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Harmonizing Biological and Chemical Strategies for Hazardous Chemical Detoxification: An Integrative Review

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Authors' contributions

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ABSTRACT

The management and mitigation of hazardous chemicals pose significant challenges to environmental and human health. This comprehensive review critically examines the efficacy of biological and chemical methods for the detoxification of hazardous chemicals. Hazardous chemicals, ranging from organic pollutants to heavy metals, often contaminate soil, water, and air, leading to adverse ecological and health impacts. Traditional chemical-based approaches have limitations, such as secondary pollutant generation and high operational costs. In contrast, biological methods harness the metabolic activities of microorganisms, plants, and enzymes to transform or degrade hazardous compounds. This review evaluates the performance of biological systems, including bioremediation, phytoremediation, and enzyme-based approaches, in

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detoxifying various classes of hazardous chemicals. Additionally, chemical methods, such as advanced oxidation processes, redox reactions, and adsorption, are scrutinized for their efficiency in chemical degradation and transformation. The comparative analysis considers factors like effectiveness, cost, environmental impact, and applicability to different chemical classes. Understanding the strengths and weaknesses of these detoxification approaches is essential for informed decision-making in environmental remediation and industrial processes. This review offers valuable insights into the selection of appropriate detoxification methods, based on the nature of the hazardous chemicals and the desired environmental and economic outcomes.

Keywords: Biological approaches; chemical methods; comparative analysis; detoxification; hazardous chemicals.

1. INTRODUCTION

1.1 Hazardous Chemicals

Hazardous chemical (HC), as defined by the Hazard Communication Standard (HCS), is any chemical that can cause a physical or a health hazard to humans, and the environment [1]. There are many types of HCs, including neurotoxins, immune agents, dermatologic agents, carcinogens, reproductive toxins, systemic toxins, asthmagens, pneumoconiotic agents, and sensitizers. Many HCs are also classified as dangerous goods; as they can cause fires, explosions, corrosion, and hazardous reactions if not handled safely. Common examples of HCs include paints, cleaning chemicals, detergents, pesticides, herbicides, diesel fuel, and asbestos. The basic characteristics of HCs are ignitability, corrosivity, reactivity, and toxicity [1].

Huge quantities of HCs are released into the ecosystem from agricultural practices (where fertilizers and pesticides are largely in use), municipal wastes (containing polyethylene, metal casings, electronic refuse, and a host of others), industrial, commercial, military, laboratory, and hospital wastes, and through other human anthropogenic activities. Some of them are not biodegradable as they persist in the environment thereby contaminating air, water, and soil, posing a serious threat to human health, and adversely affecting flora and fauna [2].

Human anthropogenic activities have led to an increase in various types of HCs in the environment to critical levels and produced a wide range of previously unknown contaminants in the form of xenobiotics [2]. Some of these chemicals are highly recalcitrant, toxic (lethal effect, genotoxic, mutagenic, and carcinogenic), and have high bioaccumulation and biomagnification properties [1,3,4].

HCs can be classified into organic such as polychlorinated hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs); inorganic such as heavy metals (Hg, As, Cd, Pb); and xenobiotics, which are often toxic to life and very hard for microorganisms to metabolize [1,5,6]. The presence of these chemicals in the environment may undergo many processes and transform into more toxic compounds and negatively impact the atmosphere, hydrosphere, and lithosphere, leading to environmental degradation [7].

The large-scale application of HCs led to the development of methods by which they can be removed from the environment. Accumulations of HCs have harmful effects; hence, the scientific community has taken notice of this problem and sought to develop effective, economical, and environmentally friendly removal techniques. HCs can be treated by chemical, thermal, biological, and physical methods; though, the most common are chemical and biological methods. Chemical methods include ion exchange, precipitation, oxidation and reduction, and neutralization. In biological methods, agents such as microorganisms, plants, or enzymes from different origins are used to detoxify different classes of HCs [8].

Overall, the primary purpose of this review is to critically analyze and compare biological and chemical approaches for the detoxification of hazardous chemicals. Hazardous chemicals pose significant environmental and human health risks, and finding effective methods for their detoxification is of paramount importance [9]. While both biological and chemical approaches have been widely employed in this regard, this review aims to provide a comprehensive evaluation of their mechanisms, applications, efficiency, and sustainability. By systematically comparing these two approaches, we intend to offer insights into their strengths and limitations and help readers make informed choices when dealing with hazardous chemical contamination. Furthermore, this review explores the growing importance of sustainability and green chemistry principles in the context of detoxification practices, shedding light on eco-friendly alternatives to traditional methods. By achieving these objectives, this review contributes to the broader discourse on environmental management and the safe handling of hazardous chemicals.

2. CHEMICAL METHODS OF DETOXIFYING HAZARDOUS CHEMICALS

In chemical detoxification, neutralization of the HCs is accelerated by using chemicals and transforming them into a less harmful state. Chemical methods include ion exchange, precipitation, oxidation and reduction, and neutralization [10,11].

Chemical oxidation: This uses chemicals called “oxidants” to help detoxify HCs into less toxic forms. It can be used *in situ* because it is conducted in place, without having to excavate soil or pump groundwater for aboveground cleanup. These chemicals oxidize the metals and reduce the oxidation state of contaminants [12]. Oxidants such as permanganate, persulfate, hydrogen peroxide, and ozone have effectively been used in the detoxification of HCs in soil and (ground)water. This method can be used to treat many types of HCs such as fuels, solvents, and pesticides, and to treat soil and groundwater contamination in the source area where contaminants were originally released [13].

Chemical reduction: This uses chemicals called “reducing agents” such as polysulfides, sodium dithionite, ferrous iron, and bimetallic nanoparticles to detoxify HCs into less toxic or less mobile forms, such as carbon dioxide and water. Nanoscale zero-valent iron (nZVI) is also an extensively employed nanomaterial for detoxification purposes. This technology is most often used to clean up heavy metals such as hexavalent chromium, arsenic, lead, and cadmium, chlorinated ethenes and ethanes, lindane, organochlorine pesticides, and inorganic anions [14,15].

Solar detoxification: Solar detoxification of HCs in wastewater could happen at near ambient temperature using low solar concentration – a typical photocatalytic process, where water containing hazardous organic chemicals such as dye is exposed to sunlight in the presence of a semiconductor catalyst such as titanium dioxide. It could also happen by using high temperatures and higher solar concentration (high-temperature, high-flux process for destroying hazardous and toxic compounds) [16].

2.1 Advantages of Chemical Approaches for Hazardous Chemical Detoxification

Chemical detoxification destroys HCs very fast and onsite. For instance, *in situ,* chemical oxidation and reduction of HCs destroy the bulk of contaminants *in situ* without having to dig up soil or pump out groundwater for aboveground treatment. This can save time and money. Chemical detoxification techniques pose little risk to the environment and the chemicals in use are not harmful to the environment or people [13]. It can clean up several types of contaminants dissolved in groundwater and can also be used to clean up contaminants known as dense non-aqueous phase liquids, which are difficult to detoxify by other detoxification methods [15].

2.2 Disadvantages of Chemical Approaches for Hazardous Chemical Detoxification

Chemical detoxification is used to reduce or remove the toxicity of HCs; however, management of huge amounts of HCs by chemical detoxification methods has proved to be inefficient, insufficient, and uneconomical [17]. In addition, it has been reported that toxicity and/or persistence of most of the chemical agents used in chemical detoxification can cause some serious environmental issues. For instance, the epoxidation of aldrin, a pesticide, produces more toxic dieldrin [18]. In some cases, the conditions necessary for the chemical's detoxification are not present. Most chemical detoxification processes do not biodegrade HCs at concentrations that meet regulatory and health standards as they require further decontamination method(s) to achieve maximum contaminant limit [18] hence, further detoxification methods are required.

3. BIOLOGICAL METHODS OF DETOXIFYING HAZARDOUS CHEMICALS

Biological detoxification is a treatment process that controls and accelerates the breakdown of

HCs into non-toxic or less toxic secondary products. Biological detoxification has been used to treat HCs in contaminated water, sludges, and soils [19]. Organisms such as fungi, bacteria, algae, enzymes, and plants perform detoxification by using organic chemicals for food similar to humans' digestive process. The organisms used in the process may be native to the area or specially grown in a laboratory [20,21] and added to the contaminated sites for detoxification.

Microbial detoxification: Microbes that can metabolize the HCs may be added, along with nutrients (biostimulation). In some cases, genetically engineered species of organisms are used [14,22,3,23]. Microorganisms help in converting the toxic components of HCs into less toxic forms. Genetic engineering of microorganisms helps in their better absorption efficiency or bioconversion efficiency of toxins. Molecular methods such as plasmid breeding or genetic engineering can proficiently produce microorganisms (such as *Achromobacter*, *Dehalococcoides*, *Pseudomonas*, *Burkholderia*, *Rhodococcus*, *Comamonas*, *Alcaligenes*, *Sphingomonas*, and *Ralstonia*) having a constructive catalytic perspective, which can reduce the toxicity of HCs. Many bacteria and Achaea have been used to recognize and detoxify HCs such as pesticides, polyethylene, polypropylene, polyvinyl chloride (PVC), and 1,2,3-trichloropropane (TCP) in the environment (Bhatt, et al., 2022; Koul and Taak, [23].

Enzymatic detoxification: This is the use of enzymes to render HCs harmless. Several enzymes such as tyrosinases, phosphor-triesterases, lignin peroxidases, manganese peroxidases, laccases, nitro-reductases, quinone reductases, manganese peroxidases, and reductive dehalogenases have great potential applications in the detoxification of anthracene, perylene, phenanthrene, benzopyrene, pyrene, fluoranthene, and benzothiophene [14]. This approach is also valuable in detoxifying BITBX (benzene, toluene, ethyl benzene, and xylene), known carcinogenic hydrocarbons found in petroleum [18].

Phyto-detoxification: This is the use of plants for the detoxification of HCs. The main reason for the use of this technique was to collect the contaminants from the media and turn them into easily extractable form (plant tissues) (Bhatt, et al., 2022). The phytoremediation of contaminants is categorized under four major sub-groups, which are: phytoextraction, phytostabilization, phytovolatilization, and rhizofiltration. Various plants such as willow, poplar tree, Indian grass, sunflower, rice, corn, bald cypress, tupelo, sweet gum, and oak are applicable to take up and sequestrate a broad range of HCs, ranging from numerous metals and radionuclides, chlorinated solvents, BTEX, PCBs, PAHs, pesticides, explosives, nutrients, and surfactants [18]. This natural and environmental friendly technology is cost-effective, aesthetically pleasant, soil organism friendly, diversity enhancer, and uses energy derivation from sunlight. However, this relatively new technology poses some disadvantages such as the possibility of HCs entrance into the food chain through consumption of the plant by animals [24] these have limited its application.

3.1 Advantages of Biological Approaches for Hazardous Chemical Detoxification

Biological detoxification methods are straightforward and cheap remediation techniques. In the microbial method, microorganisms detoxify and metabolize any HC and re-establish environmental quality [25]. Microorganisms fasten the natural weakling process by assimilating organic molecules to cell biomass with carbon dioxide, water, and heat as by-products [12]. If the treatment system is properly designed, biological detoxification is capable of detoxifying HCs well below minimum substrate concentrations as specified by the regulatory agencies [18].

3.2 Disadvantages of Biological Approaches for Hazardous Chemical Detoxification

These methods also have several disadvantages including the need for appropriate physical and chemical properties of the HCs, water or soil, and surrounding environment, and longtime of action. In some cases, a more hazardous daughter product is formed during biological detoxification. For instance, the anaerobic biological detoxification of the tetrachloroethene produces vinyl chloride – a known human carcinogen and the microbial conversion of secondary amines produces highly toxic N-nitroso compounds [18]. At low concentrations of HCs, the detoxification process may not be effective [26]. Also, at high concentrations of HCs, phyto-detoxification may not be applicable [27].

3.3 Comparative Analysis

Biological and chemical detoxification approaches are similar in some cases. Mixing microbial strains in the form of consortia aids in the rapid detoxification of HCs when they are added to contaminated soil or water. This is also possible with chemical detoxification, which utilizes a combination of chemicals for faster detoxification of HCs. Also, both methods are suitable for *in-situ* and *ex-situ* applications [14,28].

In contrast, chemical methods of HC detoxification are prohibitively expensive and have limited effectiveness. Biological methods, on the other hand, are inexpensive and environmentally friendly approaches for detoxification of HC-contaminated sites [28]. Biotransformation of HCs undergoes slow detoxification processes, making this technology not applicable in the short time clean-up. However, HCs in contaminated sites can be detoxified immediately using chemical methods. This could be advantageous, in that HC-contaminated sites are cleaned up as soon as possible to avert food chain transmission [14,28]. Furthermore, the conversion of HCs into less toxic or nontoxic forms is a desirable feature of using biological methods; whereas, in chemical methods, the products of detoxification might be toxic [14,28]. Biological methods such as the use of microorganisms can mineralize HCs through their metabolisms and remediate traces from the environment. Biological methods can be modified using various genetic engineering tools to fulfill the goal of detoxification; however, this is not possible with chemical methods [28]. Biological approaches may introduce invasive species into the environment after the detoxification process. Biological methods can be applied to the detoxification of a large array of HCs [14]. In addition to detoxification, biological methods such as enzymatic detoxification can enhance soil health through the process of nutrient cycling [14]. Biological approaches confer several technical advantages, such as better efficacy, cost reduction, and easier recovery and reuse of secondary products for industrial applications [28]. The use of biological materials (plants, enzymes, plants) for detoxification may not adapt to diverse environmental conditions; hence, clean-up may not be achieved. Also, biological methods may not be effective in HCs contaminated sites with persistent toxic contaminants, as this may poison the organisms [28] intended to be used as detoxification agents.

3.4 Challenges in Hazardous Chemical Detoxification

HC detoxification poses several common challenges, ranging from technical issues to environmental and regulatory concerns. Addressing these challenges requires interdisciplinary efforts involving chemists, environmental scientists, engineers, and policymakers. It also involves a commitment to research and innovation to develop more efficient, cost-effective, and environmentally friendly detoxification strategies. Here is an examination of some of these challenges:

HCs encompass a wide range of compounds, each with unique properties and toxicities. Developing a one-size-fits-all detoxification approach is challenging due to this diversity [29]. Also, some HCs are chemically stable and resistant to degradation. Breaking down these compounds can be technically challenging, requiring specialized treatments [5]. In some cases, detoxification processes may not completely break down HCs, leading to the formation of harmful byproducts or intermediate compounds [6]. Furthermore, the release of detoxification byproducts into the environment can lead to secondary pollution. Balancing the reduction of the target chemical's toxicity with potential environmental harm is a significant challenge [30].

HCs are constantly evolving, and new compounds may pose threats. Detoxification methods need to address emerging hazards effectively [31]. Many HC detoxification methods require substantial resources and energy. Finding sustainable and energy-efficient processes is a concern [32]. Some detoxification methods may involve the use of hazardous reagents or processes that pose safety risks to workers and the surrounding community. Understanding the long-term effects of detoxification byproducts on human health and the environment is an ongoing challenge [20].

Moreover, meeting stringent environmental regulations and ensuring that detoxification processes comply with legal requirements can be complex. Accurate monitoring and analysis of the detoxification process are essential but can be expensive and technically challenging, limiting their application, especially in resource-constrained settings [33]. In all, public perception and acceptance of detoxification methods can influence the feasibility of their implementation. Controversial techniques may face resistance [34].

4. EMERGING TRENDS AND TECHNOLOGIES IN THE DETOXIFICATION OF HAZARDOUS CHEMICALS

In the ever-evolving landscape of environmental management, the detoxification of HCs has seen significant advancements in recent years. This section of the review delves into the latest trends and innovative technologies that are shaping the field. With a growing awareness of the environmental and health consequences of HC exposure, there is a heightened demand for efficient and sustainable detoxification methods. By exploring these emerging trends and technologies, this review provides an up-to-date understanding of the dynamic field of HC detoxification. These innovations hold the promise of more efficient, cost-effective, and environmentally friendly solutions, offering a glimpse into the future of this critical environmental management practice.

Nanotechnology and Advanced Materials: One of the most promising trends is the integration of nanotechnology and advanced materials like graphene and carbon nanotubes. Nanoparticles and nanocomposites are being harnessed for their exceptional reactivity and surface area, offering new possibilities for chemical degradation and adsorption. These materials, functionalized with various catalytic groups, exhibit enhanced efficiency in breaking down hazardous compounds [35,36].

Bioremediation Strategies: In biological detoxification, cutting-edge bioremediation strategies are gaining traction. Engineered microorganisms and genetically modified plants are increasingly being used to target and metabolize specific contaminants. The use of synthetic biology and genetic engineering in creating tailored bioremediation solutions showcases the potential of this field [23,24].

Green and Sustainable Chemistry: Detoxification processes are now aligning more closely with the principles of green and sustainable chemistry. Emerging technologies focus on reducing the environmental footprint of detoxification, emphasizing the use of benign reagents and the minimization of waste generation [37,38].

In-situ and Ex-situ Methods: The boundary between *in-situ* and *ex-situ* methods is blurring as hybrid approaches gain popularity. These approaches combine the benefits of on-site and off-site treatment, optimizing the detoxification process while minimizing transportation and handling risks [39,36].

4.1 Potential Areas for Further Research and Innovation

The development of more precise and rapid analytical methods for detecting and quantifying HCs is an ongoing need. Research in this area can focus on creating innovative sensor technologies and diagnostic tools that provide real-time monitoring and data for effective detoxification strategies [40]. Moreover, many real-world scenarios involve complex mixtures of HCs. Future research can explore efficient methods for the simultaneous removal of multiple contaminants, addressing the challenges of synergy and interference between different chemicals [41]. The reduction of waste generation during detoxification processes is also a key goal. Innovative approaches should aim to not only detoxify but also valorize waste streams, converting them into useful products or materials, in line with the principles of circular economy [42]. In the same way, understanding the long-term fate and ecological impact of detoxified HCs is essential. Research can delve into the persistence of breakdown products, their potential transformation into other hazardous compounds, and their effects on ecosystems [37,43].

Effective communication and engagement with affected communities play a pivotal role in the success of detoxification efforts. Research can explore innovative ways to involve communities in decision-making processes and raise public awareness regarding the hazards of chemicals and the available detoxification technologies [43]. The development of comprehensive and up-to-date policies and regulations is also crucial. Researchers can contribute by conducting studies that inform policymaking, considering emerging technologies and newly identified HCs [44]. In addition, collaboration between experts from various disciplines, such as chemistry, biology, environmental science, and engineering, is vital. Research can focus on fostering interdisciplinary approaches to tackle the multifaceted challenges of HC detoxification [37,43]. Innovations in detoxification methods should be adaptable to different regions and ecosystems. Future research can emphasize the development of scalable and context-specific technologies that can be applied globally [40].

These research areas and innovations aim to push the boundaries of hazardous chemical detoxification, striving for more sustainable, efficient, and comprehensive methods that safeguard both human health and the environment. Collaborative efforts between researchers, industries, and policymakers will be essential in driving progress in these areas. By considering these potential research areas and innovations, this review not only consolidates existing knowledge but also serves as an inspirational source for researchers and professionals aiming to advance the field of HC detoxification. It underscores the importance of continued exploration and innovation in addressing environmental and human health challenges [45].

4.2 Key Findings and Insights

Increases in industrial, agricultural, and residential usage of HCs have resulted in the release of a huge quantity of organic and inorganic contaminants into the environment. Chemical, physical, and biological approaches have all been used to efficiently detoxify HCs. Despite their fast detoxification processes, chemical methods are less effective and costly. On the other hand, biological methods are increasingly attracting the attention of scientists as they are more environmentally benign than other strategies. Although the quantity of these HCs in the air, soil, and water systems varies from place to place, it is important to detoxify them using sustainable environmental-friendly approaches. The development of advanced microbial technologies based on microbial engineering, strain improvements, and biotechnological methods is known to improve microbial detoxification of HCs both *in-situ* and *ex-situ*. Microbial engineering is a robust approach for improving the abilities of microbes to degrade and metabolize HCs. Biological methods are powerful tools for the large-scale detoxification of HCs. Microbial engineering provides new ways to solve the problems of HCs. Further study on the behavior of HCs in the environment and the performance of appropriate detoxification technology would further assist the scientific understanding of effective means of detoxifying HCs. Harnessing microbial metabolism to reduce the load of HCs in the environment would create a sustainable way to reduce air, soil, and water contamination. More high-throughput research works on microbial and phyo-detoxification technologies are warranted to develop management strategies for the detoxification of HC-contaminated environments.

5. CONCLUSION

In conclusion, this integrated review has provided an insightful comparison of biological and chemical methods for the detoxification of HCs. The assessment revealed that both approaches offer distinct advantages and limitations, emphasizing the importance of selecting the most suitable method based on the specific chemical contaminants and environmental conditions. Biological methods, relying on the enzymatic activity of microorganisms or plants, display eco-friendly characteristics and are highly effective for organic pollutants. On the other hand, chemical methods, employing diverse reactive agents, demonstrate versatility in treating a wide range of contaminants. Critical considerations should be given to the cost-effectiveness, sustainability, and environmental impact of these methods in the context of real-world applications. Collaborative efforts between researchers and environmental practitioners are crucial for advancing the field of chemical detoxification and addressing complex pollution challenges. Ultimately, the choice between biological and chemical methods should be made in alignment with the principles of green chemistry and sustainable environmental management to ensure a healthier and safer world and to be responsible for future generations.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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