Biosorption and phytoremediation are complementary because they are slow, but very inexpensive and involve community participation (e.g., local farmers planting remediative crops).

3. **Biodegradation of Harmful Organic Compounds**

Gaza likely has chemical residues such as solvents, explosives (TNT/ trinitrotoluene, RDX/ hexahydro-1,3,5-trinitro-1,3,5-triazine), pesticides, etc. The biotechnology solution is to utilize a consortium of degrader microbes. *Pseudomonas putida* is known to be able to degrade aromatic compounds; *Phanerochaete chrysosporium* (white weathering fungus) is able to break down lignin and analogues of complex aromatic compounds with peroxidase enzymes. Practical approach: create a *Biopile* or mound of contaminated soil, inoculate it with a mixture of bacteria and fungi decomposing (it can be obtained from composted soil or culture from outside), apply additional nutrients (such as nitrogen-phosphorus fertilizer to stimulate microbial growth), and then let the biodegradation process last a few months. This technology is commonly used for oil-contaminated soil (landfarming) and can be adapted to war compounds such as rocket propellant residues. As a result, the concentration of organic pollutants decreases over time to below the danger threshold. Of course, additional assistance is needed for highly stable POPs (e.g., PCBs), such as additional surfactant, biosynthetic or co-substrate, so that microbes can degrade more effectively (Palanisamy et al., 2023).

4. **Medical Waste Treatment with Enzymes and Microbes**

Hazardous waste also includes infectious medical waste (Vardanyan et al., 2022). Gaza could implement Enzymatic digestion and composting instead of incinerators (which are difficult to operate because of limited electricity and dioxin emissions). Medical waste in organic tissues can be broken down by protease and cellulase enzymes produced by a mixture of bacteria (e.g., Bacillus subtilis) in a closed reactor, so its volume and pathogenicity drop drastically. Furthermore, the residue can be mixed with carbon-rich materials (wood powder) and composted for non-food horticultural use. This technique has already been tried in several African rural hospitals as an alternative to incineration. The key is to ensure that the temperature and time are sufficient for all pathogens to die (e.g., compost temperature > 55°C for a few days to kill the virus/bacteria).

The above results confirm that biotechnology provides economically and operationally feasible solutions in Gaza. Many biological processes can be carried out with simple equipment (barrels, air pumps, open land) and utilize local resources (native microbes, local biomass). This is especially important considering that 5 out of 6 waste treatment facilities in Gaza are severely damaged, causing 1,200 tons of waste to accumulate daily in open landfills. The application of in-situ Bioremediation, such as landfarming or biopiles in strategic locations, can ease the burden on landfills and reduce the need for waste transportation.

The weaknesses of the biotechnology identified are the relatively slow speed and sensitivity to environmental conditions. Prolonged genocide in Gaza can disrupt operations (e.g., damage to biopiles or bioreactors in the event of an attack). Also, there is a possibility that the *Strains* Introduced microbes are not competitive in the Gaza environment or inhibited by specific pollutants. For this reason, synergy with nanotechnology can be a solution: the use of nanomaterials as microbial supports. For example, magnetic nanoparticles can Fe_3O_4 be used as carriers of degradation enzymes. The enzymes are coordinated on the surface of the nanoparticles, so they are stable and can be separated magnetically after use (Sah et al., 2025). Similarly, the application of iron nanoparticles in bioleaching can increase the rate of iron oxidation by bacteria (since the nanoparticles act as an *Electron Shuttle*). The concept of integration is discussed in the following sub-chapters.

4.3 Integration of Nanotechnology and Biotechnology in Gaza

The best approach for Gaza is likely not to select nano or bio separately, but to integrate the two in a single hazardous waste treatment system. The study's results reinforce the idea that this integration can increase the efficacy and overcome the constraints of each method. Some integration scenarios include:

1. **Nano-Bio in Contaminated Water Treatment**

   Contaminated wastewater or groundwater (e.g., from debris seepage) can be treated through a combination of Bioreactor + Nano Filter. The first stage is to drain the contaminated water to a biofilter containing biofilm of decomposing bacteria (e.g., bacteria that eat toxic organic compounds). Bacteria will reduce the load of organic pollutants and some metals through biosorption. In the second stage, water flows to a second filter containing nanomaterials (nano zeolite, nano-activated carbon) to absorb the rest of the heavy metals to a safe concentration (Chahar et al., 2023). The final stage can be added by using a UV lamp + nano-TiO_2 photocatalyst to disinfect and decompose micro-organic residues. In this order, the workload of each component is lighter: the biofilter is not killed by heavy metals because most of it is later captured in the nanofilter; the Nano filters do not quickly saturate organics because they have been decomposed in the bio stage. The water output can be reused for non-food land irrigation or recycled for cooling.

The synergy of applying this approach is that the bioreactor reduces the initial pollutant load, thereby extending the life of the nano filter membrane (reducing fouling). Nano filters produce high-quality water, even approaching drinking water standards.

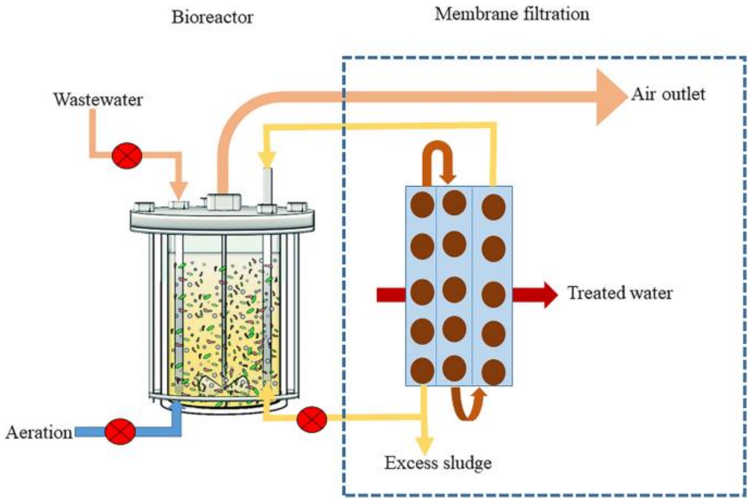

Figure 5. Combination approach: Bioreactor and Bio-nanofiltration to treat hazardous wastewater (Chandran et al., 2025)

2. Nano-Bio in E-Waste Recycling

Electronic materials contain precious metals (Cu, Au, Ag) that can be recycled. Instead of conventional methods (burning or soaking harmful, strong acids), the approach of *nano-biorecovery* can be applied. First, e-waste fragments are fermented with microbes (bioleaching) to dissolve the metals (Palanisamy et al., 2023). Then the metal solution is subjected to the addition of Nanoparticle Adsorbent selective, e.g., magnetite (Fe_3O_4) nanoparticles modified with specific functional groups to capture gold or copper ions. The metal-charged nanoparticles are then separated with magnets, and the metal is recovered (eluted) for sale. This process has been tested on a laboratory scale: one study obtained gold recovery >90% of e-waste solutions using thiourea-coated magnetic nanoparticles as gold adsorbents (Edgar et al., 2020). For Gaza, this technique means that e-waste can be a useful material source rather than a threat. In addition, solid residues of e-waste after metal extraction are relatively heavy metal-free, so they can be disposed of more safely or reused (e.g., the plastic is recycled into low-quality products).

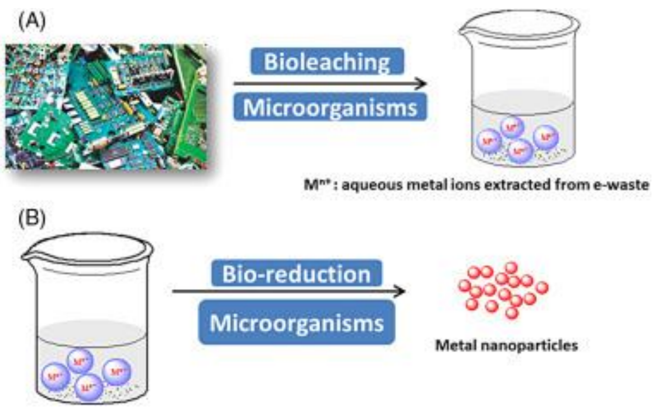

Figure 6. Combination nanobiotechnology for E-waste (Dodamani et al., 2021)

3. **Nano-Bio for Debris Soil Remediation**
   The debris of Gaza's buildings is a lot mixed with soil and chemical residues (from paint, burnt plastic, etc.). Remediation of former ruins can be done with a combination of biological and nano agents. One of the concepts is mixing Biocarbon (biochar) biomass pyrolysis results with *catalytic nanoparticles* (e.g., nano Fe/TiO_2) and sprinkling it on contaminated soil. Biochar improves soil structure and provides habitat for soil microbes, while catalytic nanoparticles in biochar accelerate the degradation reaction of pollutants in the soil (e.g., through the Fenton reaction, which produces hydroxyl radicals that destroy organic molecules). Studies show that nano-impregnated biochar can Fe_2O_3 lower the content of polyaromatic hydrocarbons in the soil by up to 60% higher than regular biochar within a period of 8 weeks (Chahar et al., 2023). This is promising for Gaza, given that many of the bombing sites have fuel/explosive-contaminated soil.

4.4 Implications and Policy Recommendations

Nano-biotechnology integration also has an institutional dimension: this approach can involve collaboration between local universities (for nanoresearch and microbial cultures) and the environmental services sector (for implementation in the field). Labor-intensive schemes can be implemented, such as employing local youth in *bioremediation gardening projects* (planting remediation plants with the help of nanofertilizers) or training technicians to produce activated carbon from organic waste. This aligns with the social goals of reducing unemployment and building Gaza's internal capacity.

Regarding international regulations, this integrative solution supports Gaza's compliance with global norms. By treating hazardous waste at its source, Gaza prevents the risk of illegal cross-border waste movement (as per the Basel Convention). The elimination of POPs through bio-nanodegradation also aligns with the Stockholm Convention's target of removing persistent organic matter. In fact, if the implementation results are promising, Gaza can become an example of applying *best practices* in other genocide zones, encouraging international policy adjustments to better support appropriate technologies in the blockaded areas. International community support will still be needed, for example, microfunding to build communal bioleaching facilities, or assistance in procuring key nanomaterials – but Gaza's dependence on waste export-import will be significantly reduced.

5. CONCLUSION

The treatment of hazardous waste in Gaza can be optimized through nanotechnology and biotechnology innovations adapted to local limitations. Nanotechnology provides functional materials (nanosorbents, reactive nanoparticles, nanomembranes) capable of effectively filtering heavy metals and extracting toxic compounds. Meanwhile, biotechnology offers a natural process (bioleaching, biosorption, biodegradation) that is inexpensive, environmentally friendly, and can gradually break down persistent organic pollutants and stabilize hazardous wastes. The integration of the two proved complementary: the combination *of nano-bioremediation* reduced contaminant levels to safe levels according to international standards, without the need for sophisticated infrastructure or imported chemicals, which are difficult to access.

Specifically, the proposed solutions include: bioleaching e-waste with iron-oxidizing bacteria to extract precious metals, followed by purification of the solution with magnetic nanoparticles; phytoremediation of polluted lands accompanied by the addition of catalytic nanoparticles-impregnated biochar to accelerate soil recovery; as well as a bio-nano tiered water filtration system to provide poison-free water to Gaza residents. The practical application of these solutions requires training support and minimal initial investment (e.g., for manufacturing simple reactors and small-scale nanomaterial synthesis). However, if implemented, Gaza can meet its obligations to manage B3 waste independently and prevent more severe health impacts in the future, while complying with the framework of the Basel, Rotterdam, and Stockholm Conventions.

As a region with acute health and environmental crises due to the genocide, Gaza needs an out of the box approach. Nanotechnology and biotechnology provide real hope for rising above limitations, transforming toxic waste heaps into environmental and resource recovery opportunities. Naturally, follow-up research and pilot projects are highly recommended to test the field scale of each solution. The commitment of local stakeholders and the support of the international community (in the form of microfunding and knowledge transfer) will accelerate the realization of this initiative. Ultimately, the success of hazardous waste treatment in Gaza not only protects the local population from toxic hazards but also safeguards the regional and global environment, in harmony with the spirit of environmental justice in genocide situations.

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