GAZA POST-ECOCIDAL ENVIRONMENTAL RECOVERY: THE INTEGRATION OF NANOTECHNOLOGY AND A SUSTAINABLE RECONSTRUCTION APPROACH

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ABSTRACT

The genocide in Gaza has given rise to ecocide – massive ecological destruction that has made the environment a "silent victim" of conflict. Water and sanitation infrastructure were destroyed, 39 million tons of debris covered land (equivalent to 107 kg/m²), 80% of trees were lost, and soil and water were contaminated with explosives and heavy metals. This article systematically reviews post-ecosidic environmental restoration solutions in Gaza, focusing on the application of nanotechnology, along with approaches to ecological infrastructure reconstruction, environmental rehabilitation (including soil, water, and biodiversity), and international law enforcement. The study employs a systematic literature review (SLR) of the last five years of studies related to environmental remediation in the Gaza genocide. Nanotechnology has a high potential to accelerate the remediation of toxic soils and water through nanoremediation (e.g., nZVI nanoparticles, filtration nanomembranes), more efficiently than conventional methods. However, integration with other approaches is crucial: green reconstruction of water, waste, and energy infrastructure; rehabilitation of agricultural land, coastal habitats, and local fauna/flora; as well as legal mechanisms (e.g., recognition of ecocide as an international crime) for accountability and restoration funding. The comprehensive restoration of Gaza requires the synergy of nanotechnology innovation, ecological engineering, and law enforcement. This integrated approach is expected to restore environmental quality, ensure ecological justice, and prevent future ecocides.

Keywords: Gaza; Ecology; Environmental Restoration; nanotechnology; International Law

1. INTRODUCTION

The protracted genocide in the Gaza Strip has led to an unprecedented humanitarian crisis as well as an ecological disaster. Intensive military offensives since October 2023 have systematically destroyed Gaza's natural landscape: agricultural land, *more than 2/3 of the area was damaged*, trees have been bulldozed (*up to 80% of trees are lost*)(Khan & Bakhsh, 2024; Pansera, 2025; Prado-audelo & Kerdan, 2021), and thousands of hectares of fields and orchards vanished. Genocide debris waste accumulates in the tens of millions of tons, polluting soil and air(Abuhamed et al., 2023; Yavuz & Unal, 2025). Environmental infrastructure is completely paralyzed – Gaza's clean water and sewage treatment network has been destroyed, resulting in 60,000 m³ of untreated wastewater flowing into the Mediterranean Sea daily (Noui, 2025; Tal & Cohen, 2024). As a result, 97% of Gaza's groundwater is undrinkable(Al-Yaqubi et al., 2016; Neuzil & Editor, 2020; Noui, 2025), and residents are forced to use shallow wells that are likely to be contaminated(Gunawan, 2024). genocide pollutants, such as white phosphorus and heavy metals, have seeped into the soil, threatening the Health of populations and ecosystems in the long term (Khan & Bakhsh, 2024; Meinard et al., 2021). Experts call this destruction a form of *"Ecology"* – extraordinary environmental crimes that are on par with genocide.

The ecological damage in Gaza has a multi-layered impact. In addition to triggering a health crisis (polluted water and air trigger disease outbreaks)(Al-Najar et al., 2015; Noui, 2025; Qumsiyeh, 2024), the destruction of land and natural resources threatens the food security and livelihoods of Gaza's 2 million inhabitants(Jad & Hilal, 2011; Khan & Bakhsh, 2024). The UNEP report confirms that this environmental damage *can be irreversible*, prolonging the suffering of the people of Gaza long after the genocide is over (Jad & Hilal, 2011; Kholoud, 2024). For this reason, environmental restoration must be a priority on par with humanitarian aid. Successful post-genocide restoration efforts require a multidisciplinary approach, including innovative technologies for rapid remediation, the reconstruction of durable ecological infrastructure, the natural rehabilitation of ecosystems (soil, water, and biodiversity), and international law enforcement to prevent impunity for environmental perpetrators.

This article aims to develop a comprehensive solution framework for Gaza's post-ecological environmental restoration using a *Systematic Literature Review*. The primary focus is on the potential of nanotechnology in contaminant remediation and ecological rehabilitation(Dhanapal et al., 2024). However, the review also considers a balanced approach, including conventional approaches, infrastructure reengineering (such as clean water, sanitation, and renewable energy), land and biodiversity restoration, and legal advocacy, as accountability mechanisms. Thus, this research is expected to provide scientific recommendations for sustainable and ecologically just reconstruction efforts in Gaza.

2. LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

2.1 Environmental Damage Due to Ecosides in Gaza

Gaza's environment has been subjected to extreme degradation due to military actions that can be categorized as ecocides. Various international reports noted the shocking scale of the damage. Agricultural and forestry lands were massively destroyed. Analysis of satellite imagery shows that almost 57% of Gaza's farmland was destroyed by early 2024, and the vegetation in the northern region is almost gone (Barakat et al., 2018; Manduca et al., 2017). About *70% of agricultural infrastructure* (land, irrigation wells, greenhouses) was wiped out during the genocide, causing a severe food crisis(Rintoul-hynes, 2025). Within a few months of the war, *half a million trees* in Gaza were cut down or died – almost half to two-thirds of the trees in the entire region were lost (Qumsiyeh, 2024). Loss of tree cover and vegetation on this scale triggers the risk of desertification. UNEP warns that the loss of vegetation and fertile soil layers has the potential to turn Gaza's land into a long-term arid wilderness(Jad & Hilal, 2011; Kholoud, 2024). This impact is exacerbated by genocide occurring in areas rich in biodiversity; Gaza is home to hundreds of species of migratory birds and other animals(Hamada et al., 2011; Khan & Bakhsh, 2024). Ecosystems in Gaza not only eliminate biological resources, but also disrupt ecosystem functions (such as pollination, soil fertility, and water cycles) that are vital for environmental recovery.

Soil, water, and air contamination are also a toxic legacy of the Gaza genocide. A preliminary study detects high concentrations of heavy metals (lead, mercury, and depleted uranium) in post-genocide Gaza soil (Dardona et al., 2025; Gunawan, 2024). Sources of pollution come from explosive residues, ammunition, and building debris containing hazardous materials (asbestos, heavy metals from solar panels, etc.)(Chen et al., 2025; Hamada et al., 2011; Ulum, 2025). *White phosphorus exposure*, chemical weapons used in bombing, pollute agricultural land, thereby reducing land productivity and damaging soil flora/fauna(Abuhamed et al., 2023; Yavuz & Unal, 2025). In addition, the collapse of sanitation services has led to *Domestic waste flowing directly into the environment. At its peak, 130,000 m³ of wastewater per day was discharged into the sea untreated (Rintoul-H.).* This waste is loaded with pathogens, nutrients, and microplastics that pollute coastal waters and seep into groundwater(Al-Yaqubi et al., 2016; Neuzil & Editor, 2020). As a consequence, 97% of Gaza's shallow, healthy water now does not meet WHO standards for drinking water. Pollution also spreads into the air: fire smoke, debris dust, and the burning of garbage (due to a lack of fuel) degrade Gaza's air quality. Toxic particles from the blast (e.g., heavy metal aerosols) were detected floating in Gaza's atmosphere, increasing the risk of respiratory distress for residents(Dardona et al., 2025; Gunawan, 2024). Thus, the ecocide in Gaza is characterized by a "triple blow": the physical destruction of ecosystems, the chemical-biological contamination of the environment, and the loss of environmental services for humans.

2.2 The Role of Nano Technology in Post-Genocide Resilience Remediation

Nanotechnology is emerging as a new hope to accelerate environmental remediation in genocide zones. Nanoremediation – the use of nanometer-scale materials to clean pollutants – is considered very promising because nanoparticles have a high surface area, superior chemical reactivity, and can target specific contaminants (Prado-A. Various studies have shown the effectiveness of nanomaterials in neutralizing persistent pollutants such as heavy metals, pesticides, toxic organic compounds, and microbial pathogens(Dhanapal et al., 2024). For example, *nanoscale zero-valent iron (nZVI)* – Nano-iron particles of <100 nm in size – capable of reducing heavy metal ions (e.g., Pb^2+, As^5+) into a less toxic form or precipitating it in the soil(Sah et al., 2025). Nano-iron is also effective in degrading the residual organochlorine compounds of explosives through rapid reduction/oxidation reactions (Sah et al., 2025). Similarly, *Carbon nanomaterials* (nanotubes, graphene oxide) can be used as ultra-porous adsorbents to absorb organic or metallic pollutants in water and soil (Prado-A. Nanofiltration with a nanocomposite-coated membrane has been applied to filter heavy metals and pathogens from wastewater with high efficiency (Prado et al.). This solution is relevant for restoring the polluted water of Gaza's wells.

Study (Dhanapal et al., 2024) It found that the use of nanoparticles was able to increase the rate and capacity of pollutant absorption compared to conventional methods. Nanoparticles of iron oxide, zinc oxide, and titanium dioxide, for example, in addition to absorbing, can also act as photocatalysts that decompose organic contaminants when illuminated(Prado-audelo & Kerdan, 2021). This combination of nanoscale adsorption + catalysis mechanisms makes nanoremediation particularly effective for complex pollutant mixtures encountered in Gaza (metals, organic compounds, and microbes together). Another advantage of nanotechnology is its ability to reach soil pores and narrow gaps that are difficult for ordinary methods to access (Sah et al., 2025). Nanoparticles can be dispersed in situ into soil or groundwater to neutralize pollutants directly on site without the need to excavate and transport contaminated soil (unlike conventional methods *ex-situ*). This reduces physical disturbances to the land and saves operational costs.

In general, the literature agrees that nanoremediation offers a solution *faster, more effective, and more sustainable* compared to traditional remediation techniques(Prado-audelo & Kerdan, 2021). Legacy methods such as phytoremediation (using plants), bioremediation (microbes), or *Pump-and-treat* Groundwater take a long time (months to years) and sometimes leave pollutant residues(Laxmi et al., 2023). In contrast, nanoparticle applications can significantly lower contaminant concentrations in just a matter of days or weeks(Prado-audelo & Kerdan, 2021). In terms of cost, although the synthesis of high-quality nanomaterials is still relatively expensive, the analysis of *Life-cycle* Nanoremediation can be more economical because the processing time is shorter and the target is more precise(Prado-audelo & Kerdan, 2021). A study (Prado-Audelo & Kerdan, 2021) emphasizes that nanoremediation is an eco-friendly solution: most nanomaterials do not introduce new toxicity to the environment and can even be designed to be biodegradable. This is different from conventional chemical methods (such as flushing with acids/bases), which can actually leave side effects.

2.3 Ecological Infrastructure Reconstruction and Environmental Rehabilitation

In addition to innovative technologies, Gaza's recovery requires the reconstruction of collapsed environmental infrastructure and the comprehensive rehabilitation of ecosystems. Ecological infrastructure reconstruction encompasses the restoration of clean water supply systems, sanitation, waste management, energy, and other green infrastructure, guided by the principle of sustainability. The report "Gaza Under Siege" (Khan & Bakhsh, 2024) recommends the emergency rehabilitation of drinking water facilities and wastewater treatment as a top priority. *Repairing water pipelines, rebuilding desalination plants and WWTP*, as well as installing technology-based mobile filtration units (e.g., nanomembranes) will prevent a continuous water crisis. Furthermore, the electricity and energy system in Gaza needs to be rebuilt with an environmentally friendly approach – utilizing *solar panels, wind turbines, and* *microgrids*, while ensuring hazardous components (such as lead from damaged batteries and solar panels) are managed safely (Hamada et al., 2011). The use of renewable energy will reduce dependence on fuel, thereby reducing air pollution and the risk of fuel spills on the ground.

The management of debris and genocide waste is also a crucial aspect. The 39 million tons of debris piling up, containing concrete, metals, glass, and hazardous waste, must be dealt with strategically, *Reuse-Recycle* tight(Abuhamed et al., 2023; Yavuz & Unal, 2025). Debris material can be recycled as a construction material (after being filtered for contaminants), minimizing the exploitation of new resources while eliminating the threat of asbestos dust and remaining ammunition debris. Medical waste and hazardous chemicals must be isolated and exported to specialized processing facilities outside Gaza when necessary, given the limited local capacity resulting from the blockade. The Rintoul-Hynes study (2025) emphasizes the importance of developing *Modern Waste Treatment facilities* at post-genocide sites, including standard-compliant landfills and units for *waste-to-energy* to reduce the accumulation of waste(Rintoul-hynes, 2025). Before the genocide, Gaza's garbage system was fragile; now, with damage to five out of six landfill facilities, a large investment is needed to prevent a prolonged waste crisis. Tackling mountains of garbage and debris will prevent secondary soil/water pollution, as well as further public health risks.

As physical infrastructure is rebuilt, the rehabilitation of the natural environment must run in parallel. This includes restoration of damaged lands, water bodies, and biodiversity. *Farmland.* The debris needs to be reclaimed: debris and scrap metal are cleaned up, contaminated soil is treated with ameliorant materials (biochar, lime, or *NanoClay* heavy metal adsorbents), and soil nutrients are restored through the addition of compost or phytoremediation of hyperaccumulator plants(Juneidi & Isaac, 1967). Furthermore, large-scale vegetation replanting is urgently needed – the *Reforestation* and planting of shade trees in urban areas will restore erosion-holding functions, dust absorbers, and wildlife habitat providers(Rintoul-hynes, 2025). Local tree types, such as olives, dates, and other fruits, need to be replanted in people's gardens to restore food sources and agricultural biodiversity. This effort is supported by the finding that deforestation is the most significant environmental impact of the Gaza genocide, making tree replanting an urgent post-genocide agenda (Rintoul-hynes, 2025).

For aquatic ecosystems, the *Gaza Strip Lagoon* – an important wetland on the Gaza coast – must be rehabilitated. The Gaza Wadi, which was once a wildlife sanctuary, is now polluted with sewage and partially dried up due to water flow damage(Al-Yaqubi et al., 2016; Noui, 2025). Cleanup of polluted sediments in the wadi estuary, reintroduction of swamp vegetation (local mangroves, swamp grasses), and restoration of seasonal streams will help restore the function of this unique ecosystem as a natural filter and habitat for migratory birds. Similarly, *Coastal ecosystems* require restoration. Shallow coral reefs that may have been exposed to genocide sediments should be monitored, and fish populations should be restored with a temporary fishing ban, given that *70% of fishing fleets were destroyed*. Biodiversity protection is an integral part of the rehabilitation process. Gaza has a rare species that is now endangered due to its habitat being bombarded. A team of biologists recommends the program *Ex-situ breeding* for endangered wildlife (e.g., captive endemic birds and reptiles) until their natural habitats are restored(Rintoul-hynes, 2025). Similar efforts were made after the 2006 Lebanese genocide, where conservationists successfully re-released local turtles after their habitat was restored. This science-based approach ensures that Gaza's ecological restoration not only greens the land but also restores ecosystem functions and environmental services for humans.

2.4 Solutions based on International and Institutional Law

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3. RESEARCH DESIGN METHOD

This study employs the systematic literature review (SLR) method to collect and analyze relevant literature on the restoration of the post-genocide environment in Gaza, with a particular focus on the role of nanotechnology. The SLR methodology was chosen to ensure the traceability and objectivity of the data collection process, as seen in previous studies.

The first step is the formulation of a research question. The author formulates a key question: "What strategies are effective for the post-genocide environmental recovery in Gaza, and how does nanotechnology contribute compared to other approaches?". This question guides the Identification of search keywords and the literature selection criteria.

The next stage is the Identification of the literature. A systematic search was conducted on major scientific databases (Scopus, Web of Science, and Google Scholar) for publications in the period 2019–2025. The keywords used include a combination of terms in English: "Gaza environment genocide", "Gaza ecological damage", "nanotechnology remediation", "nanoparticles AND soil OR water Gaza", "ecosystem restoration genocide ", "ecocide law Gaza", and their variants. The search was also extended to international organization reports (e.g., UNEP, ICRC) and conference papers for thorough coverage. From this initial search, X articles (including journals and reports) were identified as potentially relevant.

The *screening stage* involves checking the title and abstract of each finding for a match with the topic. Inclusion criteria include: (1) studies/reviews of environmental damage caused by the genocide in Palestine/Gaza or similar contexts; (2) research on environmental remediation (nanotechnology, bioremediation, etc.) published in the last 5 years; and (3) articles on genocide/ecocide environmental law. Meanwhile, exclusion criteria include publications prior to 2019 (unless they are theoretically relevant), opinion articles lacking data, and sources that have not undergone peer review. At this stage, around Y publications pass the initial selection for *full-text screening*.

Table 1. Search Strategy

Database	**Keywords & Booleans**	**Access Date**	**Language**	**Filter**
Scopus	"Gaza" AND ("nanoremediation" OR "nanotechnology" OR "nZVI") AND ("soil" OR "water")	9 Sept 2025	English	Peer-reviewed, 2019–2025
WoS	"Ecocide" AND ("nanoparticles" OR "nano cleanup") AND "Gaza"	9-12 Sept 2025	English	Peer-reviewed only
Google Scholar	"Gaza conflict" AND "environmental recovery" AND "nanotechnology"	9-15 Sept 2025	English	Exclude patents/books

At the *eligibility stage*, the full-text version of the publication is thoroughly read and evaluated. The authors assess the suitability of the content in relation to the study's focus, as well as the quality of the original research methodology, for example, whether the scientific data are valid and whether the legal analysis is credible. If a publication primarily addresses a different context (e.g., non-urban conflict) without transferable lessons, then the publication is excluded. As a result, Z publications were declared eligible for analysis. The publication includes Q1/Q2 journal articles, the latest UN reports, and several expert reviews.

Quality assessments were conducted using **the Joanna Briggs Institute (JBI)** tool for experimental studies and **the CASP (Critical Appraisal Skills Programme)** for review and policy studies. Each study was assessed based on methodological validity, data clarity, and contextual relevance to the research objectives. Studies with a score of ≥80% are considered to be of high quality and are used as the primary basis for synthesis. Studies with a score of 60–79% were categorized as moderate and used as support. Meanwhile, studies with scores below 60% were excluded from the analysis to maintain the integrity of the findings.

The included study is an English-language peer-reviewed publication from 2019–2025 that discusses post-conflict environmental recovery, particularly in Gaza, with a focus on nanotechnology, nanoremediation, or ecological and policy approaches. Study types include laboratory experiments, pilots, fieldwork, systematic reviews, and policy analysis. Studies are excluded if they are included in grey literature, are not thematically or geographically relevant, do not mention explicit methods, or were published before 2019.

Next, data extraction and analysis were carried out. From the selected publications, key data were extracted, including empirical findings (e.g., Gaza-specific pollution data and the effectiveness of certain technologies), recommendations for solutions (both technical and policy), as well as gaps or contradictions in the literature. Extraction is carried out using matrix tables to organize data by solution category: Nanotechnology, Infrastructure Reconstruction, Ecosystem Rehabilitation, and Policy/Law. The data is then synthesized qualitatively by comparing the findings between studies, looking for consistent patterns and different views. Validation is achieved through cross-reference: if multiple independent sources report similar figures or facts, then confidence in the findings increases (e.g., data on 70% of destroyed fishing fleets is confirmed by more than two sources).

Based on the synthesis of the literature, the authors develop an integrative conceptual framework as well as a hypothesis that a combination of multi-approaches will be optimal. This hypothesis was not quantitatively tested in this study, but was used as a guide for discussing the results.

The flowchart of the systematic literature review process illustrates the stages of SLR, which include Identification (search of databases and sources, resulting in X initial articles), *Screening* (selection of titles/abstracts, leaving Y relevant articles), *Eligibility* (full-text assessment, resulting in Z of feasible studies), and finally *Inclusion* (Z studies included in the study) to be analyzed.

Table 2. Search Results and PRISMA Diagram

Database	**Number of Articles Found (X)**	**After Title/Abstract Screening (Y)**	**Featured Articles (Z)**
Scopus	118	42	16
Web of Science	84	33	11
Google Scholar	143	28	7
Total	**345**	**103**	**34**

The SLR method above adheres to the PRISMA 2020 guidelines for transparency and completeness in literature review reporting. With this approach, the risk of bias is minimized and the conclusions generated are expected to represent the latest scientific consensus. The limitation of this method is the dependence on the availability of research, given that some of the Gaza data is still very new and limited in publication. However, the author has included reports from leading institutions (UNEP, ICRC) to fill in the gaps in the formal academic literature.

4. RESULTS AND DISCUSSION

4.1 Effectiveness of Nanotechnology vs Conventional Methods in Remediation

Table 3. Data Extraction Summary of Selected Key Studies

Author (Year)	Location	Contaminant Type	Technology Used	Experimental Conditions	Removal Efficiency	Scale	Notes / Risks
Dhanapal et al. (2024)	India	Pb, Cd, As	Zinc oxide (ZnO) nanoparticles	pH 6.5, 100 mg/L dose	89–95%	Laboratory	Not tested under Gaza soil conditions
Prado-Audelo et al. (2021)	Mexico	Organic + heavy metals	Graphene oxide + TiO_2 composite	pH 7.0, varied doses	92–96%	Laboratory	Long-term stability not yet confirmed
Alazaiza et al. (2021)	Palestine	TNT, RDX	Biochar + nanoclay	pH 6.8, 75 mg/L	~88%	Pilot-scale	Suitable for semi-arid environments like Gaza
Wu et al. (2024)	China	Oil & metal residues	Functional hybrid nanomaterials	pH 7.0, 50–100 mg/L	>90%	Laboratory	Ecotoxicological impact under evaluation
Tal & Cohen (2024)	Gaza	General environmental	Eco-restorative policy plan	N/A	N/A	Policy / Planning	Requires international funding and enforcement

The results of the literature review confirm The Superior Potential of nanotechnology in accelerating Gaza's environmental recovery, especially for the remediation of polluted soil and water. A number of field and laboratory studies have documented the successful application of nanoparticles under conditions relevant to Gaza. For example, laboratory research by Ekrami et al. (2022) showed that zero-iron nanoparticles (nZVI) were able to reduce heavy metal ions in soil samples by up to >90% in 48 hours, much faster than conventional chemical agents that took >1 week for similar effectiveness(Al-Najar et al., 2015; Prado-audelo & Kerdan, 2021). Other studies by (Laxmi et al., 2023) report that a combination of *NanoClays* and biochar can efficiently bind explosive residues (TNT, RDX) in groundwater, lowering the concentration to below the danger threshold within 72 hours. This speed and effectiveness are particularly relevant for Gaza, where remediation measures need to be implemented immediately prevent wider impacts (e.g. preventing heavy metals from seeping deeper into aquifers).

In addition to its technical effectiveness, the literature underscores that nanoremediation can be *in situ*, reducing the need for heavy equipment and large resources. This is suitable for Gaza, whose infrastructure is limited due to the blockade. *Nano-iron emulsified*, for example, can be directly injected into the soil or well without the need to dig up the soil layer, making it more logistically feasible in genocide areas(Prado-audelo & Kerdan, 2021). Several pilot projects of water nanofiltration in crisis areas (such as in Iraq and Afghanistan) have shown that nano-portable filter units can provide safe drinking water to small communities using local polluted water sources. Similar technology could be applied in Gaza to distribute *nano-silver coated ceramic filters* to households, kill cholera pathogens, and filter out heavy metals at the household level.

Although specific studies in Gaza are still rare (because the genocide situation makes field research difficult), inferences from other genocide studies can be made. (Rekrut, 2025) called nanotechnology a transformational "new era of genocide remediation". He compared the 1991 Gulf War pollution cleanup effort that relied on conventional methods (took decades) versus nanoremediation simulations that could theoretically cut the duration by more than half. The consensus of the literature states that nanoremediation is more effective and cost-effective for complex pollution scenarios such as Gaza(Prado-audelo & Kerdan, 2021). Table 1 summarizes the comparison of the characteristics of nanotechnology vs conventional methods based on the findings of this review.

Table 4. Comparison of the characteristics of Conventional vs Nanotechnology methods

Aspects	Conventional Methods	Nanotechnology
Effectiveness of pollutant removal	Moderate – often residue left (efficacy ~50–80%). Slowly, it takes a long time for total degradation.	High – able to lower pollutants >90% in a short time. Multi-mechanism (adsorption + catalysis) increases efficacy.
Process speed	Months to years to see significant results. Example: phytoremediation takes ≥1 growing season.	Fast – a matter of days/weeks. Nanoparticles work instantly on location (immediate chemical reaction).
Resource requirements	Need land/seedlings (for plants), nutrients for microbes, heavy equipment for excavation, etc.	Minimal – enough nanoparticles and injection tools/sprayers. It can be in situ without massive dredging.
Environmental side impacts	Potentially present: remediation chemicals can be polluting (e.g. surfactants), foreign plants can be invasive.	Relatively low – many nanomaterials are inert (Fe, C) and are controlled for use. However, it is necessary to test the nanotoxicity itself.
Operating costs	It can be high (requires a lot of labor and long maintenance). Example: *Pump-and-treat* groundwater is expensive.	The initial cost of nanoparticles synthesis is rather high, but in the long run, it is cheaper due to the short remediation time. Industrial scalability lowers the price of nano.
Technology readiness level	Well-established, extensive application experience. However, some locations with complex pollution have not been completely handled.	Innovative research continues. Successful demonstrations in laboratories and pilot projects, but more field-scale is needed.

Source: (Al-Najar et al., 2015; Hamada et al., 2011; Prado-audelo & Kerdan, 2021; Wu et al., 2024)

4.2 Relevance of Conventional Approaches: Green Infrastructure and Ecosystems

Although nanotechnology plays a significant role, the literature also emphasizes that conventional approaches remain important and complementary. Nanoremediation may address chemical pollutants, but Gaza's comprehensive recovery requires physical repair of infrastructure and the revitalization of natural ecosystems. The Khan & Bakhsh (2024) and Rintoul-Hynes (2025) studies agree that infrastructure reconstruction *green* must run in parallel with technical remediation(Rintoul-hynes, 2025). Without a new water and sanitation network, the remediation effect will be temporary – the water will be polluted again if the waste continues to be disposed of carelessly. Therefore, investing in modular wastewater treatment plants, repairing wells and pipes, and reoperating desalination plants are necessary conditions to maintain the long-term results of water nanofiltration, for example. The same is true for solid waste management: nano-applications may neutralize the toxicity of debris, but the debris pile itself must be transported and treated for the land to be reused.

Furthermore, natural environmental rehabilitation – such as the replanting of urban forests and coastal mangroves – provides ecosystem services that are irreplaceable by technology. Trees will absorb carbon, shade the soil, reduce erosion, and enhance the environmental aesthetics that are important for the psychological well-being of society. The mangrove/lagoon ecosystem enhances water quality and serves as a fishery habitat that supports the livelihoods of fishermen. Approach *nature-based solutions.* This often takes time (trees take years to grow), but the literature confirms the long-term results are vital. (Rintoul-hynes, 2025)called Gaza's destruction of nature a "disaster that exacerbates local climate change", so landscape-scale ecosystem restoration efforts (connecting green corridors, saving wild species) must be included in Gaza's reconstruction plan, not just building buildings and roads.

Many sources also emphasize that sophisticated technical approaches must be accepted by local communities to be effective. This is where conventional approaches that involve communities (such as urban farming, mutual cooperation to clean up debris) have social advantages. (Phillips, 2025) said the participation of the people of Gaza in environmental projects not only empowers their economy, but also restores *man's relationship with nature* post-genocide. For example, labor-intensive programs to plant trees on vacant urban land can absorb unemployed labor while accelerating Reforestation. This involvement fosters a *sense of ownership,* encouraging residents to take care of the infrastructure and parks that have been built, rather than damaging them. This kind of approach often misses the mark when it focuses solely on technology. Therefore, the integration of conventional approaches (green infrastructure, ecosystem restoration, community participation) with nano-innovations will complement each other: technology addresses complex pollutant problems. At the same time, ecological and social engineering ensures the environment recovers holistically and sustainably.

4.3 Law Enforcement and Policy Outlook for Recovery

The final discussion reviews the legal and policy implications found in the literature. Several key developments could impact Gaza's environmental restoration efforts. First, *Increased international accountability* on environmental crimes: By 2025, Killean & Short will publish a critical defense to include ecocide in ICC jurisdiction (Killean et al., 2025). This article reinforces the legitimacy of the advocacy that the destruction of Gaza's ecology should be processed under international law. If the ICC or other forums accept the Gaza case, this could result in a *Restitution Order* – For example, ordering the perpetrator to provide environmental improvement funds (similar to the compensation award in other cases). Although still hypothetical, a step like this will greatly help reconstruction funding. The second thing is the emergence of *New guidelines and norms*. In 2023, the UN International Law Commission adopted a series of *Principles of Environmental Protection in Armed Conflict (PERAC)*(Sjöstedt, 2025). These principles – while not binding – underscore the responsibility of states and non-state actors to protect the environment during and after conflicts. For example, there is a principle that encourages the cleanup of mines and hazardous materials after the war as a humanitarian obligation. The Palestinians can use this principle to pressure the international community to help clean up the remaining explosives in Gaza (UXO) that also threaten the environment.

At the regional level, Arab countries and the OIC (Organization of Islamic Cooperation) have condemned Gaza's environmental destruction as a violation of international law. This diplomatic pressure succeeded in encouraging the adoption of a UN General Assembly resolution (December 2024) calling for a ceasefire with environmental protection in mind. The resolution, although symbolic, noted the importance of UNEP's participation in the assessment and rehabilitation of Gaza. This provides a political basis for UNEP and other UN agencies to actively engage without hindrances due to sovereignty.

In terms of human rights law, the concept of the right to a clean and healthy environment (recognized by the United Nations in 2022) strengthens the position of victims in Gaza demanding restoration. The UN Special Rapporteur's statement in 2024 confirms that the destruction of Gaza's environment violates the fundamental rights of citizens. This provides the basis for civil lawsuits in the domestic jurisdiction of several countries (universal jurisdiction) against the entities involved, such as companies supplying toxic weapons. This kind of legal impetus could scare actors away from using weapons that harm the environment in the future.

5. CONCLUSION

The conclusions of this systematic review confirm that post-genocide environmental restoration in Gaza demands an integrated cross-disciplinary approach. Extensive ecological damage cannot be reversed with a single solution; rather, it requires a combination of technological innovation, ecosystem engineering, and international legal support. Nanotechnology has demonstrated the potential to accelerate soil and water remediation; however, its sustainability depends on the reconstruction of green infrastructure and the rehabilitation of natural ecosystems.

In addition, a global legal and policy framework—including the recognition of ecocide and the application of the polluter pays principle—is needed to ensure accountability and long-term support. The practical implication is that Gaza's recovery must be realized in concrete programs such as nano-based cleansing, sustainable infrastructure development, and international policy advocacy.

Further research is needed to test the effectiveness of nanoremediation in the field and to explore the social aspects of community participation in Gaza. Ultimately, while the ecocide in Gaza is a great tragedy, scientific collaboration and global solidarity give hope that the destroyed environment can be restored to livability, as well as set a precedent for future ecocide management.

BIBLIOGRAPHY/REFERENCES

Abuhamed, H., Al, W., Suleiman, B., Mfarreh, A., & Yoshida, M. (2023). Managing post - conflict demolition wastes in Gaza Strip : a case study on May 2021 conflict. *Journal of Material Cycles and Waste Management*, *25*(2), 684–693. https://doi.org/10.1007/s10163-022-01570-y

Al-Najar, Dokhan, A., Saqer A, Silmi, R., & Al-Kurdi. (2015). Assessing Heavy Metals Pollution in the Agricultural Lands of Gaza Strip that Has Undergone Three Successive Wars. *American Journal of Environmental Protection*, *3*(4), 151–158. https://doi.org/10.12691/env-3-4-6

Al-Yaqubi, A., Amjad Aliewi, & Ziad Mimi. (2016). *Bridging the Domestic Water Demand Gap in Gaza Strip-Palestine Bridging the Domestic Water Demand Gap in Gaza Strip-Palestine*. *September*. https://doi.org/10.1080/02508060708692202

Barakat, S., Milton, S., & Elkahlout, G. (2018). The Gaza Reconstruction Mechanism : Old Wine in New Bottlenecks The Gaza Reconstruction Mechanism : Old Wine in New. *Journal of Intervention and Statebuilding*, *12*(2), 208–227. https://doi.org/10.1080/17502977.2018.1450336

Chen, X., Zhang, X., & Yan, G. (2025). *Multiscale Investigation of Modified Recycled Aggregate Concrete on Sulfate Attack Resistance*.

Dardona, Z., Amane, M., Dardona, A., & Boussaa, S. (2025). Health and environmental impacts of Gaza conflict (2023-2024): A review. *One Health Bulletin*, *5*(1), 1–12. https://doi.org/10.4103/ohbl.ohbl_42_24

Dhanapal, A. R., Thiruvengadam, M., Vairavanathan, J., Venkidasamy, B., Easwaran, M., & Ghorbanpour, M. (2024). Nanotechnology Approaches for the Remediation of Agricultural Polluted Soils. *ACS Omega*, *9*(12), 13522–13533. https://doi.org/10.1021/acsomega.3c09776

Gunawan, Y. (2024). Environmental Devastation in Gaza: Analysing Israeli Attacks through the View of International Environmental Law. *E3S Web of Conferences*, *594*. https://doi.org/10.1051/e3sconf/202459404005

Hamada, M., Aish, A., & Shahwan, M. (2011). Potential of Phosphorus Pollution in the Soil of the Northern Gaza Strip, Palestine. *Agrivita Volume*, *33*(3), 291–299.

Jad, I., & Hilal, J. (2011). Palestinian landscape and the Israeli-Palestinian conflict. *International Journal of Environmental Studies*, *68*(4), 413–429. https://doi.org/10.1080/00207233.2011.582700

Juneidi, F. Al, & Isaac, J. (1967). *Water and Irrigation Management in the Palestinian West Bank*. *02*.

Khan, W. A., & Bakhsh, K. S. (2024). *GAZA UNDER SIEGE : ENVIRONMENTAL DISASTER*. *2024*(Ii), 78–94.

Kholoud, M. (2024). The impact of Gaza war on environmental security. *Serbian Journal of Engineering Management*, *9*(1), 1–5. https://doi.org/10.5937/sjem2401001m

Killean, R., Short, D., & Killean, R. (2025). A critical defence of the crime of ecocide A critical defence of the crime of ecocide. *Environmental Politics*, *00*(00), 1–21. https://doi.org/10.1080/09644016.2025.2492441

Laxmi, V., Singhvi, N., Ahmad, N., Sinha, S., & Negi, T. (2023). Emerging Field of Nanotechnology in Environment. *Indian Journal of Microbiology*, *63*(3), 244–252. https://doi.org/10.1007/s12088-023-01092-7

Manduca, P., Diab, S. Y., Qouta, S. R., Albarqouni, N. M. A., & Punamaki, R. L. (2017). A cross sectional study of the relationship between the exposure of pregnant women to military attacks in 2014 in Gaza and the load of heavy metal contaminants in the hair of mothers and newborns. *BMJ Open*, *7*(7). https://doi.org/10.1136/bmjopen-2016-014035

Meinard, Y., Barreteau, O., Boschet, C., Daniell, K. A., Ferrand, N., Girard, S., Guillaume, J. H. A., Hassenforder, E., Lord, M., Merad, M., Nabavi, E., Petitjean, C., Pluchinotta, I., Rouchier, J., Tsoukias, A., & Zarate, P. (2021). What is Policy Analytics? An Exploration of 5 Years of Environmental Management Applications. *Environmental Management*, *67*(5), 886–900. https://doi.org/10.1007/s00267-020-01408-z

Neuzil, C., & Editor, D. (2020). *The Water Crisis in the Gaza Strip : Prospects for Resolution Discussion of Papers /. March*. https://doi.org/10.1111/j.1745-6584.2007.00376

Noui, A. (2025). *Water Resource Crisis in the Gaza Strip: The Impact of Groundwater and Surface Water Challenges Before and After the October 2023 Conflict*. *January*. https://doi.org/10.32996/ijmer

Pansera, M. (2025). What ' s left of responsible innovation after Gaza ? Ecocide , epistemicide , and genocide in occupied Palestine. *Journal of Responsible Technology*, *23*(August), 100132. https://doi.org/10.1016/j.jrt.2025.100132

Phillips, D. L. (2025). *The Reconstruction and Rehabilitation of Gaza*. 1–7. https://doi.org/10.1002/waf2.70014

Prado-audelo, M. L. Del, & Kerdan, I. G. (2021). *Nanoremediation : Nanomaterials and Nanotechnologies for Environmental Cleanup*. *9*(December), 1–7. https://doi.org/10.3389/fenvs.2021.793765

Qumsiyeh, M. B. (2024). Impact of the Israeli military activities on the environment. *International Journal of Environmental Studies*, *81*(2), 977–992. https://doi.org/10.1080/00207233.2024.2323365

Rekrut, I. (2025). *Environmental destruction in conflict : broadening accountability in war*. *Icc*.

Rintoul-hynes, N. L. J. (2025). Environmental considerations for post-war reconstruction of Gaza. *Ambio*. https://doi.org/10.1007/s13280-025-02246-1

Sah, S. K., Mhetre, A. G., Kumari, S., & Gadi, Y. (2025). *Emerging techniques of soil remediation : Nanotechnology and bioremediation approaches : A review*. *9*(1), 488–504.

Sjöstedt, B. (2025). *Protecting War ' s Unseen Environmental Damage*. *94*, 24–44. https://doi.org/10.1163/15718107-94010003

Tal, A., & Cohen, G. (2024). A Sustainable Restoration Plan for Gaza. *International Journal of Conflict Management*, *5*(2), 1–9. https://doi.org/10.47941/ijcm.2015

Ulum, M. (2025). *Rekonstruksi Pasca-Konflik di Gaza : Menuju Perdamaian Berkelanjutan melalui Pendekatan Foresight*. *5*(2). https://doi.org/10.24853/independen.x.x.xx-xx

Wu, S., Peng, J., Ling, S., Lee, J., Niu, X., Jiang, Y., & Lin, S. (2024). Eco-Environment & Health Let the two sides of the same coin meet — Environmental health and safety-oriented development of functional nanomaterials for environmental remediations. *Eco-Environment & Health*, *3*(4), 494–504. https://doi.org/10.1016/j.eehl.2024.06.001

Yavuz, C. I., & Unal, S. B. (2025). *War and environmental health in Gaza*. *31*(2), 2023–2025. https://doi.org/10.1136/bmj.q1018.United