



Original Article

Plant–Microbe-Based Circular Approaches for Remediating Conflict-Induced Environmental Pollution-Implications for Cancer, Respiratory, and Waterborne Diseases

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OPEN ACCESS

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Received: 21-06-2026

Accepted: 06-07-2026

Available online: 15-07-2026

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Medical and Pharmaceutical Research

ABSTRACT

Background: There has been an increase in the recognition of the role played by conflicts in causing environmental pollution due to the release of pollutants to the atmosphere, water, and soil. The war activities result in production of heavy metals, explosion residues, particulates, petroleum hydrocarbons, and pathogens that pollute the environment. People who live in areas where conflicts are occurring are subjected to this polluted environment, leading to health problems such as cancer, respiratory problems, and waterborne diseases. Normal means of decontamination are usually expensive and challenging to carry out due to conflict.

Aim and Objectives: In this review, we aim to investigate the major causes of conflict-induced pollution and their impact on environmental pollution and human health. We will also assess the possibility of using plant–microbe-based strategies to achieve sustainable restoration of the contaminated environment and their compatibility with circular economy concepts.

Methodology: A narrative review of literature was conducted regarding the major pollutants of the environment resulting from conflicts such as heavy metals, explosive residues, particulate matters, petroleum-based hydrocarbons, and pathogens. Literature reviews of plant–microbe-based environmental restoration techniques were critically analysed.

Results: As suggested by the findings of this review, armed conflicts lead to pollution of the environment, which causes prolonged environmental degradation and human contamination through the exposure to these pollutants. A polluted environment will result in a higher chance of contracting cancers and respiratory conditions and water-borne diseases by the members of the communities. Some of the remediation methods that are derived from plant-microbe interactions include detoxification, immobilization of heavy metals, and rejuvenation of soil fertility.

Conclusion: The approach of using plant-microbes in remediation is a promising, affordable, and eco-friendly approach compared to other forms of remediation techniques. This technique is capable of working within the framework of a circular economy to restore the environment and reduce health hazards associated with pollutants.

Keywords: Phytoremediation, Pollution, Rhizosphere interactions, Heavy metal contamination, Explosive residues, Circular economy, Public health risks.

INTRODUCTION

Armed conflicts have been traditionally linked to direct human losses and infrastructure destruction, but their impact on the environment cannot be underestimated. Environmental degradation resulting from warfare has been found to persist for decades. A cocktail of pollutants resulting from warfare, such as heavy metals, hydrocarbons, explosive residues, and radioactive materials, has been found to accumulate in the soil, water, and air systems [1,2]. While environmental degradation resulting from warfare has been found to negatively affect environmental quality, there has been recognition of the long-

term exposure risks to environmental pollutants resulting from warfare. In recent times, there has been an acknowledgment of the relationship between warfare-induced environmental pollution and adverse health effects, particularly in resource-poor settings [3, 4].

The health risk due to environmental contamination in war zones is quite significant. For instance, exposure to toxic chemicals and particulate matter has been known to cause various types of cancer, including lung cancer and leukemia, as well as respiratory problems like asthma and COPD [5, 6]. At the same time, the destruction of water and sanitation facilities in war zones causes the proliferation of various types of harmful microorganisms, leading to outbreaks of waterborne diseases like cholera, dysentery, and typhoid [7, 8].

The conventional remediation techniques, including physical removal and chemical treatment, are not feasible in war zones due to their complexity and cost [9, 10]. Therefore, there is an urgent need to develop new techniques that are not only sustainable but also easily applicable to the existing environment. The biological remediation techniques, including the use of plants and microorganisms, have been found to be effective.

Plant-microbe interaction in the rhizosphere can be viewed as a dynamic system capable of transforming or detoxifying environmental pollutants. Plants can take up, stabilize, or transform environmental pollutants, while associated microbes can increase the efficiency of such processes through metabolic activities or alleviating plant stresses [11, 12]. When integrated with circular economy approaches, such biological systems not only remediate a polluted environment but can also promote resource recovery or sustainable resource management [13, 14]. This manuscript examines the possibilities of such approaches in addressing environmental and health challenges resulting from conflict-induced pollution.

Sources of Conflict-Induced Environmental Pollution

Chemical and Explosive Residues

Conflicts involving military actions lead to the significant release of chemical and explosive residues into the environment. These residues come from various sources, including explosives and detonators used during conflicts. Trinitrotoluene (TNT) and cyclotrimethylenetrinitramine (RDX) are examples of chemical residues that are highly resistant to environmental degradation and can penetrate the soil and groundwater systems. These residues are toxic, mutagenic, and carcinogenic and can significantly impact the health of ecosystems and humans in the long term. These residues can significantly alter the soil productivity and microbial populations in the soil ecosystem [15].

Heavy Metals

The release of heavy metals into the environment is another significant impact of conflicts on the environment. These metals come from various sources, including military equipment and infrastructure destroyed during conflicts. Lead (Pb), cadmium (Cd), mercury (Hg), and uranium are examples of metals that are introduced into the environment as a result of conflicts. These metals are non-biodegradable and can persist in the environment for long periods. These metals can be transferred into the food chain via plant uptake and can biomagnify in the ecosystem. The prolonged use of these metals has been associated with various health issues, including neurological disorders, renal dysfunction, and increased cancer risk [16, 17].

Airborne Pollutants

Air pollution in conflict zones is attributed to explosions, fossil fuel combustion, and destruction of industrial infrastructure. These processes emit PM_{2.5} and PM₁₀, as well as polycyclic aromatic hydrocarbons (PAHs) and toxic gases, into the atmosphere. These airborne pollutants are known to travel extensively and cause respiratory problems, cardiovascular problems, and increased mortality rates [5, 18].

Water Contamination

Conflicts cause damage to water and sanitation infrastructure, thereby contaminating water sources. The prevalence of pathogenic microorganisms in drinking water causes increased incidence rates of waterborne diseases like cholera, dysentery, and typhoid fever. The situation is worsened due to the lack of access to clean drinking water and healthcare facilities in conflict zones [7, 19] and details are given in Table 1.

Table 1: Major Pollutants in Conflict Zones, Their Sources, Health Impacts, and Plant-Microbe-Based Remediation Strategies

Pollutant Type	Source	Environmental Compartment	Health Impact	Plant-Microbe-Based Remediation Strategy
Heavy metals (Pb, Cd, Hg, U)	Weapons, ammunition, military vehicles	Soil, water	Carcinogenicity, neurotoxicity, kidney damage	Phytoextraction using Brassica juncea, Vetiveria zizanioides + PGPR (e.g., Bacillus, Pseudomonas)

Explosive residues (TNT, RDX)	Ammunition, bomb blasts	Soil, groundwater	Toxicity, mutagenicity, endocrine disruption	Rhizodegradation using <i>Populus</i> spp. + microbial degradation by <i>Pseudomonas</i> , <i>Rhodococcus</i>
Particulate matter (PM2.5, PM10), PAHs	Bombings, burning infrastructure	Air	Respiratory diseases, cardiovascular disorders	Urban phytoremediation using <i>Azadirachta indica</i> , <i>Ficus religiosa</i> + phyllosphere microbes
Petroleum hydrocarbons	Fuel spills, destroyed storage units	Soil, water	Liver toxicity, carcinogenic effects	Bioremediation using hydrocarbon-degrading bacteria (<i>Bacillus</i> , <i>Alcanivorax</i>) + phytoremediation
Pathogens (bacteria, viruses, protozoa)	Contaminated water, poor sanitation	Water	Cholera, typhoid, dysentery	Biofiltration systems, constructed wetlands, microbial treatment (<i>E. coli</i> removal consortia)

Health Implications of War-Induced Pollution

Cancer

War-induced pollution has been linked with a high risk of cancer in war-torn countries. Environmental pollutants like polycyclic aromatic hydrocarbons (PAHs), metals, and radioactive materials are known carcinogens that are usually released into the environment as a result of explosions, burning of infrastructure, and the use of high-tech warfare. These substances are known to be long-term health hazards that can induce cancer in humans after entering the human body and causing oxidative stress, DNA damage, and genetic mutations that can lead to cancer types such as leukemia, lung cancer, and breast cancer. Epidemiological studies that were conducted in war-torn countries revealed that there was a high incidence of cancer compared to non-war areas ^[20, 21].

Respiratory Diseases

Respiratory health is one of the sectors of health that is easily affected by environmental pollution resulting from military activities. This is mainly due to the release of particulate matter such as PM2.5 and PM10, as well as toxic gases and combustion products, which are released during bombing and burning. This particulate matter can easily reach the lungs, causing inflammation. There is a notable increase in respiratory infections such as asthma, COPD, bronchitis, and respiratory infections. This affects mortality rates, particularly in vulnerable ^[5, 22].

Waterborne Diseases

One of the primary concerns in war-torn countries is waterborne diseases, which arise from the disruption of water supply and sanitation facilities. Drinking water contaminated with pathogenic bacteria, viruses, and parasites causes outbreaks of waterborne diseases such as cholera, typhoid, and dysentery. Lack of access to clean and safe water, combined with poor personal hygiene and living in overcrowded conditions, contributes to the rapid spread of waterborne diseases. Waterborne diseases have a significant impact on children and immunocompromised people, resulting in high morbidity and mortality in war-torn countries ^[19, 23].

Plant-Microbe-Based Circular Remediation Approaches

Phytoremediation

Phytoremediation is an eco-friendly and economically viable technique in which plants are used to clean up, detoxify, or remove pollutants from contaminated sites in soil, water, and air media. This technique is based on various mechanisms, such as phytoextraction, phytodegradation, and phytostabilization, to clean up pollutants from contaminated sites. Phytoextraction is a technique in which plants uptake heavy metals, such as lead, cadmium, and zinc, from contaminated sites through their root system and translocate them to their shoots, where they are harvested and removed from contaminated sites. On the other hand, phytodegradation is a technique in which plants degrade organic pollutants, such as hydrocarbons and pesticides, into less toxic compounds in their shoots and roots. Lastly, phytostabilization is a technique in which plants reduce the mobility of pollutants by immobilizing them in their rhizosphere, thereby controlling their spread to groundwater and the food chain. Plant species, such as *Brassica juncea*, *Vetiveria zizanioides*, and *Populus*, are well known for their tolerance to contaminated environments, high growth rate, and high biomass production, which make them potential candidates for phytoremediation of contaminated sites ^[20, 21].

Microbial Remediation

Microbial remediation is a process that uses microorganisms such as bacteria and fungi for the degradation and detoxification of hazardous pollutants in the environment. Some bacterial species such as *Pseudomonas* and *Bacillus* have the enzymatic ability to degrade complex organic pollutants such as petroleum hydrocarbons and explosive residues into

less complex and non-toxic forms. Fungi such as *Trichoderma* have been found to play a key role in the degradation of recalcitrant organic pollutants and improve the health of the soil environment. These microorganisms not only improve the degradation of pollutants but also improve plant growth by producing phytohormones and reducing stress conditions in the environment [11, 22].

Plant-Microbe Synergy

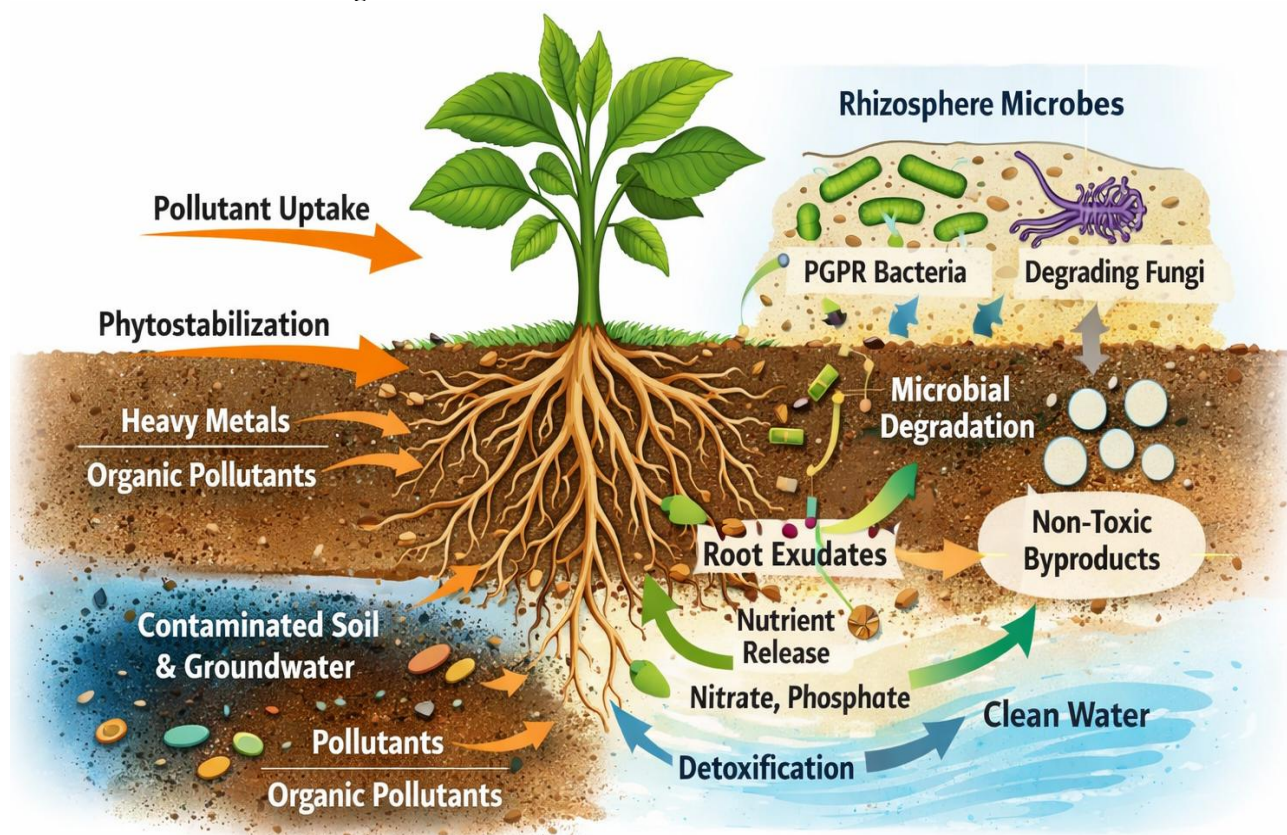
The symbiosis between plants and microbes in the rhizosphere results in a highly dynamic and efficient mechanism for pollutant removal. Plants release a variety of organic compounds from their roots, which are collectively known as root exudates. These exudates provide nutrients to microbes, promoting their growth. Consequently, microbes play a role in nutrient availability, soil structure, and plant tolerance to environmental stress. This symbiosis hastens pollutant removal through a combination of plant uptake mechanisms and microbial metabolism. This mechanism also plays a role in fertility recovery and the establishment of a stable ecosystem in a degraded environment. By integrating all these mechanisms in a circular fashion, it becomes possible to achieve pollutant removal sustainably while simultaneously promoting resource recovery [14, 24].

Circular Economy Integration

The circular economy concept has been centered on the idea of converting waste into a resource in a way that is environmentally friendly and sustainable. In the context of conflict-caused environmental pollution, incorporating plant-microbe systems into a circular economy has several advantages for the restoration of war-torn ecosystems. One of the major advantages of this system is the use of biomass that is produced during the process of phytoremediation. The plant species that are used for the process of phytoremediation produce a significant amount of biomass that can be converted into a valuable resource in the form of biofuel [13, 25].

In addition to the use of biomass for resource creation, nutrient cycling is another significant advantage that can be obtained from plant-microbe systems for the restoration of war-torn ecosystems. The presence of microbes in the rhizosphere increases the nutrient value of the soil, thereby increasing its fertility. In addition to this, water that has been purified using plant-microbe systems can be used for other purposes, thereby helping to overcome water scarcity that is common in war-torn ecosystems [13, 14] is shown in Figure 1.

Figure 2. Circular Remediation Framework in Post-Conflict Areas



Graphical representation of the mechanism of action of plant-microbe interactions in the rhizosphere, where plants absorb pollutants such as heavy metals and other toxic compounds, while rhizosphere microbes degrade other pollutants to less

toxic compounds. It shows exudation from the root, microbial degradation, nutrient uptake, and production of non-toxic compounds, leading to remediation of contaminated water and soil.

Strategies to Overcome War-Based Pollution in the Future

Pre-Conflict Environmental Planning

The first step to overcome war-based environmental pollution is to take effective measures to mitigate it before conflicts arise. This can be achieved through a detailed risk assessment of regions containing industries, military bases, and environmentally sensitive zones, which are likely to be adversely affected during conflicts. Once the high-risk zones are identified, it is possible to take effective measures to prevent environmental degradation during conflicts, which can result in significant environmental pollution [26].

Deployment of Green Technologies

The deployment of green technologies plays a vital role in addressing environmental pollution in conflict zones through quick remediation measures. The deployment of new technologies, like mobile bioreactors and phytoremediation systems, can be used to clean contaminated soil and water in conflict zones. These technologies use a combination of microorganisms and pollutant-tolerant plants to accelerate the cleaning process, which can be deployed in conflict zones to overcome environmental pollution [12, 22].

Restoration Ecology

Restoration ecology is very crucial in rehabilitating ecosystems that have been destroyed by war. This is achieved by reforestation with local species tolerant to pollutants, which helps in soil fixation, erosion control, and biodiversity increase. Soil improvement strategies, such as biofertilizers, also help in improving soil fertility and structure, thus promoting gradual ecological recovery and sustainability [27].

Policy and Governance

Policy and governance are very vital in addressing issues of environmental degradation resulting from conflicts and wars. There is a need to improve international regulations to safeguard the environment during war and conflicts. It is also important to integrate advanced monitoring technology, such as remote sensing and artificial intelligence, to help in assessing and monitoring environmental degradation. This ensures timely decision-making and promotes accountability for ecological degradation [28].

Community-Based Approaches

The role of the community is significant in the success of environmental restoration programs. Involving the community in environmental remediation not only increases the efficiency of the remediation process but also promotes a sense of ownership and responsibility. Educational programs aimed at promoting proper usage of water, sanitation, and environmental conservation can go a long way in reducing health risks. The amalgamation of community-based approaches with scientific remediation strategies can result in sustainable remediation in conflict-affected countries and details is given in Figure 2.

Figure 2. Circular Remediation Framework in Post-Conflict Areas



An illustration of a circular plant-microbe-based remediation framework from the stage of pollution to the stage of ecosystem development. The flowchart illustrates the major steps in the process, from exposure to pollutants to biological treatment, biomass production, soil development, water purification, and finally, the formation of a sustainable ecosystem.

DISCUSSION

Plant-microbe-based remediation has been identified as a promising approach for sustainable pollution remediation compared to other conventional physicochemical methods, particularly in conflict zones where there is a lack of financial, technical, and infrastructural facilities. The biological system for pollution remediation is a sustainable approach that not only removes pollutants from the environment but also maintains ecological balance ^[10]. The combined action of both plant and rhizospheric microbes has been reported to degrade a wide variety of pollutants in the environment, including heavy metals, hydrocarbons, and explosives ^[11, 12].

One of the major advantages of these biological systems for pollution remediation is that these systems provide multiple ecosystem benefits in addition to pollution remediation. Phytoremediation systems play a significant role in soil stabilization, carbon sequestration, and habitat creation, thereby enhancing biodiversity and ecosystem functionality ^[14, 20]. In addition, these systems can be made economically viable by incorporating them into a circular economy system for resource recovery through biomass use and nutrient cycling ^[13, 25].

However, there are a number of challenges that need to be addressed in order to make this process more efficient in its application. The process is a long-drawn-out one that requires several growth cycles in order to produce significant reductions in pollutants. The efficiency of this process is also dependent on various factors that are specific to each location, including the type of soil, climatic conditions, and concentration of pollutants ^[17]. There is also the possibility that some pollutants may be of low bioavailability.

Recent advances in science and technology provide a new scope for overcoming the limitations that are associated with this process. The application of artificial intelligence and remote sensing has the potential to provide real-time monitoring and assessment of polluted sites ^[26]. Genetic engineering in plants and microbes has the potential to improve the capacity of these living systems to tolerate and degrade pollutants thereby enhancing the efficiency of the process ^[21, 22].

Another significant factor in resolving the issue of conflict-induced environmental pollution is international collaboration. International collaboration is significant, as effective collaboration is required to develop guidelines and utilize technological innovations to apply effective strategies to solve the problem ^[28].

CONCLUSION

Conflict-induced environmental pollution is one of the significant problems that need to be resolved, as it affects the health and sustainability of the environment. The introduction of harmful substances during conflicts pollutes the environment, and the pollution affects the health and well-being of people, resulting in cancer, respiratory problems, and waterborne diseases. Therefore, to solve the problem, effective and sustainable strategies need to be developed and implemented to reduce the negative consequences.

The use of plant-microbe-based circular remediation strategies offers hope for mitigating the challenges associated with the use of such approaches. For instance, the detoxification of pollutants is achieved, and at the same time, ecological remediation and resource recovery are promoted. The use of circular economy concepts makes the strategies even more sustainable, as they reduce waste and increase resource productivity.

Going forward, it is crucial to adopt a comprehensive approach that incorporates environmental planning, technological advancements, and community mobilization. For instance, the use of advanced technologies such as artificial intelligence will be instrumental in improving remediation strategies. Additionally, community mobilization will be crucial in the success of remediation strategies.

In conclusion, the use of plant-microbe-based circular remediation strategies is crucial in mitigating the environmental and health problems associated with armed conflicts. The use of such remediation strategies will be instrumental in improving public health and promoting resilience in conflict-prone areas across the globe.

Nomenclature

TNT – Trinitrotoluene

RDX – Cyclotrimethylenetrinitramine

PAHs – Polycyclic aromatic hydrocarbons

PM – Particulate matter

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