ECOTOXICOLOGY AND SUSTAINABLE ENVIRONMENT

Principles, Challenges, and Innovations in Environmental Protection

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Regards,

The Editors,

Dr. Pooja Kumari *and* ***Dr. Fahad Ali***

Preface

The editors thank all authors for their intellectual dedication and commitment toward promoting environmental awareness and sustainable development. Each author has made a distinct and valuable contribution to the advancement of knowledge in the field of ecotoxicology, sustainability, and protection of the environment. Profound understanding of environmental legislation and its implementation will provide readers with a strong legal and ethical framework for sustainable environmental management. The literature in the book also bridges chemistry and sustainability, demonstrating how eco-friendly synthesis, renewable feedstocks, and catalytic processes can minimize ecological footprints while supporting sustainable industrial growth. Moreover, Integration of AI and machine learning techniques into environmental research highlights the role of digital innovation in sustainability. Knowledge, research experiences, and professional skills of the Authors have collectively shaped this book into a valuable resource for environmental scientists, educators, and policymakers. This book stands as a testament to their collective vision and scientific contribution toward a cleaner and safer planet.

Contents

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Chapter-1

Municipal Solid Waste: From Environmental Threat to Resource Opportunity

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ABSTRACT

Solid waste refers to unwanted solid materials generated by human activities in households, businesses and industries. It encompasses municipal waste, biomedical waste and industrial waste. Often, these wastes lack appropriate and effective methods of disposal. Improperly disposed or indiscriminately dumped solid waste has become a major concern in urban and suburban areas of our country. Littered waste piles are commonly seen in various locations. India has over 5,000 cities and towns, generating approximately 40 million tonnes of municipal solid waste (MSW) annually. According to an estimate by The Energy and Resources Institute (TERI), this figure could rise to 260 million tonnes per year by 2047. Notably, India's urban population is projected to grow from the current 330 million to about 600 million by 2030. In this context, managing the MSW generated by such a vast population poses a significant challenge to environmentalists and government authorities.

MSW management strategies typically include four main components: recycling, composting, landfilling and energy recovery from waste. In developing countries, Waste-to-Energy Technologies (WTE-T) offer a viable solution for MSW management by converting waste into usable energy. These technologies include biological treatment methods, thermal treatment processes, landfill gas utilization and biorefineries. Thermal treatment technologies involve processes such as pyrolysis, gasification and incineration. In contrast, developed countries have adopted Integrated Solid Waste Management Systems (ISWMS) for more effective MSW management. This chapter aims to review the emerging techniques currently being explored or proposed for solid waste disposal and sustainable management.

Keywords: Municipal solid waste, gasification, pyrolysis, composting, incineration, technologies

1. Introduction

Solid waste refers to all non-liquid waste generated by the human population. It includes municipal waste, biomedical waste and industrial waste, but excludes human excreta. Municipal solid waste (MSW) comprises food waste, paper, cardboard, plastics, PET, glass, textiles, metals, wood, ash, leather and other materials. India has more than 5,000 cities and towns, which collectively generate about 40 million tonnes of municipal solid waste annually. According to estimates by The Energy and Resources Institute (TERI), this figure could rise to 260 million tonnes by 2047. The World Bank estimates that global MSW generation will reach 2.2 billion tonnes per year, highlighting the urgent need for effective strategies to manage this growing volume of waste (Moya et al., 2017). Rapid population growth, urban migration and industrial expansion are the key drivers of the increasing quantity of solid waste. This surge in waste generation poses serious socio-economic and environmental challenges (Melare et al., 2017).

One of the most serious problems resulting from urbanization is the accumulation of garbage heaps throughout cities. The amount and the nature of solid waste are also changing. A lot of plastic and packaging materials contribute to municipal waste. Urban local bodies are unable to cope up with their current resources and laws. In most cities, municipal waste dumping sites remain open and exposed, along with the waste transport vehicles. Fires are frequently ignited at these sites, causing significant air pollution. Usually, a liquid seeps out from heaps of garbage, known as leachate. It is considered a serious pollutant for both surface and groundwater. Improper disposal of solid waste can lead to health problems, poor living conditions and environmental pollution. It also provides breeding grounds for various disease-spreading vectors such as flies and rats.

Currently, unsanitary landfill practices, open dumping and open incineration are commonly used methods to manage municipal solid waste (MSW) in cities. However, if solid waste is disposed of using scientific methods, it can become a valuable source of energy. The management of MSW remains a significant challenge, yet it holds potential as a source of recyclable materials, heat and energy (Pareira and Lee, 2016). Methane can be produced through the digestion of the organic fraction of municipal waste. In developing countries, waste-to-energy technologies (WTE-T) offer a viable solution to the MSW problem by converting waste into energy. In contrast, developed countries utilize Integrated Solid Waste Management Systems (ISWM-S), where waste-to-energy plants form a key component. WTE-Ts are playing a crucial role in sustainable waste management (Brunner and Rechberger, 2014). At present, research is increasingly focused on environmental friendly methods for the disposal of municipal waste and the generation of energy from it.

2. Present Scenario

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Heaps of garbage can be seen at the entrances of many cities. In urban areas of India, an individual generates between 200 grams to 600 grams of waste per day. With the rapid growth of India's urban population, the proper disposal of municipal solid waste generated by this large population poses a major challenge for environmentalists and the government. The permissible height for municipal waste at dumping sites is 20 meters; however, most dumping sites in metropolitan cities have far exceeded their capacity. Currently, authorities are able to collect only about three-fourths of the total municipal waste and merely one-fourth of the collected waste is processed and treated.

3. Types of Solid Waste

Various sources of solid waste include domestic areas, food stores, feeding centers, food distribution points, slaughter houses, warehouses, markets and similar establishments. Solid waste can be categorized in multiple ways. Organic waste includes kitchen waste generated during food preparation, such as vegetable and fruit peels. Combustible waste comprises materials with high organic content, like paper, wood, dried leaves and cardboard used in packaging. Non-combustible waste includes metals, tin cans, glass bottles and stones. Ashes are the residues left from household fires used for cooking. Bulky waste consists of items like tree branches and tyres. Carcasses of domestic animals and livestock also fall under solid waste. Hazardous waste includes substances such as oil, battery acids and medical waste. Construction waste consists of materials like roofing debris, rubble and broken concrete. The type of municipal solid waste varies depending on several factors. It is influenced by the geographical region and whether the area is part of a developed or developing country. Seasonal variations and the level of food packaging also impact the nature of the waste generated. It has been observed that rural populations generate a smaller quantity of largely biodegradable waste, whereas displaced urban populations, especially those reliant on packaged foods, tend to produce larger amounts of non-biodegradable waste. According to guidelines, each person is estimated to produce about 0.5 to 1.0 liters of refuse per day, with organic content accounting for 25–30% and moisture content ranging from 10–60% (Adams, 1999).

4. Impact on Health

The accumulation of solid waste near human settlements poses health risks and has the following impacts:

1. **Transmission of diseases:** Municipal solid waste contains a significant amount of organic matter. As it decomposes, it attracts animals, worms and flies. Flies are known vectors for the transmission of food- and water-borne diseases. Moreover, municipal solid waste can serve as breeding grounds for various insects. *Aedes* mosquitoes, which transmit dengue and yellow fever, breed in water collected in discarded items such as tyres, tins, drums and boxes. *Culex* mosquitoes, responsible for spreading filariasis, lay eggs in stagnant water rich in organic matter. Rodents such as rats often forage for food in garbage heaps and act as vectors for diseases like leptospirosis and food poisoning. Their presence also attracts snakes to these areas. Additionally, poor and homeless individuals who scavenge for food in waste heaps are at high risk of contracting illnesses such as gastroenteritis, dysentery and other infections.

2. **Leachate**: It is liquid manifestation from municipal solid waste. It has been considered as a serious pollutant, which affects natural resources like surface and ground waters, human health and hygiene (Naveen et al., 2017). It is a foul liquid leaking from the bottom of the landfills, containing soluble inorganic and organic compounds as well as suspended particles. The composition of landfill leachate depends upon the nature of solid waste buried, chemical

and biochemical processes involved in the decomposition of waste materials and the water content present in it (Fatta et al., 1999). Unscientific collection and non-segregation of solid waste result in production of highly concentrated leachate. The leakage of leachate is a potential threat to surface and ground water quality (Jorstad et al., 2004). In developing countries like India, water contamination is a serious problem, because landfills do not have proper system for collection and treatment (Kumar and Alappat, 2005). In our country older landfills do not have a barrier system and leachate collection system to restrict migration of leachate into ground water. The soil of these landfills becomes over-permeable with shallow water table beneath, which increases chances of ground water contamination. Many hazardous compounds such as aromatic compounds, halogenated compounds, phenols, pesticides and heavy metals have been reported from leachate (Devare and Bahadir, 1994). These impose risks on the health of human beings along with safety of other aquatic fauna. Trace metals present in leachate have negative impact on growth of beneficial microflora of soil.

5. Government Laws

The Government of India has enacted several laws to manage solid waste effectively. The Municipal Solid Waste (Management and Handling) Rules, 2000 came into force on 25th September 2000. Under these rules, all municipal authorities are responsible for the collection, segregation, storage, transportation, processing and disposal of municipal solid waste. These rules were later replaced by the Solid Waste Management Rules, 2016, which expanded their applicability beyond municipal areas to include urban agglomerations, census towns, notified industrial townships and other relevant regions. The 2016 rules emphasize the promotion of composting, waste-to-energy conversion, and the revision of parameters for landfill location and capacity. To ensure the effective implementation of these rules, the government constituted a Central Monitoring Committee, chaired by the Secretary of the Ministry of Environment, Forest and Climate Change. This committee is tasked with overseeing and monitoring the implementation process across the country. Additionally, for the safe treatment of legacy waste, the rules prescribe the use of bio-remediation and bio-mining techniques at all open and operational dumpsites. According to Article 51A(g) of the Constitution of India, it is the fundamental duty of every citizen to protect and improve the natural environment, including forests, lakes, rivers, wildlife and show compassion for all living creatures.

6. Disposal of Solid Waste

The four main methods of solid waste disposal are Land-filling, composting, incineration and recycling. There are two major options for disposal of solid waste:

6.1 On-site Disposal

This method involves the treatment and disposal of waste at or near the point of generation. It includes the following approaches:

1. **Communal Pit disposal:** This is the simplest method, where people dispose of waste directly into a communal pit. The size of the pit varies based on the number of users. Generally, a pit of six cubic meters is considered sufficient for around 50 people. For safety, especially for children, the pit must be fenced off. It should not be more than 100 meters from the community. Waste should be covered with a thin layer of soil every week to prevent the breeding of flies and other vectors. This method allows for rapid implementation, and requires minimal operation and maintenance. However, if the pit is located far from the community, it may lead to indiscriminate disposal and maintenance staff may be required.

2. **Family pit disposal:** This method is appropriate where sufficient land is available, and the waste is primarily organic in nature. Families maintain their own pits, eliminating the need for external waste workers. However, the requirement of large space and the construction of pits can be limiting factors.

3. **Communal bins:** These are large containers placed in public areas where waste is collected, protected from animals and wind, and can be easily removed for disposal. Typically, old oil drums are used, cut in half with holes drilled in the base for drainage. Each bin should have a handle and a lid. They are suitable for places like market stalls and should be emptied daily.

4. **Family bins:** These are household containers used by families to collect waste. The waste should be regularly transferred to communal bins or disposal depots. This method requires an efficient collection and transportation system, typically operated by municipal authorities.

6.2 Off-site Disposal

This involves the transportation of waste to a designated site for final treatment or disposal. Common strategies include:

1. **Land-filling:** Landfilling is one of the most widely used off-site disposal methods. It involves digging a large pit or trench, placing the waste into it, and covering it daily with a 0.5-meter layer of soil. This practice prevents the breeding of flies and other vectors, and discourages animal scavenging. The location of the landfill must be chosen in consultation with local authorities and the community. While it is a sanitary and effective method if managed properly, the major constraint is the requirement of a large land area.

2. **Composting:** Composting is the biological decomposition of organic waste (e.g., food and plant matter) by bacteria, fungi and other microorganisms under controlled aerobic conditions. It is ideal for individuals with gardens or agricultural land. The organic matter is dug into the soil, where it decomposes and adds humus, acting as a natural fertilizer. Composting is a long-established method for converting organic waste into nutrient-rich material, improving the physical, chemical and biological properties of soil (Atalia et al., 2015). While safe and environmentally friendly, this method requires proper monitoring of moisture and chemical levels to support microbial activity. The compost pile should be turned periodically, especially when the internal temperature reaches around 140°F.

3. **Recycling:** Recycling involves converting waste materials into new products, thereby reducing the consumption of fresh raw materials. It is the third element of the Reduce, Reuse, and Recycle (3Rs) waste management hierarchy. Recyclable materials include paper, cardboard, glass, metal, plastic, textiles, batteries and electronic items. Recycling is environmentally beneficial but can be costly to establish and maintain.

7. Waste as a Resource to Generate Energy

Municipal solid waste is a potential source of renewable energy. Energy can be derived from waste by converting it into biogas, syngas or heat (Pandey et al., 2016). Energy generation from waste is at infancy stage in India. Various technologies are to be developed in industrial sectors. Techniques of converting waste into energy can be divided into following three methods:

7.1 Physical method

Waste is processed mechanically to produce materials that can be used as fuel, such as pellets, wood chips, and wood briquettes.

These materials are more durable, easier to handle and suitable for use.

7.2 Thermal methods

In these methods, heat is generated from waste and utilized in various ways. The primary techniques include:

i. **Direct combustion**: In this method, waste is dried and burned to generate heat, which is then used to produce steam from water. The steam is subsequently utilized in steam turbines to generate energy.

ii. **Pyrolysis:** Pyrolysis is the thermal decomposition of waste at elevated temperatures in an inert environment, i.e., in the absence of oxygen. It is primarily used for treating organic waste. The decomposition typically begins at 350°C–550°C and can reach up to 700°C–800°C. The temperature is maintained within the 300°C–800°C range using external heat sources. Before pyrolysis, MSW is segregated to remove glass, metals and other inert materials (Agarwal et al., 2013). The remaining waste is then processed in pyrolysis reactors such as rotary kilns, rotary hearth furnaces or fluidized bed furnaces. The main products of the pyrolysis process include methane, hydrogen, hydrocarbons, vinyl chloride, carbon monoxide, bio-fuel and char. The bio-fuel, also referred to as bio-oil or pyrolysis oil, is a dark brown liquid that can either be upgraded for use as engine fuel or converted into syngas or biodiesel. The syngas generated during pyrolysis consists of methane, hydrogen, carbon monoxide and carbon dioxide. This versatile gas mixture can be used as fuel in engines, boilers, turbines, fuel cells and heat pumps (Alessandro et al., 2013). It is also suitable for diesel engines and gas turbines for electricity production. In addition, syngas is relatively easy to store and transport and serves as a valuable source for the synthesis of various organic compounds and specialty chemicals. Another by-product of pyrolysis is char, a solid residue made up of non-combustible materials and carbon. Since it is nearly pure carbon, char is highly suitable for the production of activated carbon, which is extensively used in water filtration systems and other environmental applications.

iii. **Thermal gasification:** Thermal gasification is a bioprocess involving partial oxidation, which converts organic waste into fuel gas (biogas or syngas). This method can reduce 70% of the waste mass and 90% of its volume, making it an effective solution for treating MSW.Gasification not only limits greenhouse gas emissions but also reduces the need for landfilling. The energy-rich and clean biogas produced can be used in gas turbines or engines, and to generate electricity in turbine-based power plants (Arafat and Jijakli, 2013). Currently, eight types of reactors are used for gasification:

- Fixed bed
- Entrained bed
- Fluidized bed
- Rotary kilns
- Plasma reactors
- Vertical shaft furnaces
- Moving grate furnaces
- Other specialized plant configurations

iv. **Incineration:** In this method, waste is burned in a combustion chamber at 900°C–950°C using flue gases and a preheated chamber. The process generates superheated steam, which is used to produce energy and heat. Electricity is produced via a turbine connected to a generator, and heat is supplied through district heating systems. However, incineration contributes to greenhouse gas emissions, posing environmental and public health risks (Ashworth, 2014). To mitigate these impacts, hybrid plants combining incineration and gasification have been developed, significantly reducing harmful emissions (Wu et al., 2014).

v. **Plasma arc gasification:** Plasma arc gasification converts organic waste into syngas and slag using a plasma arc torch, which produces electric arcs at temperatures ranging from 2,200°C to 13,900°C (USAEPR, 2005). This extreme heat breaks down the waste into simpler chemical components. The resulting Syngas can be used to heat up boiler for heat and steam generation or it can be used in internal combustion engine as a fuel (Klein, 2002; Taylor, 1990).

7.3 Biological methods

Biological treatment of waste involves the use of microorganisms to convert waste into useful products such as fuel. In these methods, waste is decomposed by microbes in the absence of oxygen. The main biological treatment methods include the following:

1. **Fermentation:** It is a metabolic process in which microbes like yeast and bacteria convert sugars into acids, alcohols and gases. This method is used to manage waste and produce ethanol, acids and traces of gases from it, which can be used as fuel in power gas engines (Boundy et al., 2001; Bezboruah and Bhargava, 2003; Nagayama, 2010).

2. **Biogas formation:** It includes anaerobic digestion of biodegradable waste by micro-organisms in absence of oxygen. It produces gases like methane, carbon dioxide and traces of other gases, which is known as biogas. It can be used in boilers or as a natural gas to produce power in power cycle operation (USAEPR, 2005; Nagayama, 2010).

3. **Methane production:** Landfill gas (LFG), which is primarily composed of methane, is generated during the treatment of municipal solid waste. Since methane is a potent greenhouse gas, its proper management is essential. In municipal solid waste management plants, landfill gas is collected, treated, and then utilized for power generation (Tozlu et al., 2016).

7.4 Landfill gas utilization

Municipal solid waste (MSW) is often disposed of at landfill sites, which represent the oldest form of waste treatment. However, the emission of gases from landfills has become a significant environmental concern worldwide. Landfill gas, which is rich in methane, should be captured and utilized to produce heat and energy in cogeneration plants (Mostbauer, 2014). Several innovative energy system technologies such as gas turbines operating in the Brayton cycle, the Organic Rankine cycle, Stirling engines and Solid Oxide Fuel Cells can generate electricity from landfill gas (Bove and Lunghi, 2006).

7.5 Biorefineries

The concept of Biorefineries is same as petroleum refineries. In this technology biomass from MSW can be converted into various products like biofuels, power, heat and biofertilizers. Biofuels can be used to produce heat, power in thermal plants or as transport fuel. Syngas can be used to synthesize biodiesel and bioethanol by an integrated gasification system having fuel synthesis facility (Nair et al., 2017).

7.6 Integrated solid waste management systems (ISWMS)

In developed countries, Integrated Solid Waste Management Systems (ISWMS) are widely used for the efficient handling of municipal solid waste (MSW). These systems incorporate various technologies to manage different fractions of waste. Typically, an incineration plant is used for the inorganic fraction, while gasification and composting plants are employed to treat the organic fraction of MSW. ISWMS operate through four main stages. The first stage involves the generation of waste from various sources such as households, industries and institutions. In the second stage, the waste is collected by municipal authorities. The third stage focuses on the treatment of waste using the appropriate facilities within the system. Finally, in the fourth stage, useful products such as energy, compost and recyclable materials are recovered (Herva et al., 2014).

8. Recommendations and Conclusions

This chapter highlights the sources, types, current scenario and impacts of municipal solid waste (MSW), along with the legal aspects of solid waste management and various disposal strategies. It recommends strict enforcement of the Solid Waste Management Rules, 2016, by all responsible agencies at both the State and Central levels. Proper disposal of MSW, as discussed, is essential. Economic development, population growth, urbanization, and industrialization are contributing to the increasing generation of municipal solid waste, as well as a rising demand for energy. MSW is a potential source of renewable energy and the government should actively promote research on energy production from waste. In developed countries, Integrated Solid Waste Management Systems (ISWMS) are already in use to address this issue effectively (Moya et al., 2017). The implementation of Waste-to-Energy (WTE) technologies can be a key part of the solution to the MSW problem and should be considered a valuable resource for renewable energy generation.

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Chapter-2

Environmental Security and National Security: Interconnections and Implications

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AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration between two authors. Author AS conceptualized the study, prepared the initial draft, and finalized the manuscript. Author PKV critically reviewed and improved the first draft of the paper. Both authors contributed to the literature review and selection of relevant sources. Author AS also formatted the references according to the book's guidelines. All authors have read and approved the final version of the manuscript.

ABSTRACT

Environmental Security and National Security are increasingly intertwined as global environmental challenges, such as climate change, resource scarcity and ecological degradation, pose significant threats to societal stability and state sovereignty. This paper explores the interconnections between environmental and national security, analyzing how environmental stressors exacerbate conflict, undermine governance, and necessitate adaptive policy frameworks. By examining case studies, theoretical frameworks, and empirical data, this research highlights the implications of environmental security for national defense, economic stability and human well-being. The paper concludes with recommendations for integrating environmental security into national security strategies to foster resilience and global cooperation.

Keywords: National Seurity, ecological, environmental, sovereignty, governance, adaptive

1. Introduction

The concept of security has evolved beyond traditional military concerns to encompass environmental factors that threaten human survival and state stability. Environmental security addresses the risks posed by environmental degradation, climate change and resource competition, which can destabilize economies, displace populations and fuel conflicts. National security, traditionally focused on protecting state sovereignty from external threats, now recognizes environmental challenges as critical drivers of instability. This paper investigates the linkages between environmental and national security, exploring how environmental stressors amplify security risks and proposing strategies for mitigation.

2. Research Objectives

- To analyze the interconnections between environmental degradation and national security threats.
- To evaluate the role of climate change and resource scarcity in exacerbating conflicts and instability.
- To propose policy recommendations for integrating environmental security into national security frameworks.

3. Environmental Stressors and Security Implications

Historically, national security has been primarily concerned with safeguarding the state from external threats, emphasizing military strength, protection of borders, and the preservation of political sovereignty (Buzan, 1991; Walt, 1991). In this traditional framework, the state was viewed as the central actor, and security threats were largely seen in terms of warfare, aggression and territorial disputes.

The traditional understanding of national security centers on protection from organized violence perpetrated by foreign armed forces or enemy states. Safeguarding a state's territorial integrity is considered vital for its survival. In this context, international relations have historically been evaluated through the lens of inter-state relations, emphasizing the concepts of war and peace. As the supreme authority, the state pursues a foreign policy grounded in national interest, primarily aimed at securing its borders, an essential aspect of its security relations with other states. However, the scope of security challenges has significantly widened due to globalization. It is now impossible to address security threats-whether at the local, regional, national, or international level, through a limited set of variables, given the complex and often catastrophic nature of these issues (Özcan, 2023). The evolving realities of the modern world marked by globalization, environmental degradation, pandemics and economic interdependence have revealed the limitations of this narrow, state-centric approach to security (UNDP, 1994). The most pressing security threats today often emerge from these non-traditional domains. Consequently, these globalization-induced challenges suggest that national security must be reconceptualised in a broader, more comprehensive manner.

The rise of non-traditional threats, particularly environmental risks, has catalysed a broader understanding of security. Climate change-induced disasters, water scarcity, food insecurity and ecosystem collapse are not confined within national borders; they threaten human lives directly, often without a clear "enemy" to confront. This recognition has fueled the evolution toward a human security approach (Matthew et al., 2004; UNDP, 1994).

The *United Nations Development Programme* (UNDP) introduced the concept of human security in its 1994 Human Development Report, emphasizing a shift from protecting states to safeguarding individuals. Human security shifts the focus from protecting the state to protecting individuals and communities. It emphasizes freedom from fear, freedom from want, and freedom to live with dignity (UNDP, 1994; Tadjbakhsh and Chenoy, 2007). In this paradigm, security is not just about defending territory, but about ensuring access to clean water, food, health care and a sustainable environment. Human security is multidimensional, comprising **seven elements** (UNDP, 1994):

- Economic Security
- Food Security
- Health Security
- Environmental Security
- Personal Security
- Community Security
- Political Security

Each of these elements is increasingly threatened by environmental stressors, underlining the deep interconnections between ecological health and national stability. Environmental security refers to the protection of ecosystems and human populations from environmental threats, such as pollution, deforestation, and climate-induced disasters (Homer-Dixon, 1994). It's a direct threat to ecosystems, compromise the natural systems that support human life. Environmental degradation in places like Haiti, a country in the Caribbean, has intensified vulnerability to hurricanes and floods, leading to recurrent humanitarian crises and social instability (Matthew, 2014).

Environmental security intersects with national security when environmental stressors, such as droughts or rising sea levels, trigger resource conflicts, mass migrations or governance failures. For instance, competition over scarce water resources can escalate into interstate conflicts, while climate-induced displacement can strain national infrastructure (Barnett and Adger, 2007). It shows that Environmental stressors are no longer peripheral concerns; they are central to contemporary security challenges. By threatening all seven dimensions of human security, environmental degradation transforms localized ecological problems into broader national and global security risks. Addressing these issues demands an integrated approach that incorporates environmental stewardship into economic planning, public health policy, resource management and international diplomacy. Moving forward, national security frameworks must evolve to recognize and respond to the fundamental interdependence between human well-being, ecological sustainability and global stability.

4. Climate Change and National Security

According to the United Nations Environment Programme (UNEP, 2021), global temperatures are projected to rise by 2.7°C by the end of the century. Similarly, the Intergovernmental Panel on Climate Change (IPCC, 2021) has indicated that even a modest increase of 2°C could severely impact agricultural productivity and human health. In a 2007 report by the Center for Strategic and International Studies, experts including former CIA Director James Woolsey and Nobel laureate Thomas Schelling warned that climate change poses one of the greatest national security challenges. It could destabilize nearly every facet of modern life and potentially trigger new global conflicts (Campbell et al., 2007). Climate change is increasingly recognized as a significant threat to national and international security. Referred to as a "threat multiplier" by the

CNA Corporation's Military Advisory Board (2007), climate change exacerbates existing vulnerabilities, magnifies political instability, and complicates national and global security strategies. Its impacts ranging from rising temperatures and extreme weather events to sea-level rise have direct and indirect consequences on agriculture, infrastructure, livelihoods and governance. In this way, climate change is not only an environmental issue but a profound security challenge.

One clear example is the case of **Syria**. Studies have shown that severe droughts between 2006 and 2010, exacerbated by climate change led to massive crop failures, economic hardship, and rural-to-urban migration. This, in turn, intensified social stresses and contributed to the conditions that sparked the 2011 Syrian civil war (Kelley et al., 2015). The humanitarian disaster triggered social unrest, weakened the legitimacy of state institutions, and created openings for militant groups to exploit the chaos. This case underlines the complex relationship between climate-related disasters and internal security risks. Broadly, the security implications of climate change can be classified into several interlinked domains.

5. Extreme Weather Events

The frequency and severity of extreme weather events—such as hurricanes, floods, droughts and wildfires are rising, fueled by global warming. These events not only devastate local economies and displace populations but also create large-scale humanitarian crises that require rapid and resource-intensive responses. Governments and military forces are increasingly called upon to perform disaster relief operations, often beyond their traditional mandates.

For instance, Hurricane Katrina in 2005 demonstrated how a natural disaster could overwhelm local and federal resources in a developed country like the United States, temporarily degrading critical security infrastructure (Brinkley, 2006). In vulnerable regions with weaker governance, such events can collapse administrative structures altogether, leading to lawlessness, increased criminal activities and fertile ground for extremist recruitment.

The additional burden placed on military and emergency services by recurrent extreme weather events strains national resilience. Resources allocated for defense readiness must increasingly be diverted to emergency responses, reducing a country's ability to respond to external threats. Moreover, as infrastructure such as ports, roads and communication networks are damaged, the strategic mobility and operational effectiveness of national security forces can be significantly compromised.

6. Migration and Displacement

One of the most alarming security implications of climate change is large-scale human migration. Rising sea levels, desertification and extreme weather events are projected to displace millions of people over the coming decades. According to the World Bank (2018), climate change could force more than 143 million people in sub-Saharan Africa, South Asia, and Latin America to migrate internally by 2050 without urgent climate action. These environmental migrants, often termed "climate refugees," will face severe humanitarian hardships while simultaneously placing immense pressure on receiving regions' housing, healthcare, education and employment systems (Internal Displacement Monitoring Centre, 2021).

In fragile states, sudden influxes of displaced populations may heighten social tensions, fuel xenophobia, and destabilize political systems, increasing the risk of conflict and violence (Werz and Conley, 2012). Cross-border migration driven by environmental stressors could also ignite diplomatic tensions between neighbouring countries. For instance, potential displacement from

Bangladesh due to rising sea levels raises difficult questions about refugee rights and state sovereignty. Moreover, military forces may increasingly be called upon to manage borders and deliver humanitarian assistance roles for which they are not primarily trained complicating national security strategies (U.S. Department of Defense, 2015). Climate-induced migration thus poses a profound and multifaceted threat to global stability.

7. Resource Scarcity and Conflict

Resource scarcity is emerging as a significant driver of conflict in the 21st century. As critical resources such as water, arable land, and energy become increasingly scarce due to overexploitation, population growth, and environmental degradation, competition over these essentials is intensifying. In many cases, resource scarcity not only fuels diplomatic tensions but also threatens regional and global stability.

The Nile River Basin provides a stark example of how resource scarcity can strain international relations. Shared by 11 countries, including Egypt, Sudan, and Ethiopia, the Nile is a lifeline for millions of people. However, as water demand rises and climate variability affects river flow, disputes over water allocation have escalated. Ethiopia's construction of the Grand Ethiopian Renaissance Dam (GERD) has particularly alarmed Egypt, which relies on the Nile for more than 90% of its freshwater needs (Swain, 2011). Negotiations have often been tense, highlighting how water scarcity can heighten diplomatic friction and potentially lead to broader regional instability.

Similarly, declining fish stocks in the South China Sea have exacerbated maritime disputes among coastal nations such as China, Vietnam, the Philippines and Malaysia. Overfishing, combined with the impacts of climate change, has reduced fish populations, making access to remaining stocks increasingly contentious. Fishing rights are deeply intertwined with territorial claims, complicating the already volatile geopolitics of the region.

More broadly, two critical sectors where resource scarcity could escalate conflict are:

- **Water Scarcity:** Access to clean water is fundamental to human survival, public health and agricultural productivity. As populations grow and climate change alters precipitation patterns, many regions are experiencing intensified water stress. Countries that share transboundary rivers or aquifers are particularly vulnerable to disputes over water rights. The Jordan River, the Mekong River and the Indus Basin are all examples where upstream and downstream interests clash. Water scarcity also directly impacts food security, as reduced water availability hampers agricultural output, heightening risks of famine, economic decline, and political unrest (Gleick, 2014).
- **Energy Security:** The global shift from fossil fuels to renewable energy sources is creating new geopolitical dynamics. Fossil fuel depletion and energy insecurity can drive nations to aggressively secure access to remaining reserves, potentially leading to territorial disputes or conflict. Meanwhile, the critical minerals needed for renewable technologies such as lithium, cobalt, and rare earth elements are unevenly distributed, opening new arenas of competition. Energy transitions, if not carefully managed, could trigger instability, particularly in regions heavily dependent on oil and gas revenues (Scholten, 2018).

8. Environmental Degradation and Public Health

Environmental degradation manifested through air and water pollution, deforestation, and land degradation poses serious risks to public health and national security. As ecosystems deteriorate, the resilience of societies weakens, exposing populations to health crises, food insecurity, economic instability, and potential social unrest. A vivid illustration of this dynamic is Haiti, where widespread deforestation has dramatically increased the country's vulnerability to hurricanes and flooding. Without tree cover to stabilize the soil, natural disasters have had devastating effects, leading to significant economic losses and exacerbating social tensions (Matthew, 2014). Haiti's experience underscores how environmental degradation can weaken national resilience and fuel broader insecurity.

Two major channels through which environmental degradation impacts national security are:

- **Health Crises:** Environmental degradation significantly contributes to the emergence and spread of diseases. Air pollution, for example, is linked to respiratory illnesses, cardiovascular diseases, and increased mortality rates worldwide. Contaminated water sources lead to outbreaks of waterborne diseases such as cholera, dysentery, and typhoid, particularly in regions with poor sanitation infrastructure. In developing countries, where healthcare systems are often already fragile, the health impacts of environmental degradation can overwhelm national capabilities, reducing the state's ability to address broader security concerns. The COVID-19 pandemic has also highlighted how environmental factors, including habitat destruction and biodiversity loss, can facilitate the emergence of zoonotic diseases, those transmitted from animals to humans. As human activity encroaches further into wildlife habitats, opportunities for disease spillover increase, creating new public health threats (Daszak et al., 2020).

- Health crises caused by environmental degradation not only strain healthcare systems but also undermine economic productivity, social cohesion and political stability. Widespread illness can lead to labor shortages, increased healthcare costs and public dissatisfaction with government responses, potentially contributing to civil unrest and weakening national security.
- **Food Security:** In 2023, approximately 733 million people faced hunger globally, with 282 million individuals experiencing high levels of acute food insecurity across 59 countries. This alarming situation necessitated urgent food and livelihood assistance (WFP, 2024). Deforestation, soil erosion, and biodiversity loss are major drivers of declining agricultural productivity. As land quality deteriorates, farmers struggle to produce sufficient food, leading to shortages, price volatility, and malnutrition. Food insecurity is particularly destabilizing in agrarian economies, where large portions of the population depend directly on agriculture for their livelihoods. In regions heavily reliant on rain-fed agriculture, land degradation and shifting climate patterns further exacerbate food insecurity. This can fuel rural-to-urban migration, increase unemployment, and intensify competition over limited resources in cities, heightening the risk of social unrest and political instability (FAO, 2011).

9. Environmental Security Threats to Regional and Global Stability

Environmental changes drive migration, creating security challenges. The Syrian civil war, partially triggered by a prolonged drought from 2006–2011, displaced millions and destabilized the region (Kelley et al., 2015). Climate refugees may strain neighboring countries, leading to social tensions and governance challenges. As climate change accelerates, millions of people may be forced to migrate due to rising sea levels, extreme weather events and environmental degradation. This migration could strain the resources of receiving countries and create tensions between communities and states. Migration due to climate change could contribute to:

- Increased **political instability** in receiving countries.
- Potential **conflict** over land and resources, particularly in border regions or areas already facing economic or social challenges.
- **Humanitarian crises** requiring international response.

10. Cross-Border Water Conflicts

Water scarcity is a growing concern in many regions, especially in areas where water sources are shared between multiple countries. Disputes over water usage and access can lead to regional tensions and conflict, particularly in arid and semi-arid regions. There are over 310 transboundary river basins worldwide, covering about 50% of the Earth's surface and supporting nearly 40% of the global population (UNESCO, 2015). While many of these shared watercourses have cooperative management frameworks, others are flashpoints for conflict, particularly where historical grievances, political distrust, and water scarcity converge.

- **The Nile River Basin:** The Nile River, the world's longest river, flows through 11 countries, including Egypt, Sudan, and Ethiopia. Historically, Egypt has asserted significant control over Nile waters, based largely on colonial-era treaties. However, Ethiopia's construction of the Grand Ethiopian Renaissance Dam (GERD) has triggered serious tensions. Egypt fears that the dam will reduce its critical water supplies, while Ethiopia views the dam as essential for its development and energy security (Swain, 2011). Despite multiple rounds of negotiations, a final agreement remains elusive, raising concerns over potential escalation.

- **The Indus Waters Treaty:** The Indus River system, shared by India and Pakistan, is governed by the Indus Waters Treaty (1960), brokered by the World Bank. Despite ongoing political hostilities between the two nations, the treaty has largely survived, demonstrating that structured agreements can mitigate conflict (Wolf, 1998). However, climate change-induced variability in river flows, coupled with rising water demands, is placing new pressures on the treaty's mechanisms.
- **The Jordan River Basin:** Shared by Israel, Jordan, Lebanon, Syria, and Palestine, the Jordan River is a critical yet heavily contested resource. Water scarcity has compounded political tensions in the region, with disputes over water access forming part of the broader Israeli-Palestinian conflict. Efforts at cooperation, such as the 1994 Israel-Jordan Peace Treaty, include specific provisions for water sharing, yet disputes periodically resurface (Zeitoun, 2008).
- **The Brahmaputra River:** Originating from the Angsi Glacier in Tibet, the Brahmaputra River flows through China, India, and Bangladesh. The river is crucial for the livelihoods of millions, especially in India's northeastern states and in Bangladesh. Concerns have grown over China's construction of dams and water diversion projects on the upper reaches of the Brahmaputra (known as Yarlung Tsangpo in Tibet). India and Bangladesh fear that upstream developments could alter river flow, affecting agriculture, hydropower generation, and water availability downstream (Biba, 2018). The lack of a comprehensive water-sharing agreement among

these countries heightens the risk of tension, especially given broader geopolitical frictions between China and its neighbors.

11. Climate-Induced Migration

As climate change accelerates, millions of people may be forced to migrate due to rising sea levels, extreme weather events, and environmental degradation. This migration could strain the resources of receiving countries and create tensions between communities and states. Migration due to climate change could contribute to:

- Increased **political instability** in receiving countries.
- Potential **conflict** over land and resources, particularly in border regions or areas already facing economic or social challenges.
- **Humanitarian crises** requiring international response.

12. Global Environmental Threats

Global challenges such as **deforestation**, **biodiversity loss**, and **pollution** have profound impacts on security:

- **Climate change mitigation**: As nations move toward greener energy sources, the competition for renewable resources (such as rare earth metals) and new energy technologies could lead to global competition and conflict.
- **Global supply chain disruptions**: Environmental disasters, such as extreme weather events and droughts, can disrupt global supply chains, affecting food production, energy distribution, and economic stability.

13. Integrating Environmental Security into National Security

Recognizing that environmental degradation and climate change pose profound and long-term threats to global stability, governments and international organizations are increasingly incorporating environmental considerations into their national security strategies. Traditional notions of national defense, once dominated by military threats, are expanding to include non-traditional risks, with environmental security emerging as a vital concern.

- **Policy integration:** One major step in integrating environmental security is the incorporation of environmental risks into national defense policies. Many countries have begun training their military forces to respond not just toarmed conflict but also to environmental disasters. For instance, the United States Department of Defense, in its *2014 Climate Change Adaptation Roadmap*, explicitly identified climate change as a "threat multiplier" that exacerbates existing vulnerabilities (U.S. Department of Defense, 2014). Sustainable resource management, carbon reduction initiatives, and investments in renewable energy have also become integral to broader national resilience strategies. Governments are emphasizing the need for climate resilience measures, such as enhancing infrastructure to withstand extreme weather events and reducing dependency on vulnerable resource systems.
- **International cooperation:** Given the transboundary nature of environmental issues, international cooperation is critical. Agreements such as the **Paris Agreement** (2015) and the **UN Framework Convention on Climate Change (UNFCCC)** provide frameworks for collaborative efforts to address climate change and

associated security risks. Environmental diplomacy has emerged as a new form of soft power, promoting joint initiatives such as water-sharing agreements, regional disaster preparedness exercises, and coordinated resource management strategies. For example, the Mekong River Commission facilitates cooperation among Southeast Asian countries to manage shared water resources, helping to prevent disputes and enhance regional stability (MRC, 2018).

- **Disaster response and preparedness:** Environmental disasters frequently necessitate large-scale humanitarian responses that often involve military assets. Military forces are uniquely positioned to provide critical assistance during and after natural disasters, including emergency logistics, search and rescue operations, medical services and infrastructure repair. Enhancing the capacity of national security agencies to prepare for and respond to natural disasters is essential. In countries like Japan and the United States, military units play key roles in disaster response, demonstrating the increasing overlap between environmental events and national security mandates (Brauch, 2005).

14. Conclusion

The intersection of environmental security and national security is a complex and evolving issue. Environmental degradation, resource scarcity, climate change and natural disasters are no longer isolated challenges; they are now central to national security considerations. Nations must recognize the interconnectedness of environmental risks and military, economic and social stability. This requires incorporating environmental factors into national security strategies, fostering international cooperation, and investing in resilience-building efforts to address emerging environmental threats. As environmental security becomes an increasingly integral part of national security, it is essential for policymakers, security professionals, and international organizations to work together to address the multifaceted risks posed by environmental challenges. Only through a proactive, integrated approach can the global community secure a sustainable future, ensuring peace, stability and resilience in the face of environmental uncertainties.

COMPETING INTERESTS

The authors have declared that no competing interest exists.

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Chapter-3

Types, Attributes, Restoration Strategies, Challenges and Significance of Wetlands

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AUTHOR'S CONTRIBUTION

This study was conducted in collaboration among all three authors. Author HA supervised the study and refined the initial draft of the manuscript. Author BRS prepared and arrange the figures and pictures and also contributed to writing the final draft. Authors BRS and HR jointly managed the literature review for the relevant sections. Author AK drafted the preliminary version of the manuscript and formatted the references according to the journal guidelines. All authors reviewed and approved the final version of the manuscript.

ABSTRACT

Many ecosystems on Earth are capable of self-healing from deterioration. One of those habitats are wetlands, which are invaluable natural sponges that naturally replenish and purify water, prevent flooding, and provide a rich diversity of flora and fauna. However, solid waste and the discharge of wastewater from homes and industries are causing indiscriminate pollution and degradation of the wetlands. Countries all across the world have recognized the vital advantages of wetland development and restoration via the Ramsar Convention on Wetlands. We addressed the global and national (India) wetland policies in this review article. The features of wetland ecosystems, biodiversity indicators, threats to wetland restoration strategies, the primary challenges they face and the economic benefits of wetlands will all be covered in this study. A clear consistency between the investigated hypothesis of wetland restoration mechanisms and the ensuing economic and social advantages came to light after a thorough analysis of research and review papers. Our results show that successful restoration improves community well-being and generates substantial economic benefits in addition to improving ecosystem services. This alignment highlights how crucial it is to support wetland restoration in order to promote sustainable development.

Keywords: Financial benefits, Indian wetlands, indicators, wetland management, wetland policies

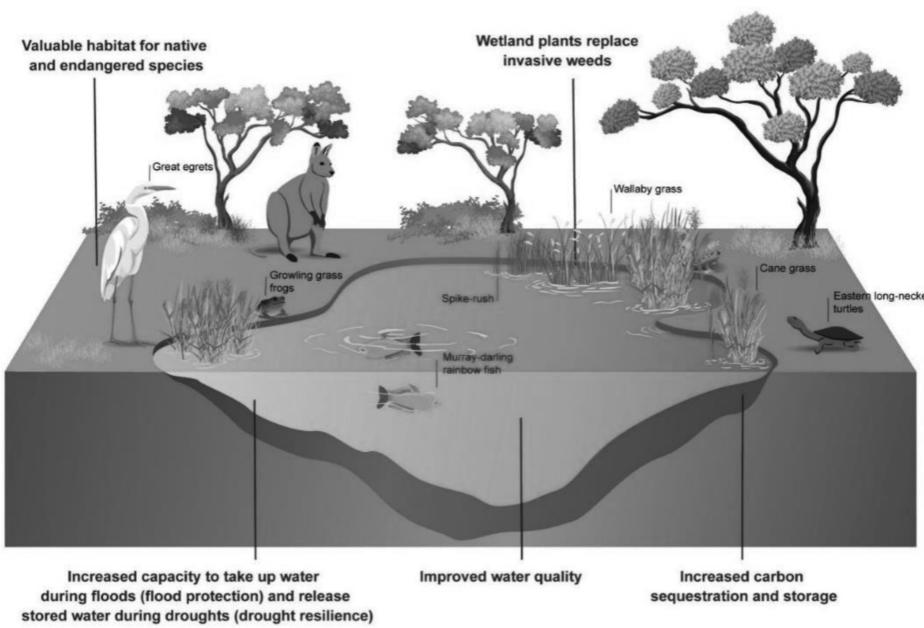
1. Introduction

According to Mitsch and Gosselink (2015), wetlands, which comprise bogs, marshes and swamps, are vital habitats that are characterized by the presence of water. In terms of ecology, they sustain a rich biodiversity, offering homes to a wide variety of plant and animal species that are essential to biodiversity worldwide Millennium Ecosystem Assessment (2005). As locations for fishing, birdwatching, and traditional activities, wetlands provide social opportunities and cultural value (Millennium Ecosystem Assessment (2005). Wetlands generate revenue and help local economies by supporting livelihoods through industries including tourism, agriculture, and fishing (Barbier et al., 1997). According to Zedler and Kercher (2005), they also provide crucial ecosystem services that benefit both nature and society, including as carbon sequestration, flood control, and water purification.

Today, there are over 2,400 Ramsar Sites across the globe. Their total size exceeds that of Mexico, at approximately 2.5 million km^2 (Ramsar Convention on Wetlands, 2018). Three-quarters or more of all threatened and endangered species can be found in wetlands. Legal safeguards and restoration initiatives are two components of wetland management techniques that aim to preserve and improve ecosystem services while encouraging sustainable use and integrating local populations to strike a balance between ecological health and human needs. In order to preserve its natural form, it is crucial to continuously monitor the functioning. Many publishers are dealing with concerns pertaining to regulations, cutting-edge technology, and ecological restoration since new technologies require the application of innovative methods (Wei et al. 2023). Degradation of wetlands has increased by around 35% worldwide since 1970 (Darrah et al., 2019; Let and Pal, 2023). According to Abramovitz (1996) unlawful land reclamations, encroachments, and pollution have resulted in the destruction of up to 90% of wetlands worldwide.

According to the United Nations (UN) Millennium ecosystems Assessment (2005), wetlands are the most degraded habitat on Earth when compared to other natural ecosystems. The United Nations' Agenda 15 for 2030 (Sustainable Development Goal 15) lays out the goals of stopping and reversed land degradation, stopping the loss of biodiversity, preventing desertification, and encouraging the sustainable use of terrestrial ecosystems. The effects of socioecological factors on wetlands worldwide have been demonstrated in the majority of literature research (Barbier et al., 1997; MEA 2005; Zedler and Kercher, 2005). More public awareness of environmental monitoring, advanced tools, and data are still required to prevent the loss of wetland habitat (Darrah et al., 2019). Many wetlands are still seen as wastelands and are being contaminated and degraded, despite the fact that some special wetlands have been designated as Ramsar areas. People are also unaware of the wetlands and how their ecosystems function. Wetlands' degradation areas are classified into four categories, according to Kexin et al., (2022): undegraded, lightly degraded, substantially degraded and extremely degraded. According to Fennessy et al., (2007), nearly all indicators were derived from three primary factors: hydrological indicators, soil indicators, and biota indicators. These elements serve as the primary indications for the wetlands' well-function analysis (Barbier et al., 1997).

In India, the local population still does not recognize many wetlands because of a lack of vulnerability assessments. By controlling the climate and offering chances for activities like fishing, irrigation, and recreation, wetlands serve as a valuable environmental resource (Engelhardt and Ritchie, 2001; Adekola and Mitchell, 2011; Malekmohammadi and Jahanishakib, 2017). Duan et al., (2022) have proposed a methodology for evaluating the ecological risk of wetlands. Abiotic features for both internal and exterior risks are included. Although many ecological restoration methods have been explored and implemented in the past ten years, there are still some gaps that need to be noticed and looked into in the systematic planning, problem-solving after the restoration is completed and overall research process. For wetland managers, preserving the ecological qualities of wetlands against socioecological activities is the primary problem in ensuring long-term sustainability (Pirali Zefrehei et al., 2022). It is imperative that a wetland be preserved and maintained at any costs. Constant monitoring and management are the most crucial aspects of wetland protection after a successful restoration procedure. Wetlands act as natural filters to improve water quality by absorbing sediments, nutrients, and pollutants through microbial activity, sedimentation, and plant uptake (Mitsch and Gosselink, 2015). Nevertheless, rising agricultural runoff, industrial discharges, and urbanization can introduce excessive amounts of nutrients, heavy metals, and organic toxins into wetland habitats. This may lead to a decline in ecosystem services, an increase in eutrophication, and biodiversity loss (Zedler and Kercher 2005). To preserve the ecological integrity and water quality of wetlands and ensure that they continue to offer vital services like habitat support and water purification, effective management and restoration initiatives are necessary (Kadlec and Wallace, 2009). Sun et al. (2023) explored the spatiotemporal study of water quality using remote sensing and the connection between land use and water quality. Wetlands, which sustain a great biodiversity with interconnected plant species and high concentrations of wildlife, are among the most productive habitats on Earth.



(Source:https://www.bluecarbonlab.org/revitalising-freshwater-wetlands/)

This review's goal is to investigate different wetland restoration strategies and assess the social and economic advantages of each. It seeks to emphasize how successful restoration may promote sustainable community development and improve environmental services.

2. Policies for Wetland Conservation

2.1 Global level policies

Policies pertaining to global wetlands are essential frameworks for preserving and repairing these significant ecosystems. The Ramsar Convention, which was established in 1971 and promotes the wise use and sustainable management of wetlands worldwide, is the cornerstone of international efforts to conserve wetlands (Ramsar Convention Secretariat, 2010). Member nations are encouraged by the Convention to identify Ramsar sites as wetlands of international concern and to take action to preserve and restore them. Furthermore, the 1992 Convention on Biological Diversity (CBD) emphasizes the conservation and sustainable use of biodiversity, particularly wetlands, as an essential part of global environmental management.

In the United States, people began to realize that wetlands offered many advantages over other natural areas (Votteler and Muir, 2002). The Conservation Foundation's management practices for wetlands are listed in Table 1. CBD member countries pledge to incorporate biodiversity considerations into national policies and promote ecosystem resilience, which is essential for wetland ecosystems at risk from climate change and human activities. Members of the CBD pledge to incorporate biodiversity concerns into national policies and to foster ecosystem resilience, which is essential for wetland ecosystems threatened by climate change and human activities. Americans began to realize that wetlands offered many advantages in addition to other natural resources (Votteler and Muir, 2002). Table 1 lists some of the management techniques used on wetlands by the Conservation Foundation.

Table 1. The management practices applied to wetlands

Physical way	Chemical way	Biological way
• Draining • Excavating • Diverting water away • Clearing • Flooding, Filling	• Changing nutrient levels • Introducing toxins • Chemical water treating	• Grazing • Disrupting natural populations • Invasive plants

According to NUWAGABA (2023), capitalism is a growth strategy that prioritizes commercialism and economic gains over the management and protection of wetlands. The UN's inclusive demands for sustainable development agendas are increasingly reflected in sectoral goals for wetland management. These objectives align with the SDGs, particularly those related to clean water and sanitation (SDG 6), life on land (SDG 15), and life below water (SDG 14). Additionally, they ensure that management approaches combine social justice, ecological preservation, and economic viability (Ramsar 2010).

2.2 Wetland policies in India

India's main legislative framework for protecting wetlands consists of the Ramsar Convention, the National Plan for Conservation of Aquatic Ecosystems, the Wetlands (Conservation and Management) Rules (2017), and the National Wetland Inventory and Assessment (NWIA). The Wetlands Rules (2017) establish a Central Wetlands Regulatory Authority and State Wetlands Authorities, and they provide guidelines for identifying and notifying wetlands, limiting certain activities, and empowering state governments to manage and protect wetlands (Sinha and Mohanty, 2002).

These regulations place a strong emphasis on integrating local communities in wetland management, acknowledging the customs and knowledge that promote sustainable wetland usage. A scientific foundation for wetland management is provided by the ISRO-funded NWIA program (Attri, 2017). There are still several issues despite these strong structures. Policies' efficacy frequently fluctuates because of variations in state-level implementation and oversight capabilities (Devabalane, 2015). Wetland degradation is exacerbated by industrialization, agricultural runoff, and rapid urbanization. Community participation in wetland conservation is typically impacted by low levels of public awareness and involvement.

Conserving biological diversity through sustainable usage and fair benefit sharing is the goal of the National Policy and Macro Level Action Strategy on Biodiversity (1999) (MoEF 2006). It incorporates biodiversity considerations into sectoral planning and places a strong emphasis on protecting natural ecosystems, especially wetlands (MoEF 2006). The EPA (1986), which gives the government the authority to impose laws against pollution and habitat damage, is essential to the conservation of wetlands in India. Additionally, it makes it easier to create and carry out regulations that support the natural balance of wetland ecosystems.

Similar to the USA, India has a strong regulatory structure, yet compliance and enforcement are still difficult. Although India places a strong emphasis on community involvement, which is consistent with Australia's strategy, more work is required to improve local involvement. India uses GIS and remote sensing technology on par with other countries, however, there is a need for improvement in how these data are applied for efficient administration.

3. Types of Wetlands

According to Frazier (1996) and Gupta et al. (2021), there are five primary types of wetlands: riverine, palustrine, estuarine, marine, and lacustrine. They are classified based on the type of water they contain and where they are located (Murthy et al., 2013).

Table 2. Types of wetlands based on various parameters

Based on their geographic location and the type of water they contain	
Types	**Composition**
Marine	Coastal wetlands include places that are connected to the ocean, such as coral reefs, stony beaches, and coastal lagoons.
Estuarine	Wetlands where fresh and salt water mix at the river-sea interface. Mangrove swamps, tidal marshes, and deltas are a few examples.
Riverine	Wetlands along rivers, streams, and creeks.
Lacustrine	Wetlands that are connected to lakes, both man-made and natural.
Palustrine	Inland, usually marshy, non-tidal wetlands. This group include bogs, fens, marshes, and swamps.
Based on their specific features and characteristics	
Marshes	Areas with herbaceous (non-woody) vegetation those are occasionally flooded or waterlogged.
Swamps	Tree and shrub-dominated wetlands those are frequently located on floodplains.
Bogs	Rainfall frequently feeds these wet peatlands, which are usually found in former lake basins.
Fens	Like bogs, however they frequently get higher flow of groundwater.

Mangroves	The intertidal zones of protected tropical coastal regions are dominated by woody communities.
Constructed wetlands: Human-Made wetlands	Canals, ditches, excavations, salt extraction sites, aquaculture ponds, reservoirs, irrigated land, wastewater treatment ponds, etc. are examples of man-made wetlands.

4. Attributes of Wetlands– Indicators

Key indications of the health and functionality of wetlands are characteristics like vegetation, soil type and hydrology. Wetlands are essential ecosystems. For wetland ecosystems to remain healthy, hydrology, the presence and flow of water is essential (Mitsch and Gosselink, 2015). Long-term saturation and the presence of wetland plant species are indicated by the kind of soil, which is frequently hydric. According to Tiner (1999), vegetation, especially hydrophytic plants, stabilizes soil, improves water quality, and offers habitat. All of these indicators work together to evaluate wetland conditions and direct conservation initiatives. The aquatic macrophytes known as hygrophytes and hydrophytes, which are free-floating and versatile with submerged leaves, make up wetland vegetation (Yue et al., 2021). In comparison to channelized watercourses, the species richness and wetland plant coverage were substantially higher in the drainage pumping station, remnant ponds, and flood control basins. Wetland vegetation patterns and ecological management depend on an understanding of how plants use water in various aquatic settings (Zhang et al., 2023a, 2023b).

Table 3. Types of attributes and indicators of wetland habitat

Indicators	Attributes
1. Hydrophytes	Hydrophytes or plants adapted to saturated or submerged soils, are that which distinguish wetlands, and the kinds of hydrophytes that are found there can reveal information about the hydrological regime and level of soil saturation of the wetland.
2. Hydric soils	Hydric soils are a significant marker of wetland presence and are used in wetland differentiation. Wetlands have hydric soils, which are defined by reduced (anoxic) conditions that result in soil color patterns and nutrient cycling. Hydric soils can be identified and defined using mapping and soil surveys.
3. Hydrologic regime	A particular hydrologic regime, which includes water depth, flow direction and inundation periods, defines wetlands. Variations in the hydrologic regime may have an effect on the general health of the wetland, vegetation and soil characteristics. A wetland's hydrologic health can be evaluated by tracking its water levels, flow rates and inundation patterns.
4. Vegetation	The diversity and composition of vegetation can serve as markers of the health of wetlands, offering insights into nutrient levels and water quality. Wetland degradation may be indicated by the presence of invasive or non-native plants. Research has demonstrated that wetland condition can be evaluated using functional characteristics of plants, such as origin and life history.

5. Other indicators	**Salinity:** Particularly in coastal regions, wetland degradation may be indicated by saltwater intrusion or variations in salinity levels. **Soil organic matter:** Wetland health and nutrient retention may be indicated by the amount of organic matter in the soil. **Biomass:** The amount of plant material produced, or biomass, can be a good indicator of a wetland ecosystem's health and productivity. **Species diversity:** A wetland's biodiversity and overall health can be determined by the number of plant and animal species found there. **Fragmention:** Wetland health and connection can be affected by the degree of fragmentation in the wetland landscape **Sediment elevation:** Sediment elevation changes may be a sign of wetland degradation or restoration success. **Nutrient levels:** Wetland health and water quality can be determined by changes in nutrient levels, such as those of nitrogen and phosphorus.

5. Restoration Strategies for Wetlands

The ecology of each type of wetland, such as marshes, mangroves, peat lands and bogs, varies, hence restoration strategies will also vary based on the features, geography, hydrological connections, and types of anthropogenic activities that surround the wetland. Rebuilding and repairing damaged wetlands was first studied in the United States (Zhou et al., 2020). According to An et al. (2019), more than 35% of the world's natural wetlands vanished between 1970 and 2015. The two main responsibilities are assistance and administration. Restoring the hydrological conditions and ecological system while prioritizing the balance of different organisms in wetlands, temperature and plants using natural and ecological laws is the process of restoring wetlands that have been disturbed or altered by human activity (Cai et al., 2021). Wetlands are ecologically restored using the following techniques:

Table 4. Wetlands restoration strategies

Strategies	Description
1. Hydrological restoration	**Restoring water flow:** This entails removing or altering man-made structures like dikes or ditches in order to restore natural drainage patterns. **Inundation by tides:** Restoring tidal access in coastal wetlands can be essential; in certain cases, these calls for site grading and excavation to permit frequent flooding. **Plugging ditches:** Floodplains and natural water levels in freshwater wetlands can be restored by plugging ditches or channels. According to Qaderi and Rahnama (2020), if rainwater collection systems were created for the marsh and its surroundings, the soil would remain moist for a prolonged period.
2. Ecological restoration	**Native vegetation:** Replanting native species is an important step that frequently entails introducing seed mixtures or shifting seedlings (Kettenring and Tarsa, 2020). The growth of trees after planting is dependent upon external variables and takes more time than other restoration techniques. Regenerating tall grass prairie from an agricultural site offers a variety of advantages to soil microbial populations and the ecosystem services they offer. This will help keep aquatic and riparian species from going extinct in wetland ecosystems (Karim et al., 2022). **Elimination of invasive species:** In order to promote the growth of native species, invasive plants must be managed and eradicated (Marchante et al., 2023). **Herbivore and invasive animal control:**

	Protecting newly planted vegetation can be achieved by controlling herbivores and invasive animal populations.
3. Structural interventions	**Sediment deposition:** In some cases, adding sediment to raise land levels or contrast erosion can help stabilize the wetland. **Fill removal:** In urban settings, fill removal can allow for natural hydrology and return the topography to its original state. **Desilting:** Improving water flow and quality can be achieved by removing accumulated sediment. **Reshaping channel morphology:** To restore a river's or flood plain's natural shape, which may involve reshaping a channel to resemble a plea or curve (Cui et al., 2021).
Other restoration strategies	
4. Phytoremediation, microbial restoration, water replenishment, and water-soil engineering restoration	The advancement of wetland restoration technologies in China and other nations was evaluated (Zhou et al., 2020).
5.Infiltration experiment	In some cases, optimal saltwater concentrations encourage the infiltration and circulation of soil water (Wang et al., 2023)
6. Blue carbon accounting model (BlueCAM	Mangroves, seagrass, saltmarsh, and supratidal forests are examples of coastal wetlands that can benefit greatly from tidal barrier removal and modification in terms of reducing greenhouse gas emissions (Lovelock et al., 2022).

Wetlands in India are usually restored using ecological plant restoration techniques that include methods to improve ecosystem services, increase biodiversity, and restore hydrological regimes. Propagation programs, like those run by the National Biodiversity

Authority (NBA) and the Salim Ali Centre for Ornithology and Natural History (SACON), and seed banking are important tactics for establishing native plant species.

In order to preserve habitat structure and support native fauna, these efforts concentrate on choosing species that are suited to the local environment. Community-based initiatives are also important because they involve local stakeholders in wetland restoration activities, ensuring sustainable management practices and promoting socioeconomic benefits.

Wetland Restoration

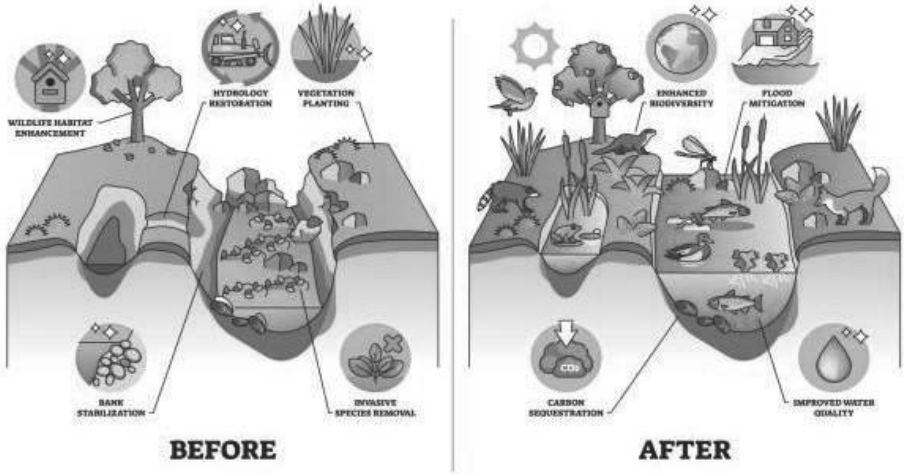


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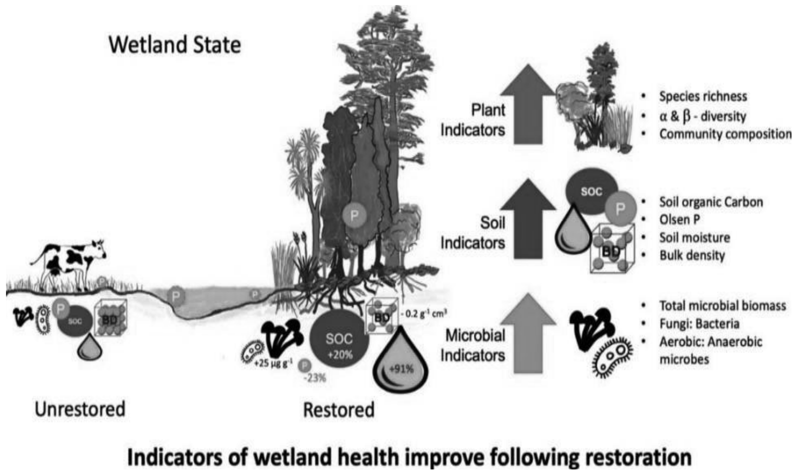
Table 5. Wetland health indicators, predicted change with restoration and a description and interpretation of their use

Indicators	Description. Predicted change with restoration
1. Water quality indicators	**Indicators:** pH, dissolved oxygen (DO), biological oxygen demand (BOD) and total coliform. **Description and interpretation:** The physical and chemical condition of the water itself is reflected in these indications. Lower DO and greater BOD, for instance, may be signs of pollution or excessive nutrient enrichment, which could cause eutrophication and damage to aquatic life. **Predicted change with restoration:** By raising DO and lowering BOD, restoration initiatives like lowering fertilizer runoff and reestablishing natural water flow can enhance water quality.
2. Plant community indicators	**Indicators:** Plant species richness, plant diversity, presence of invasive species, coverage of wetland habitat. **Description and interpretation:** Wetland ecosystems depend on plant communities because they offer food, shelter, and a boost to biodiversity. The health and resilience of the ecosystem can be evaluated with the aid of indicator species, both native and non-native. **Predicted change with restoration:** A more healthy and adaptable plant community can result from restoration, which can also boost native species and plant diversity while decreasing invasive plant dominance.
3. Biodiversity indicators	**Indicators:** Waterbird diversity, fish diversity, other animal and insect communities. **Description and interpretation:** The health and functioning of ecosystems depend primarily on wetland biodiversity. Waterbird diversity is one indicator that can show the presence of various habitats and the overall state of the food chain. **Predicted change with restoration:** A more dynamic and resilient ecosystem can result from restoration, which can increase biodiversity by fostering more diversified habitats and offering

	food and shelter to a variety of species.
4. Hydrological indicators	**Indicators:** Water levels, flow patterns, and connectivity to larger water bodies. **Description and interpretation:** Hydrology has a significant impact on wetland health since it influences habitat availability, water quality and overall ecosystem function. **Predicted change with restoration:** Restoration projects, such as restoring natural water flow and connectivity, can enhance hydrological conditions and provide more stable and resilient ecosystems.
5. Geomorphologica l indicators	**Indicators:** Soil organic matter, soil nutrient levels and the presence of soil erosion. **Description and interpretation:** The growth of plants and the cycling of nutrients in the wetland environment depend on the quality of the soil. **Predicted change with restoration:** Wetland conditions can become healthier and more productive through restoration, which can increase organic matter, nutrient availability and decrease erosion.

(Source: Zedler, 2000)

Scientists and managers may evaluate the success of restoration initiatives and make well- informed judgments on wetland management by keeping an eye on these indicators and comprehending how they can alter as a result of restoration.



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6. Key Challenges of Wetland Restoration

The main obstacles to wetland restoration include pollution from multiple sources, the effects of climate change, and habitat loss brought on by industrialization and urbanization. Inadequate finance, minimal community involvement, and a lack of public knowledge can further impede restoration attempts. Invasive species, variations in water flow, and the problem of faithfully replicating natural hydrologic conditions may also pose difficulties. The overuse of natural resources and the extreme pollution caused by urbanization and sprawl have put a great deal of strain on the natural ecological environment. We will encounter several difficulties when implementing different wetland restoration techniques. Due to different ecosystem types, research goals and disciplinary backgrounds, several assessment methods and indicator systems are used in ecology security evaluation (Fan and Fang, 2020).

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Table 6. Key challenges during wetland restoration

Key challenges	Description
Urbanization	Wetlands are frequently destroyed or degraded as a result of urbanization and industrialization, which makes restoration more challenging.
Pollution	Wetlands can get contaminated by pollutants from sewage, industrial discharge and agricultural runoff, which compromise their ecological integrity and reduces the effectiveness of restoration.
Climate change	Wetlands natural hydrology can be disturbed by rising sea levels, changed precipitation patterns, and warmer temperatures, making it difficult to return them to their original state.
Invasive species	Non-native plants can disrupt restoration efforts, change the composition and function of wetland ecosystems and compete with native vegetation.
Hydrologic changes	Dam construction and excessive water extraction are two examples of changes to water flow patterns that can upset wetlands' natural hydrology and make it challenging to restore their biological integrity.
Public awareness and participation	The success of restoration programs may be hampered by low community involvement and a lack of public understanding of the significance of wetlands.
Funding	In order to be successful, wetland restoration projects can be expensive and need a lot of funds. Obtaining sufficient funds can be very challenging.
Lack of knowledge and expertise	It can be difficult to comprehend and manage the intricate relationships between plant, hydrology, and soil dynamics in wetlands; this calls for specific training and experience.
Monitoring and adaptive management	The long-term viability of wetland restoration initiatives depends on efficient monitoring and flexible management. However, the resources and knowledge needed for these operations can be inadequate.

These issues can be resolved to increase the effectiveness of wetland restoration initiatives and contribute to the preservation of these priceless ecosystems.

7. Economic Benefits of Wetlands

Agriculture, fishing, water supply, tourism, and the regulation of nitrogen cycles and water tables are just a few of the industries that benefit economically from wetlands. Additionally, it helped to preserve floodplains, produce timber, provide energy resources (plant matter and peat), support wildlife, and create opportunities for tourism and leisure (Lambert, 2003). According to Gardner and Finlayson (2018), they offer ecological services and are home to some of the planet's most productive ecosystems. Wetlands are important in the concept of climate change because they maintain long-term carbon storage and lower greenhouse gas emissions (Malerba et al., 2022).

8. Social and Cultural Significance

In India, where they are important to local customs and livelihoods, wetland ecosystems are essential sites for a range of social and cultural activities. According to Biswas et al. (2017), these ecosystems offer vital resources, including water sources, cultivable land, and fishing grounds that are necessary for the economic and subsistence needs of populations. Wetlands are frequently used as locations for rites and rituals by indigenous and local groups, and in cultural contexts, they frequently have spiritual value (Nayak and Tripathy, 2020). Wetlands also support ecotourism, boating, and birding, which raises awareness of environmental issues and generates revenue (Gopal, 2013). In order to create sustainable management plans that strike a balance between conservation and human needs and customs and guarantee the advantages of wetlands for future generations, it is imperative to acknowledge these social and cultural factors.

9. Conclusion

In conclusion, wetland restoration is a vital endeavor for the health of our planet and its inhabitants, offering numerous ecological and societal benefits. These ecosystems are crucial for biodiversity conservation, climate change mitigation, and water purification, highlighting their importance for the well-being and sustainability of human societies. Effective restoration not only enhances ecosystem services but also leads to significant economic gains and improved community well-being. Restoring wetlands is not just the responsibility of the government; it also depends on the local community and environmentalists' awareness of its significance and the implementation of sustainable solutions. In addition to being a useful instrument for the sustainability of natural ecosystems, proper monitoring systems should be employed to preserve wetland habitats.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-4

Heavy Metal Pollution and Its Ecotoxicological Threats

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AUTHOR'S CONTRIBUTION

This chapter is a joint endeavor by the two authors. Author AS is the main source behind collecting the data and preparing the first draft. AS wrote the introduction, major portion of literature review like sources of heavy metals in the environment, their effects on humans and other living organisms, discussed mechanisms of metal toxicity and case studies, and conclusion. FA contributed in writing the abstract, comprehensive literature on remedial strategies to mitigate heavy metal led pollution, policy interventions and polished the final draft. Both authors were actively involved in shaping the chapter and gave their approval for the final version.

ABSTRACT

Environmental pollution is one of the most pressing global challenges, threatening biodiversity, human health, and ecosystem

stability. Rapid industrialization, intensive agriculture, and urbanization have introduced a range of pollutants into air, water and soil affecting plants, animals and human health. Among these, heavy metals, pesticides, microplastics and industrial contaminants are of significant concern due to their persistence, bioaccumulationand long-term ecological impact. This chapter explores the sources, effects, pathways and ecotoxicological consequences of these heavy metal pollutants and will discuss strategies for mitigation and future research directions.

Keywords: Heavy Metals, soil, ecotoxicology, remediation, bioaccumulation

1. Introduction

Environmental pollution occurs when harmful substances contaminate natural resources, thereby disrupting ecological balance. The major types of pollution include:

a) **Air pollution:** Emissions from industries, vehicles and burning fossil fuels introduce particulates, heavy metals and toxic gases.

b) **Water pollution:** Discharge of industrial effluents, sewage, agricultural runoff and plastic waste contaminates aquatic ecosystems.

c) **Soil pollution:** Heavy metal deposition, pesticide overuse and improper waste disposal degrade soil fertility and biodiversity.

d) **Microplastic pollution:** Synthetic polymer particles enter ecosystems through plastic waste degradation and industrial activities.

e) **Pesticide pollution in ecosystems:** Pesticides are chemical agents used in agriculture to control pests, but they also pose environmental risks. Major classes include:

i. Organochlorines (e.g., DDT): Persistent in the environment, highly toxic to birds and aquatic life.

ii. Organophosphates (e.g., Malathion): Affect nervous systems but degrade faster than organochlorines.

iii. Neonicotinoids (e.g., Imidacloprid): Harmful to pollinators such as bees and butterflies.

iv. Herbicides (e.g., Glyphosate): Affect plant biodiversity and soil microbiota.

Each of these pollutants can have severe consequences on ecological and human health, often leading to chronic toxicity, endocrine disruption and loss of biodiversity (Thompson et al., 2024; Garud et al., 2024; Zhou et al., 2025).

2. Heavy Metals Contamination in the Environment

The issue of heavy metal pollution is increasingly pervasive on a global scale. About 35 naturally occurring heavy metals are present in the earth's crust of which 23 of them have specific density above greater than $5g/cm^3$. Some heavy metals such as copper (Cu), Zinc (Zn), Manganese (Mn) and Iron (Fe) are essential for biological functions while others such as lead (Pb), Cobalt (Co), Nickel (Ni), Mercury (Hg), Cadmium (Cd) and Arsenic (As) are highly toxic even at low concentrations. High concentrations of heavy metals can present a serious threat. Certain substances, particularly heavy metals, resist decomposition and are non-biodegradable, leading to their accumulation in humans and animals when they enter the food chain, which makes them hazardous. Metals may enter the environment through natural sources or human activities such as waste disposal, industrial effluents, sewage discharge, smelting and mining. Mining poses a considerable risk by potentially moving and dispersing heavy metals to nearby areas during flooding or storms. Recognizing and addressing environmental dangers is vital to protect the health of both people and the ecosystem. Pollution of water by heavy metals can negatively affect human health.

These metals can find their way into our bodies through contaminated water and food. They can interact with organic molecules, resulting in the formation of harmful compounds that can damage our cells (Lawal et al., 2021). Therefore, it is essential to develop effective biological methods for cleaning up heavy metal contamination.

3. Sources of Heavy Metal Pollution

Point sources of contamination by toxic heavy metal ions in water are identified as specific types of pollution that result in significant levels of heavy metal ion contamination. It is crucial to eliminate contaminants from these sources and discharge them directly into the nearest water bodies or environmental areas. Industries located along riverbanks are major contributors to heavy metal contamination in water. The primary point sources of heavy metal pollution are as follows:

3.1. Industrial sources: The discharge of industrial wastewater significantly contributes to the contamination of water with heavy metals. This wastewater contains various hazardous substances, including heavy metal ions, which are released into the environment either directly or indirectly. These heavy metal ions can accumulate within the food chain, adversely impacting humans as well as terrestrial and aquatic animals. According to a report by the Central Pollution Control Board (CPCB), approximately 260 million litres of industrial wastewater is discharged daily into the Ganga River in India. Numerous industries, such as paper, sugar, textiles, steel, battery, leather, chemicals, pharmaceuticals, metal works, and food industries, release their wastewater into the environment. Processes such as metal smelting, battery production, and coal combustion emit Pb, Hg, Cd and As (Arif et al., 2021).

3.2. Agricultural practices: Excessive usage of phosphate fertilizers introduces cadmium and lead into soil and water systems. Pesticides and insecticides often introduce metals like copper and arsenic that accumulate in soil and crops (Roberts et al., 2014).

3.3. Mining, smelting & burning activities: Smelting, burning of fossil fuels, open-pit and underground mining results in contamination of water bodies and soil by Cadmium via leaching (Lawal et al., 2021).

3.4. Waste disposal: Electronic waste (e-waste) contains heavy metals that contaminate landfills and groundwater contaminating drinking water sources (Perkins et al., 2024).

3.5. Natural sources: Volcanic eruptions, weathering of rocks and forest fires release heavy metals into the atmosphere and hydrosphere (Lawal et al., 2021).

4. Mechanism of Heavy Metal Toxicity

4.1. Bioaccumulation (Zhou et al., 2025; Lawal et al., 2021; Uddin et al., 2024)

Bioaccumulation refers to the gradual accumulation of heavy metals in an organism over time, typically through direct exposure to contaminated air, water or food. Unlike organic pollutants, heavy metals do not degrade and persist in biological tissues. This occurs because of:

i. **Slow excretion rates:** Many heavy metals bind to proteins and cellular structures, making elimination difficult.

ii. **Fat-solubility:** Some metals, like mercury (in the form of methylmercury), dissolve in fats and accumulate in lipid-rich tissues.

iii. **Continuous exposure:** Organisms exposed to polluted environments consistently absorb heavy metals through respiration, ingestion and skin contact.

E.g., Cadmium bioaccumulation in rice plants

Cadmium (Cd) accumulates in rice crops irrigated with contaminated water, entering the food chain. Studies show that prolonged consumption of cadmium-rich rice leads to Itai-Itai disease (characterized by severe kidney damage and bone deformations) in humans, as observed in Japan's Toyama Prefecture.

4.2. Biomagnification

Biomagnification refers to the rising levels of heavy metal concentration throughout the food chain. This phenomenon happens when heavy metals accumulate in greater amounts at the top trophic levels of an ecosystem. In contrast to bioaccumulation which affects individual organisms, biomagnification impacts whole food chains, resulting in increased toxicity risks for predators and humans. Primary producers (phytoplankton, plants): Absorb heavy metals from soil and water. Primary consumers (herbivores, small fish): Consume contaminated plants and plankton, accumulating metals in their tissues, Secondary consumers (carnivores, larger fish): Eat multiple contaminated organisms, leading to higher metal concentrations and Tertiary consumers (top predators, humans): Experience the most severe effects as heavy metals reach toxic levels (Szynkowska et al., 2018; Kidd et al., 2012).

E.g., Biomagnification of mercury in aquatic food chains (Lavoie et al., 2013; Watras and Bloom, 1992)

Mercury pollution from industrial waste and coal-fired power plants enters water bodies, where bacteria convert inorganic mercury into a highly toxic organic form methylmercury. The concentration of methylmercury increases as follows:

1. Phytoplankton: Absorb mercury from water (0.01 ppm).
2. Zooplankton: Feed on phytoplankton, accumulating mercury (0.1 ppm).
3. Small Fish: Consume zooplankton, leading to higher mercury levels (1.0 ppm).

4. Large Fish (e.g., Tuna, sharks): Eat multiple smaller fish, increasing mercury concentration in their body to 5.0 ppm.
5. Humans and Predatory Birds (e.g., Eagles, Ospreys): At the top of the food chain, humans consuming large fish experience 10 times higher mercury levels (10.0 ppm or more) than the original water contamination.

5. Ecotoxicological Effects of Heavy Metals in General (Garud et al., 2024; Zhou et al., 2025)

Heavy metals persist in the environment, bioaccumulate in organisms, and biomagnify through food chains. Their common toxic effects are:

a) **Ecosystem disruptions**: Species decline due to toxicity. E.g., mercury poisoning in fish reduces populations of predatory birds.

b) **Reproductive failures**: Heavy metals interfere with hormone systems, leading to infertility and birth defects in wildlife.

c) **Neurological damage**: Methylmercury exposure in humans leads to Minamata disease, causing brain damage and motor dysfunction.

d) **Public health risks**: Top-level consumers (including humans) suffer from cancer, kidney failure, and developmental disorders due to high metal exposure.

e) **Disruption of cellular processes:** Heavy metals generate reactive oxygen species (ROS), causing oxidative stress and DNA damage. Metals interfere with enzymatic activities and metabolic functions.

f) **Neuro-endocrine disruptions**

Lead and mercury exposure causes neurotoxicity, affecting cognitive functions. Cadmium disrupts calcium metabolism, leading to kidney and bone diseases.

6. Effects of Various Heavy Metals in Concentration Beyond Their Permissible Limits on Human Health (Thompson et al., 2024; Garud et al., 2024; Zhou et al., 2025; Uddin et al., 2024).

a) **Lead (Pb):** Causes neurological disorders, kidney damage, and developmental toxicity in children.

b) **Mercury (Hg):** Mercuric mercury is not absorbed through intestine. Mercuric ions have strong tendency to bind thiol groups leading to the depletion of glutathione (Kazantzis, 2002). This causes oxidative stress. Methyl mercury increases calcium levels in the cytosol through influx of calcium from outside the cell. Leads to Minamata disease in humans, bioaccumulates in fish, and disrupts aquatic food webs.

c) **Cadmium (Cd):** Damages renal systems, weakens bones (Itai-Itai disease) and affects soil microbial communities.

d) **Arsenic (As):** Highly toxic at low concentrations, causing skin lesions, cancers, and groundwater contamination. There is decreased production of both red blood cells and white blood cells. Also causes infertility and DNA damage.

e) **Vanadium (V):** Two oxidation states of vanadium +IV (vanadyl) and +VI (vanadate). These bind reversibly with protein transferrin in the blood. Vanadate inhibits the Na^+/K^+ ATPase hence is more toxic than vanadyl (Monfort and Petrisková, 2021).

f) **Aluminium (Al):** It mainly affects bones, lungs and central nervous system. It is introduced through antacids, dialysis fluid and the patients suffering from hyperphosphatemia.

g) **Chromium (Cr):** It exists mainly as Cr (VI) and Cr (III). Former is more toxic than latter. Chromate compounds induce DNA damage leading to the production of DNA adducts and chromosomal changes (Yang et al., 2023).

h) **Manganese (Mn):** Manganese tends to accumulate in the neurons and disrupt ATP synthesis. This causes oxidative stress and generation of free radicals.

i) **Cobalt (Co):** Cobalt has the high affinity for sulfhydryl groups which causes inhibition of important enzymes. It acts as calcium channel antagonist and competes with calcium to bind with intracellular binding sites. Thus there is formation of reactive oxygen species (ROS) which leads to oxidative damage to proteins, DNA and lipids.

j) **Nickel (Ni):** Nickel sulphide, nickel oxide, and soluble nickel compounds have all been identified as carcinogenic. At elevated levels, nickel is taken up through passive diffusion and binds with albumin alongside small molecules like amino acids and polypeptides, enabling it to travel within the bloodstream. It interferes with calcium channels, resulting in reduced calcium entry into the intracellular space. The decrease in calcium levels contributes to cell growth and apoptosis.

k) **Molybdenum (Mo):** High doses of molybdenum leads to anaemia and decrease in body weight. Copper concentration was found to increase in the liver and kidney in case of molybdenum toxicity. Ruminants are found to be more susceptible to Mo toxicity.

7. Soil Contamination and Its Impact on Plants

Heavy metals such as Chromium, cadmium, lead, mercury, antimony, arsenic, silver etc. are dangerous to plants even at lower concentrations. They reduce soil microbial diversity and enzyme activity by interfering with homeostasis. Contaminated soils impair plant growth, reducing agricultural yields (Lawal et al., 2021).Tanneries in Kanpur release hexavalent chromium (Cr^{6+})

into the Ganga River, contaminating surrounding agricultural fields. Chromium toxicity in soil has reduced wheat yields by 40% in affected areas (Singh et al., 2025).

8. Water Pollution and Aquatic Toxicity

Heavy metals accumulate in fish and aquatic organisms, reducing reproductive success. Mercury contamination in fish leads to Minamata disease in humans. According to a study elevated concentrations of total mercury were consistently observed in *Beryx splendens* (0.78±0.56 μg/g), Atlantic *Thunnus thynnus* (0.42±0.06 μg/g), Pacific *T. thynnus* (0.59±0.34 μg/g), *Thunnus obesus* (0.98±0.34 μg/g), *Makaira nigricans* (0.56±0.05 μg/g), *Tetraptus audax* (0.51±0.08 μg/g), and *Xiphias gladius* (0.47±0.24 μg/g). Other fish species exhibited lower total mercury or methylmercury levels in their muscle than the maximum allowable mercury concentration in fish set by Japan (0.4 μg/g) (Yamashita et al., 2005).

9. Impact on Terrestrial and Aquatic Fauna

Bioaccumulation in birds and mammals leads to reproductive failures. Amphibians and fish show developmental deformities due to metal toxicity. Lead contamination in Flint, Michigan's USA drinking water supply affected over 100,000 residents, with elevated blood lead levels in children leading to developmental issues (Roy and Edwards, 2019).

10. Strategies for Mitigation and Remediation of Heavy Metals

10.1 Biosorption

This technology is efficient and environmentally friendly, designed to eliminate heavy metal ions from contaminated water, providing both cost benefits and ecological advantages. Biosorption techniques can serve as substitutes for traditional methods and should be considered viable alternatives to existing physicochemical approaches due to their environmentally friendly and cost-effective characteristics. The biosorption process makes use of a variety of raw materials sourced from agricultural waste, plant residues, as well as algal and microbial biomass. This method operates independently of metabolic processes, eliminating the requirement for living organisms, which simplifies its application and user experience. A wide array of materials, including rice and wheat husks, activated carbon, agricultural by-products, banana and citrus peels, and nanoparticles synthesized through green methods, can be effectively employed for biosorption. It is crucial to highlight that these materials possess unique surface properties that significantly improve their ability to absorb heavy metal ions present in water (Ali and Hassaan, 2017).

10.2 Phytoremediation

These are the eco-friendly and cost effective ways for detoxification. These processes use plants and microbes to absorb or degrade heavy metals from contaminated soil and water before they enter food chains (Shakoor et al., 2017). Phytoremediation occurs through several processes, depending on the plant species and the type of heavy metal contamination:

i. **Phytoextraction (Hyperaccumulation):** Plants absorb heavy metals from the soil and accumulate them in their shoots and leaves. Hyperaccumulator plants like *Brassica juncea* (Indian mustard), *Thlaspi caerulescens* (Alpine pennycress) *Helianthus annuus* (sunflower), *Medicago sativa* (Alfalfa) and *Castor communis* (Castor) store high concentrations of metals such as Pb, Cd and As. These plants can be harvested and disposed of safely, reducing soil contamination (Shakoor et al., 2017).

ii. **Phytostabilization:** Some plants prevent the mobility of heavy metals by binding them in their roots.This reduces the risk of groundwater contamination and prevents metals from entering the food chain. For example: Two Vetiver grass *sp., Chrysopogon zizanioides* and *Chrysopogon nemoralis* showed accumulation of Zn, Cd, Pb (Wasino et al., 2019; Phusantisampan et al., 2016), antimony (Sb) and As (Yu et al., 2020); while *Spondias mombin* (Hog plum), *Cola gigantea* (Giant cola) and *Ceiba pentandra* (Kapok) were found to stabilize Pb, Zn, and Hg in field experiments or in the mine-affected fields (Mashi et al., 2025).

iii. **Rhizofiltration:** Plant roots absorb and filter heavy metals from polluted water bodies.This is useful for treating industrial effluents and wastewater. For example: There are three most commonly found water plants such as *Eichhornia crassipes* (Water hyacinth), *Azolla* (water fern) and *Pistia* (water lettuce). Among these plants *Eichhornia crassipes* has shown highest efficiency in removing As, Ni, Pb, Cu, Zn and Cd from polluted water bodies (Banerjee and Roychoudhary, 2022; Zaida et al., 2021; Yadav et al., 2015).

iv. **Phytovolatilization:** Plants absorb metals and convert them into volatile forms, which are then released into the atmosphere. This method is primarily used for removal of Hg and Se. Pilon-Smits (1999) found 20 aquatic plant species which can volatilize and accumulate Se. Plant species which most effectively showed phytovolatilization were *Myriophyllum brasiliense* (Parrot's feather), *Juncus xiphioides* (Iris-leaved rush), *Scirpus robustus* (Saltmarsh bulrush) and *Typha latifolia* (Cat tail), (Pilon-Smits et al., 1999). Studies suggested that certain plants can also remove mercury through phytovolatilization (Sharma et al., 2024).

v. **Phytodegradation:** Some plants and their associated microbes degrade complex organic pollutants into less toxic forms, though this is more effective for organic pollutants than heavy metals (Newman and Reynolds, 2004).

10.3 Bioremediation

Bioremediation is harnessing the microorganisms for heavy metal detoxification. It involves the use of bacteria, fungi, and other microbes to detoxify heavy metal-contaminated environments. These microorganisms can absorb, reduce, or transform toxic metals into less harmful forms. Microbial remediation occurs through different biochemical processes which are as follows:

i. **Bioaccumulation:** Microorganisms absorb and store heavy metals in their cells. For example *Pseudomonas aeruginosa* accumulates Cd and Pb from wastewater (Chellaiah, 2018).

ii. **Biosorption:** Dead microbial biomass (e.g., fungi and algae) passively binds heavy metals onto their cell surfaces. For example: *Aspergillus niger*(a fungus) removes Cr, Ni and Cd from industrial effluents (Ahmad et al., 2006).

iii. **Biotransformation:** Bacteria convert toxic heavy metals into less toxic or volatile forms. For example: *Desulfovibrio desulfuricans* reduces hexavalent chromium (Cr^{6+}) to its less toxic form (Cr^{3+}) (Chen and Tian, 2021).

iv. **Bioleaching:** Some bacteria dissolve metal contaminants, making them easier to extract.

For example: *Acidithiobacillus ferroxidans* and *Acidithiobacillus thiooxidans* leaches metals like Cu, Zn, Pb and As from from printed circuit boards and contaminated mining sites respectively (Ko et al., 2013; Wang et al., 2008).

v. **Enzymatic degradation:** Microbes produce enzymes that detoxify metals and organic pollutants.

10.4 Chemical and physical remediation

Adsorption using activated carbon, bio-char, clay, mineralsand nanomaterials to remove heavy metals from wastewater or soil. Membrane filtration and electrochemical treatment improve water quality. Chemical methods focus on transforming heavy metals into less toxic or less mobile forms by using methods such as precipitation, oxidation and reduction, ion exchange methods, electrokinetic remediation washing and extraction.

11. Case Studies of Phytoremediation and Bioremediation

11.1. Case Study 1: Phytoremediation of arsenic in West Bengal, India

The groundwater in parts of West Bengal is contaminated with arsenic beyond WHO limits. Scientists have successfully used *Pteris vittata* (Chinese brake fern) to extract arsenic from affected soils. Over five years, arsenic concentrations were reduced by 50% in experimental fields (Mandal et al., 2012). *Pteris vittata* has also shown to improve microbial properties in phosphate contaminated soils (Mandal et al., 2018).

11.2. Case Study 2: Bioremediation of chromium from tanneries in Kanpur, India

Kanpur's tannery industries release large amounts of chromium into the Ganga River. Researchers introduced *Bacillus, Pseudomonas Kocuria, Brucella, Microbacterium, Cellulosimicrbium* and *Klebsiella sps.*to bio-remediate the wastewater. Within six months, chromium levels were found to be reduced by 1000ppm concentration, thereby improving water quality (Kumar et al., 2023).

12. Policy Interventions and Sustainable Practices (Kowalska and Biczak, 2025; Khanam et al., 2023 and Chandra et al., 2015)

- Industrial regulations and pollution monitoring programs help control contamination.
- Circular economy approaches, such as metal recycling, reduce environmental impact.
- Strict industrial discharge standards, lead-free gasoline, and mercury phase-out programs.
- Strict regulations on mercury, lead and cadmium emissions from factories.
- Spread awareness among the consumers to encourage the consumption of smaller fish (lower in mercury) rather than top predators like tuna and swordfish.
- Agreements like the Minamata Convention on Mercury aim to control mercury pollution globally.
- Green Manufacturing: Reducing waste through cleaner production technologies.
- Strict Environmental Regulations: Industrial effluent treatment and zero-discharge policies.
- Genetic Engineering: Scientists are engineering hyperaccumulator plants and metal-resistant bacteria for enhanced remediation.
- Nanotechnology: Nanoparticles are being used to boost microbial metal absorption and contamination removal.
- Integrated Approaches: Combining phytoremediation and bioremediation with physical methods for more effectiveness.

13. Future Research Directions

- Development of genetically modified plants and microbes for enhanced remediation.

- Use of nanotechnology-based adsorbents for efficient heavy metal removal.
- Climate change implications on heavy metal mobility and bioavailability.

14. Conclusion

Environmental pollution from heavy metals, pesticides, microplastics, and industrial contaminants poses significant ecological and human health risks. Ecotoxicology provides essential insights into their impact and informs sustainable solutions. By integrating scientific research with policy enforcement and public awareness, we can mitigate pollution and move towards a more sustainable future.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-5

Water Quality Monitoring: Tools and Techniques for Pollutant Detection

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ABSTRACT

Water quality monitoring is essential for maintaining the health of aquatic ecosystems and ensuring safe water supplies for human consumption. It involves the measurement of key parameters such as pH, temperature, turbidity, dissolved oxygen, salinity and contaminants including heavy metals, pesticides, and microbial pathogens. Effective monitoring enables the identification of pollution sources, evaluation of ecosystem health, and improvement of water treatment practices. Traditional laboratory-based methods, though reliable, are often time-consuming and costly. Recent technological advances have transformed monitoring approaches, offering more efficient and accurate alternatives. Remote sensing tools, such as satellites and drones, facilitate large-scale assessment of water quality, while in-situ sensors and biosensors provide continuous, real-time data on pollutants and environmental fluctuations. Molecular and genetic techniques further enhance sensitivity in detecting specific pathogens and contaminants. The integration of these data into geographic information systems (GIS) and predictive models supports

informed decision-making, risk assessment, and sustainable management of water resources.

Emerging innovations, particularly artificial intelligence (AI) and machine learning (ML), are further enhancing water quality monitoring. These approaches enable rapid processing of large datasets, recognition of hidden patterns, and prediction of water quality issues based on historical data, climatic variables, and environmental factors. Such predictive capacity supports proactive management strategies to prevent degradation. Additionally, the adoption of Internet of Things (IoT)-enabled devices has improved real-time monitoring by linking networks of sensors across diverse freshwater and marine environments. These systems provide near-instantaneous feedback, strengthening early detection and rapid response mechanisms. As global concerns about water pollution intensify, the combination of traditional methods with advanced technologies offers a powerful approach to safeguard public health and protect environmental integrity. Increasing demand for clean water underscores the urgency of developing cost-effective, efficient and innovative monitoring systems to ensure long-term water sustainability.

Keywords: Artificial Intelligence (AI), geographic information systems, Internet of Things, machine learning, genetic techniques

1. Introduction

Water quality monitoring is an essential part of environmental management that helps assess the condition of water bodies, including rivers, lakes, oceans and groundwater (UNEP, 2019). It ensures the protection of water resources for drinking, industrial use, agriculture and recreation (WHO, 2017). Pollutants such as heavy metals, nutrients, pathogens and chemicals from various anthropogenic and natural sources can degrade water quality, leading to potential risks for human health and the environment (Jarvie et al., 2018; Carpenter et al., 2011). In recent years, with the increasing pressures from industrialization, urbanization and agricultural activities, water pollution has become a significant concern worldwide Therefore, water quality monitoring plays a critical role in understanding the extent of pollution and identifying potential health hazards (EPA, 2020).

Effective monitoring not only helps in detecting contaminants but also aids in the development of strategies for water conservation, restoration and sustainable management (Palaniappan et al., 2010). Traditional methods of water quality analysis, such as laboratory-based chemical and biological assessments, provide reliable but time-consuming results (APHA, 2017). Recent advances in technology, including in-situ sensors, biosensors and remote sensing techniques, have enabled real-time and large-scale monitoring of water resources with greater efficiency (Dutta et al., 2021; Boluwade et al., 2016). Furthermore, the integration of artificial intelligence (AI), machine learning (ML) and Internet of Things (IoT)-based systems into water monitoring networks has enhanced predictive capabilities, allowing for proactive water quality management (Sharma et al., 2022; Perera et al., 2014).

The importance of monitoring programs and the challenges involved in detecting and quantifying pollutants will also be explored. Water quality monitoring is a multifaceted process that involves the collection and analysis of data related to various water parameters, such as temperature, pH, dissolved oxygen, turbidity and the presence of harmful substances (UNEP, 2019). These parameters provide vital information regarding the overall health of aquatic ecosystems and the potential risks posed to both human and environmental health (WHO, 2017). As global populations grow and industrial activities expand, the need for effective water quality monitoring becomes increasingly crucial. The degradation of water bodies due to contamination can have far-reaching consequences on biodiversity, agricultural productivity and the availability of clean water resources (Carpenter et al., 2011).

Traditional methods of water quality monitoring typically involve laboratory analysis of water samples collected from various locations over specific time intervals. While these methods are reliable, they can be time-consuming and expensive, often requiring transportation of samples and specialized equipment (APHA, 2017). In contrast, modern techniques, such as remote sensing, real-time sensor networks, and automated data collection systems, have revolutionized the monitoring process, allowing for more rapid and continuous assessments of water quality. These innovations provide valuable insights into the dynamic nature of water pollution, enabling quicker response times and more effective management strategies (Boluwade et al., 2016). This paper delves into the various tools and techniques employed in water quality monitoring for pollutant detection. It will discuss both traditional and modern methods used to evaluate water quality, including chemical, biological and sensor-based approaches.

2. Water Quality Monitoring Techniques

2.1 Chemical testing methods

Chemical testing is one of the most traditional and widely used methods for water quality monitoring. It involves the analysis of water samples to measure various chemical parameters, such as pH, dissolved oxygen (DO), turbidity, nutrients (nitrogen, phosphorus), heavy metals (lead, mercury, arsenic) and other dissolved substances (APHA, 2017). These parameters are critical in determining the chemical balance of water and assessing its suitability for different uses.

i. **pH measurement:** pH is a fundamental water quality parameter that indicates the acidity or alkalinity of water. Extreme pH values can create harmful conditions for aquatic organisms and influence the solubility and toxicity of pollutants (Chapman, 1996).

ii. **Dissolved Oxygen (DO):** The concentration of dissolved oxygen in water is a key indicator of the ability of the water to support aquatic life. Low DO levels, often resulting from organic pollution, can cause the suffocation of fish and other aquatic organisms (Wetzel, 2001).

iii. **Nutrient levels:** High concentrations of nitrogen and phosphorus, typically from agricultural runoff and wastewater discharge, can cause eutrophication, leading to algal blooms that deplete oxygen and create dead zones in water bodies (Smith et al., 1999).

iv. **Heavy metals:** Detection of toxic metals such as mercury, arsenic and cadmium is vital, as they pose significant health risks to humans and wildlife even at low concentrations (Jarup, 2003).

These tests typically require the collection of water samples from various sites and subsequent laboratory analysis, which, while accurate, can be time-consuming and expensive.

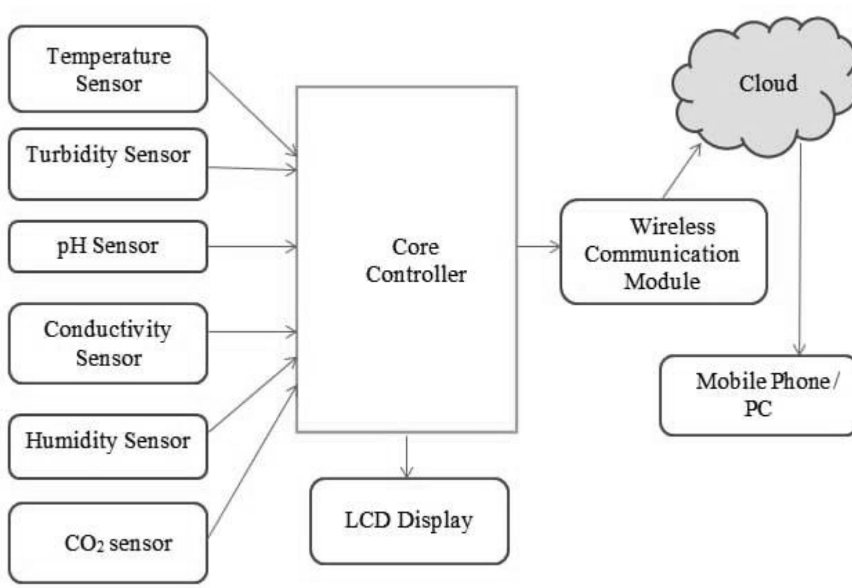

Figure 1: Water quality monitoring framework

Table 1: Common water quality parameters and their significance

Parameter	Significance	Common pollutants
pH	Indicates acidity and alkalinity of water Industrial discharges	Acid rain
Dissolved	Vital for aquatic life organic pollution	Eutrophication
Turbidity	Measures water quality, influenced by suspended solids sediment, runoff	Pollution
Heavy metals	Toxic to aquatic life and humans at high levels industrial waste	Mining runoff

2.2 Biological testing methods

i. **Bioindicators:** Species such as fish, macroinvertebrates, and algae serve as bioindicators of water quality, reflecting ecosystem health through their diversity, abundance, or behavioral changes. Sensitive taxa may disappear in polluted waters, making them reliable tools for long-term monitoring (Jayawardana et al., 2020). Benthic macroinvertebrates, for example, are widely used in freshwater biomonitoring through indices such as the Index of Biological Integrity (Ambasht and Ambasht, 2003).

ii. **Bioassays:** Bioassays involve exposing aquatic organisms to water samples to observe their physiological responses, such as growth inhibition, reproductive issues or mortality. These tests are often used to detect toxic chemicals that may not be easily measurable through traditional chemical methods. Bioassays are especially useful in identifying sublethal effects of contaminants that might not be immediately obvious. They can detect pollutants such as heavy metals, pesticides and industrial chemicals that could be harmful even in trace amounts. These tests typically involve exposing organisms to water samples under controlled conditions, allowing researchers to evaluate the effects of pollutants on growth, development and overall health. Bioassays can also help establish safe exposure limits for aquatic life (Rand, 1995).

2.3 Remote sensing and satellite imaging

Remote sensing is a crucial tool for large-scale water quality monitoring, allowing for the assessment of parameters such as chlorophyll-a,turbidity and suspended solids across extensive or inaccessible aquatic systems. It provides cost-effective, frequent data that complements traditional field sampling (Hadjimitsis et al., 2010). Satellite-based models, for example, have been successfully applied to estimate chlorophyll-a concentrations as indicators of phytoplankton biomass and eutrophication, with basin-specific calibration improving predictive accuracy (Rhee et al., 2025).

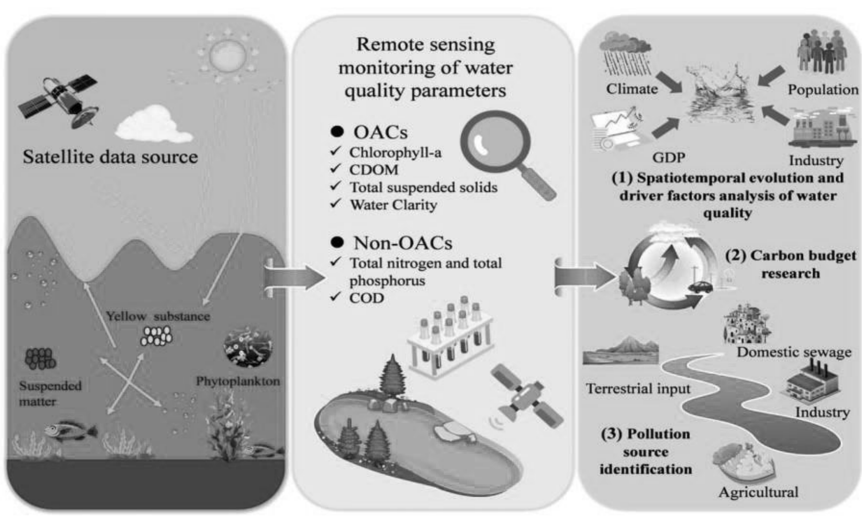

Figure 2: Showing how satellite imagery and remote sensing technologies can be used to assess water quality parameters such as chlorophyll-a concentration and turbidity.

i. **Sensor-based technologies:** The rise of sensor-based technologies has revolutionized the field of water quality monitoring. These sensors provide real-time, in-situ data on various water quality parameters, such as pH, temperature, turbidity, dissolved oxygen and specific pollutants like nitrates and heavy metals.

ii. **Electrochemical sensors:** These sensors detect specific ions and chemicals in water. For example, ion-selective electrodes can be used to measure nitrate, ammonia and pH in real-time (Bakker and Pretsch, 2007).

iii. **Optical sensors:** Optical sensors are used to measure parameters such as turbidity and chlorophyll-a concentration based on light scattering or absorption (Levine et al., 2017).

iv. **Wireless Sensor Networks (WSNs):** WSNs consist of a network of sensors deployed across a water body, transmitting real-time data to central monitoring systems. This system offers continuous, cost-effective and accurate data on water quality. These sensors can measure various water quality parameters such as pH, temperature, turbidity, dissolved oxygen, conductivity and the presence of harmful contaminants like heavy metals or pathogens (Alahi and Mukhopadhyay, 2018). The collected data is transmitted wirelessly to a central server or cloud-based platform for analysis.

2.4 Real-Time data collection and integration

The integration of real-time data collection technologies with Geographic Information Systems (GIS) has significantly improved water quality monitoring. By combining sensor data with GIS mapping tools, environmental agencies can track pollutant levels across large areas, identify pollution hotspots, and make informed decisions about water management.

Integrated Water Quality Monitoring Systems (IWQMS): These systems are capable of combining data from various sensors, remote sensing platforms, and laboratory analyses to provide a comprehensive view of water quality conditions across a region. Integrated Water Quality Monitoring Systems (IWQMS) enhance water resource management by integrating multiple data sources to provide real-time and predictive insights. These systems use advanced technologies such as:

i. **Sensor networks:** Deploying in-situ sensors to measure key parameters like pH, dissolved oxygen, turbidity, and temperature. These sensors transmit data wirelessly to a central system for analysis (Bonansea et al., 2019).

ii. **Remote sensing and GIS:** Satellite and drone-based remote sensing help in large-scale monitoring of water bodies, detecting pollution sources, and tracking changes over time. GIS (Geographic Information Systems) further aids in mapping and visualizing water quality trends (Gupta and Srivastava, 2010).

iii. **Data analytics and AI:** Advanced algorithms process and analyze data from multiple sources, identifying patterns, predicting pollution events, and supporting decision-making for authorities (Hou et al., 2021).

iv. **Cloud-based platforms:** IWQMS often leverage cloud computing to store, process, and share data in real time, allowing access from anywhere for quick response and better collaboration among stakeholders (Buyya et al., 2018).

3. Challenges in Water Quality Monitoring

Despite the numerous advancements in monitoring techniques, several challenges remain in ensuring effective water quality monitoring programs.

i. **Sampling and spatial coverage:** In-situ testing and sample collection can be labor-intensive and limited in terms of geographic coverage. It is often not feasible to monitor every part of a water body at all times, leading to potential gaps in the data (Allan et al., 2006).

ii. **Pollutant complexity:** Some pollutants, such as pharmaceuticals, personal care products, and microplastics, are challenging to detect due to their low concentrations and diverse chemical structures. This makes it difficult to design standardized monitoring techniques for all pollutants (Lapworth et al., 2012).

iii. **Data interpretation:** The interpretation of large datasets from remote sensors and satellite imagery requires sophisticated algorithms and skilled personnel to ensure accuracy. Misinterpretation can result in flawed conclusions about water quality (Li et al., 2019).

iv. **Cost and resource constraints:** High-quality monitoring technologies, such as remote sensing and sensor-based systems, are often costly to implement and maintain. Limited financial resources hinder the establishment of comprehensive monitoring programs, particularly in low-income regions (UNEP, 2016).

4. Conclusion

Water quality monitoring is a critical process for safeguarding public health, protecting aquatic ecosystems, and ensuring sustainable management of water resources. The tools and techniques employed for pollutant detection, including chemical analysis, biological testing, remote sensing, and sensor technologies, play vital roles in detecting and monitoring contaminants. While advances in technology have greatly enhanced the capabilities of water quality monitoring, challenges related to sampling, pollutant complexity, data interpretation, and costs still persist. To ensure effective water management, it is necessary to integrate various monitoring methods and develop comprehensive systems that provide real-time, accurate data. As global awareness of water pollution grows, it is crucial to invest in and expand water quality monitoring programs worldwide. This will help protect water resources, mitigate the impacts of pollution, and support sustainable development. Moreover, the integration of community-based monitoring programs can play a significant role in enhancing water quality monitoring efforts. Local communities, through citizen science initiatives, can contribute valuable data, particularly in regions where resources for traditional monitoring are limited. Collaboration between governments, research institutions, industries, and the public is essential to address the multifaceted challenges of water pollution. Looking ahead, innovations in machine learning, artificial intelligence, and data analytics are poised to further revolutionize water quality monitoring by improving the accuracy, speed, and scalability of data analysis. These technologies can help predict pollution trends, identify emerging contaminants, and optimize resource allocation for mitigation efforts. Furthermore, increased global cooperation in sharing data and best practices can create more effective policies and interventions to reduce the harmful impacts of pollution on aquatic environments and public health.

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Chapter-6

Conservation and Biodiversity Protection: Sustainable Agriculture, Habitat Restoration and Pollution Control

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AUTHOR'S CONTRIBUTION

KS played a significant role in developing the concepts and framework for this research on biodiversity protection and sustainable development. KS conducted the main literature review, analyzed the data, and prepared the initial draft of the manuscript. VK contributed essential revisions and provided valuable insights to enhance the overall analysis.

ABSTRACT

Conservation and biodiversity protection are major concerns in the face of growing environmental degradation. In this chapter, we will study various aspects of biodiversity, such as sustainable agriculture, habitat restoration, and the impacts of increasing population, while also addressing future concerns through the analysis of relevant facts. Education and awareness play a crucial

role in biodiversity protection. By promoting conservation literacy and raising awareness about the consequences of unsustainable practices, individuals and communities can make informed choices and take responsible actions to protect the biodiversity. Sustainable agriculture is essential for ensuring food security, protecting the environment, and building resilient communities. Habitat restoration is an important conservation tool that aims to restore the original biodiversity, ecological functions and services that a habitat once provided. Population increases clearly contribute to biodiversity losses, so population decreases can aid in restoring biodiversity.

Keywords: Biodiversity, sustainable agriculture, habitat restoration, population

1. Introduction

Biodiversity protection and conservation is an important topic in the 21st century. It directly affects all species of animals and plants along with humans. Therefore, various types of rules and schemes are being implemented or planned to save biodiversity. At present, various types of conservation strategies such as establishment of protected areas, sustainable practices, restoration of habitats, public awareness, creation of plans, etc. should be adopted. Over 2000 different bird species, they make up 13% of world's population and 500 different animal species may be found in India's forest.

India is an excellent home for fauna, much like it is for its flora. The country hosts approximately 2,546 species of fish, representing about 12% of the global total. In addition, India harbors around 7.6% of the world's mammalian species, 6.2% of reptile species, and 4.4% of amphibian species (Wikipedia contributors, n.d.). Preserving biodiversity requires establishing appropriate indicators to assess its status within ecosystems, which in turn helps in developing effective strategies for the conservation of biodiversity, its functions, and services (Hoban et al., 2021).

2. Conservation Ethics

As the most sentient and sociable species on the planet, humans often exploit animals for their own benefit or financial gain. However, it is unjustifiable for individuals to harm or profit from biodiversity, as such actions can have detrimental effects on ecosystems. Imagining a world where all animals and plants have disappeared, leaving only humans, illustrates how disastrous the consequences would be. Therefore, moral norms should be upheld by all, particularly by humans, given their unique capacity for ethical reasoning and responsibility.

Ethical principles play a crucial role in conserving biodiversity to protect the environment and promote long-term sustainable existence on Earth. Two key perspectives-holistic environmental ethics and extensionist environmental ethics are often discussed to better understand the ethical dimensions of conservation. Holistic environmental ethics emphasize the intrinsic value of ecological systems as a whole, including relationships, levels of organization, species, and individuals. In contrast, extensionist ethics extend moral consideration to non-human animals, recognizing that some species possess cognitive and emotional traits that may, in certain respects, even surpass those of humans.

3. Sustainable Agriculture

Agriculture is serving as an important pillar of the global economy. It is a source of foods, fibers and, increasingly, fuel. It provides livelihoods and subsistence for the largest number of people worldwide. It is vital to rural development and therefore critical to poverty alleviation. Cultivated land, including arable lands and shifting cultivation, covers approximately 24 percent of the world's land area (Hasan et al., 2018).

Sustainable agriculture is essential for ensuring food security, protecting the environment, and building resilient communities. Agriculture's impact on biodiversity (genetic, species, and ecosystem) has emerged as a major environmental concern. Sustainable agricultural techniques can lessen environmental stresses, increase species variety, and improve habitat quality. By reducing chemical inputs and providing a variety of ecological niches, systems like agroforestry and organic farming are able to support a wide variety of plant and animal species. Soil health is improved and habitat disruption is minimized through practices such as conservation tillage and integrated pest management, contributing to a more resilient ecosystem (Pankaj et al., 2023; Babu et al., 2023). Current agricultural land management techniques continue to have an impact on biodiversity. For example, agriculture production systems with low crop rotation result in enormous areas of uniform habitat, limiting biodiversity. Water pouring from agricultural fields can carry nutrients, eroded sediments, and pesticides to downstream areas, impacting aquatic biodiversity. Diverse Agro- ecosystems not only benefit humanity but also play a crucial role in supporting the balance of ecosystems worldwide. Organic farming supports greater diversity of plant and animal species compared to conventional agriculture, reduces greenhouse gas emissions, which is crucial for combating climate change and offers significant health benefits to consumers by providing food that is richer in nutrients. By promoting and supporting organic agriculture, we can achieve a sustainable balance between food production and the conservation of natural resources, ensuring long-term sustainability, environmental health, and biodiversity conservation on our planet. (Stevanović et al.,2024). Biodiversity conservation and management are paramount as they directly impact the suitability and resilience of ecosystems, ultimately affecting the livelihoods of both human and non-human species (Muruganandam, 2024). Agricultural activities have had a significant impact on wetland ecosystems. Many of the impacted species are migratory; habitat changes have a direct impact on ducks, geese, swans, shorebirds, songbirds, and butterflies. Documenting the historical impact of agriculture on biodiversity reveals that, while many agricultural practices have led to habitat loss and species decline, certain methods can enhance biodiversity and improve wildlife habitats. Practices that support pollinator species, natural pest predators, and soil fauna, along with the preservation of habitats such as wetlands, offer direct environmental benefits. These include conserving groundwater and increasing resilience to drought conditions. Healthy soils are rich in diverse microorganisms that support plant growth and contribute to overall ecosystem health. Natural enemies of insects play a crucial role in maintaining ecological balance. Predators and parasites help regulate pest populations, thereby reducing crop losses and decreasing dependence on chemical pesticides (Chen, 2025).

Agriculture contributes to the increase in greenhouse gas emissions through various land-use practices, including carbon dioxide (CO_2) emissions from deforestation, methane emissions from rice cultivation and enteric fermentation in livestock, and nitrous oxide emissions from fertilizer application. To meet the demands of a growing global population, agriculture in the coming decade must adopt Conservation Agriculture techniques that enable the sustainable production of more food from less land. This requires the efficient use of natural resources while minimizing environmental impact (Uwase and Mupenzi, 2024).

4. Habitat Restoration

Habitat restoration is the process of assisting an ecosystem's recovery after it has been degraded, damaged, or destroyed. It is an important conservation tool that aims to restore the original biodiversity, ecological functions, and services that a habitat once provided. Habitat provides refuge from predators and influences the physical traits of prey, as they adapt their surroundings for protection (Lennox et al., 2025). Ultimately, protecting biodiversity is not only about conserving species and habitats; it also involves preserving the cultural narratives and traditions that connect communities to their natural environments (Rathoure et al., 2024). Ecosystem collapse and biodiversity loss are driven by factors such as invasive species, pollution, climate change, and deforestation, all of which are tearing at the fabric of natural habitats. Successful ecological recovery requires not only the restoration of biodiversity but also the reestablishment of ecological processes and functions that are essential for ecosystem stability (Aronson et al., 2020).

Habitat loss leads to a range of negative consequences, including the loss of biodiversity, reduced ecosystem services, soil erosion and degradation, water pollution, and intensified impacts of climate change. Habitat restoration is crucial for maintaining ecological balance, protecting biodiversity, and ensuring the continued provision of essential ecosystem services. Mangrove forest restoration, for example, can significantly enhance the functions and services of adjacent coastal ecosystems. However, the effectiveness of such efforts greatly depends on understanding the specific locations and habitat requirements of target species within the given landscape (Worthington and Spalding, 2023).

The methods used for habitat restoration vary depending on the extent of damage and the topography of the ecosystem. Reforestation and afforestation help restore biodiversity, prevent soil erosion, and increase species richness. In wetland restoration, removing invasive species, maintaining natural water flow and replanting native vegetation are critical actions. Additionally, reintroducing native flora and fauna plays a vital role in restoring ecological balance.

Coral reefs, in particular, are severely threatened by climate change and other local stressors, such as overfishing and pollution, which compromise their structural integrity and reduce habitat availability. Coral reef restoration is essential for maintaining healthy, sustainable marine ecosystems (Vida et al., 2024). These efforts aim to create self-sustaining reefs that provide habitat for marine life and protect coastlines. However, challenges such as land-based pollution, disease, predation, algae overgrowth, sedimentation, and climate change continue to hinder restoration success. Restoration techniques include coral aquaculture, growing young coral fragments in controlled environments, propagating live coral in nurseries, and coral breeding. Coral reefs, along with seagrass beds and salt marshes, are vital in maintaining ecological balance. Together, they offer critical ecosystem services, such as habitat provision, food, shade, medicinal resources, industrial products, coastal protection and carbon sequestration (Ranasinghe, 2024). The Mithapur Coral Reef Restoration Project aims to strengthen the marine ecosystem and is being implemented in partnership with the Wildlife Trust of India and the State Forest Department. This initiative is expected to serve as a model for similar marine conservation projects across the country (Wildlife Trust of India, 2024).

Grassland restoration plays a vital role in rejuvenating ecosystems, enhancing biodiversity, and mitigating the effects of climate change. This process typically involves the replanting of native vegetation and the removal of invasive species to restore ecological balance (Sharma et al., 2024). Beyond supporting wildlife, restored grasslands contribute significantly to improving soil health and increasing carbon sequestration, making them essential for climate resilience (Kumar and Joshi, 2023). Riparian areas are transitional zones between land and freshwater ecosystems that are critically important for maintaining water quality and serving as wildlife corridors. These areas offer economic, ecological, and cultural benefits (Graziano et al., 2022). However, human activities such as urban development, agriculture, and deforestation have severely degraded or destroyed riverine and

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floodplain habitats, threatening both aquatic and terrestrial biodiversity (Sharma et al., 2022).

Reconnecting wetlands and estuarine systems is essential for restoring natural water flow, enhancing nutrient filtration, and providing shelter and food for juvenile aquatic organisms (Das and Mishra, 2024). Recognizing the importance of these ecosystems, The Nature Conservancy India launched its first-ever Riparian Restoration Guidefor the Narmada River. This guide is intended not only for the conservation of the Narmada but also as a reference for riparian restoration across other rivers in India (The Nature Conservancy India, 2024).

Riparian zones are among the most productive ecosystems and offer high-quality habitats for numerous species. Many terrestrial animals including several threatened species that depend on riparian habitats for foraging, breeding, and shelter (Rathore and Singh, 2023). Moreover, healthy riparian areas support aquatic ecosystems by providing critical habitat for native fish, invertebrates, amphibians, and particularly frogs. Effective riparian management significantly reduces key threats to these aquatic species such as sedimentation, temperature rise, and pollution-through vegetation buffering and habitat stabilization (Gu et al., 2025). Coastal habitat restoration is a powerful strategy for mitigating the loss of habitat-forming species, which play crucial roles in providing protection and essential habitats for fisheries. However, their ability to sustain these services is increasingly threatened by emerging stressors, particularly rising temperatures (Hensel et al., 2024).

5. Pollution Control

Human overpopulation is a major driver of biodiversity loss and presents a key obstacle to equitably sharing habitat and essential resources with other species. Addressing population issues may be challenging, but failing to do so undermines broader conservation efforts (Cafaro et al., 2022; IPBES, 2019). In the past, environmental changes unfolded gradually, but accelerated population growth has drastically increased the pace of environmental transformation.

An increasing population clearly contributes to biodiversity loss, while population reduction can aid in restoring biodiversity. The decline in biodiversity and wildlife populations represents an urgent environmental crisis with devastating consequences for ecosystems and human health. Consequently, the protection of wildlife and biodiversity has become one of humanity's most critical goals, not only to safeguard human health but also to ensure environmental, economic, and social well-being (Spentzou et al., 2025). The last great mass extinction was 65 million years ago, at the end of the Cretaceous, when the dinosaurs went extinct. The IUCN estimates that 22% of known mammals, 32% of amphibians, 14% of birds, and 32% of gymnosperms, all well-studied groups are threatened with extinction. Over the past hundred years, the human population has grown from 2 billion to nearly 8 billion, and the United Nations (2019) projects an increase of 3 billion more by 2100, unless effective measures are taken to curb this growth. Ignoring this projected increase means overlooking a major driver of the ongoing biodiversity crisis. Due to human impact, many once-continuous habitats are being reduced in size or fragmented into isolated patches. This fragmentation divides species into smaller populations that may not be viable in the long term. It also creates barriers that limit the ability of species to disperse and colonize new areas. As the human population grows, increasing amounts of forest are cleared, reducing the number of trees that help combat air pollution through photosynthesis. Consequently, the diminished capacity of forests to purify the air contributes to rising pollution levels, which cause the deaths of thousands of people each year.

6. Conclusion

Sustainable agriculture and biodiversity conservation are deeply interconnected, each reinforcing the other. Sustainable agricultural practices help preserve and enhance biodiversity, while healthy ecosystems support resilient and productive farming systems. Education and awareness are vital components of biodiversity protection. By fostering conservation literacy and highlighting the consequences of unsustainable practices, individuals and communities are empowered to make informed decisions and take meaningful actions. Environmental protection requires a multifaceted approach that includes government policies, international cooperation, community engagement, and individual responsibility. Governments play a key role by enacting and enforcing laws, regulating industrial activities, and promoting sustainable development (Chauhan, 2025). Together, these collective efforts are essential for safeguarding biodiversity and ensuring a sustainable future for both people and the planet.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-7

Impact of Heavy Metals on Aquatic Flora and Fauna: Fresh and Marine Water Perspective

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AUTHOR'S CONTRIBUTION

This chapter is a combined effort of three authors. MY drafted the chapter, while MB and SM assisted in searching references and formatting the manuscript. MB reviewed the first draft and suggested changes and MY finalized the draft. All authors approved the final version.

ABSTRACT

Aquatic ecosystems are among the most vulnerable to heavy metal contamination due to the persistent discharge of industrial effluents, mining runoff, agricultural leachates and urban waste water. Heavy metal pollution is a major environmental concern affecting soil health and ecosystem stability. Pollutants such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As) and chromium (Cr) are non-biodegradable and tend to accumulate in water

bodies, sediments, aquatic plants and animals, often entering and magnifying through the food chain. Once present in aquatic environments, heavy metals persists and leading to bioaccumulation and biomagnifications across tropic level. Heavy metals exert toxic effects on aquatic flora, including algae, phytoplankton, and submerged plants, as well as on aquatic fauna such as invertebrates, fish, and amphibians. These effects include physiological and biochemical stress responses, disruptions in reproduction and behavior, and alterations in species composition and ecosystem functioning. In fresh water, aquatic plants and animals experience physiological stress, reduced reproductive success and altered community structure due to metal toxicity. In marine environments, heavy metals disrupt phytoplankton dynamics, coral health and the survival economically important fish and invertebrates. Both ecosystems show evidence of trophic transfer and biomagnifications, resulting in ecological imbalances and potential human health risks through seafood consumption.

This chapter provides a comparative analysis of heavy metals affect aquatic flora and fauna in freshwater and marine ecosystems, detailing mechanisms of toxicity, ecological consequences and species level response.

Keywords: Biomagnifications, aquatic fauna, aquatic flora, phytoplankton, invertebrates

1. Introduction

Aquatic ecosystems both freshwater and marine are crucial for maintaining global diversity, regulating climate and supporting millions of livelihoods through fisheries, aquaculture and agriculture. However these ecosystems are increasingly threatened by wide range pollutants among which heavy metals represent a particularly persistent and hazardous. Heavy metal pollution has emerged as one of the most pressing environmental concerns due to rapid industrialization, urban runoff, agricultural discharge and mining activities. Some organic pollutants, heavy metal such as lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As) and chromium (Cr) are non-biodegradable and can persist in water bodies and sediments for long periods, leading to chronic contamination and ecological imbalances (Ali et al., 2019, Singh et al., 2018). Heavy metals enter aquatic environments through various anthropogenic activities such as urban waste water and atmospheric deposition. Once introduced, these metals interact with the physical, chemical and biological components of the ecosystem, altering water quality, sediment and food web dynamics (Forstner and Wittmann, 2012). In aquatic ecosystems, heavy metals can have detrimental effects on both flora and fauna. Aquatic plants are sensitive to metal toxicity (Liu et al., 2020).

Aquatic flora including phytoplankton, algae and submerged macrophytes are often the first organisms to experience the toxic effects of heavy metals. These effects range from inhibited photosynthesis and oxidative stress to reduced growth and biodiversity shifts, ultimately affecting primary productivity. It plays a foundational role in aquatic ecosystems by contributing to primary production, oxygen generation and nutrient cycling. These organisms are highly sensitive to heavy metal contamination, which can significantly disrupt their physiological, biochemical and ecological function. Aquatic plants play crucial role in primary productivity, nutrient cycling and providing habitat and food for aquatic organisms. Heavy metal contamination can severely impact these organisms at both physiological and biological levels. Metals can inhibit photosynthesis by interfering with damaging photo systems and disrupting the electron transport chain (Liu et al., 2020). Cadmium exposure in algae has been shown to reduce pigment concentration and carbon fixation, ultimately leading to reduced growth and productivity. Additionally heavy metals can interfere with nutrient uptake and enzymatic activities in aquatic plants. Metals such as copper and zinc although essential become phytotoxic when concentrations exceed tolerance thresholds. Their excess can lead to oxidative stress by generative reactive oxygen species, which damage lipids, proteins and DNA.

Aquatic fauna such as zooplankton, mollusc, crustaceans, fish and amphibians also exhibit a wide range of toxicological response including bioaccumulation, reproductive failure, immune suppression and behavioural change (Shahid et al., 2020). Fresh water ecosystem, due to their relatively closed nature and lower buffering capacity, tend to exhibit more acute symptoms of heavy metal contamination. In contrast, marine ecosystem, although more dynamic and ecosystem. Heavy metals enter aquatic systems through various natural and anthropogenic processes. Natural sources include weathering of rocks and volcanic activity, but anthropogenic activities have dramatically accelerated metal input into environment. Once introduced into aquatic ecosystems, heavy metal exhibit complex behaviour: they can exist in dissolved forms, bind to suspended particles or precipitate.

2. Difference between Fresh Water and Marine Water

Fresh water and marine water environments differ significantly in their physical, chemical and biological characteristics, which influence the fate and toxicity of heavy metals. Fresh water systems especially rivers, lakes and wetlands are often enclosed or semi enclosed and receive substantial inputs from terrestrial sources. These systems typically have lower ionic strength and buffering capacity, making them more susceptible to pH changes that effect metal solubility and speciation.

Marine environment, in contrast contain higher concentrations of salts and other ions, which can complex with metals and reduce their ionic forms the most toxic species. For instance, chloride ions in seawater can form complexes with metals such as silver and mercury, decreasing their bioavailability. However, this protective effect can be overridden in coastal areas where anthropogenic pollution is intense. In term of biological response, species inhabiting marine systems may have evolved greater tolerance to certain metal exposures due to naturally higher background levels of salts and metals. Pollution induced changes in species composition, community structure and ecosystem functions have been widely documented in both freshwater and marine water.

3. Sources and Pathways of Heavy Metals in Aquatic System

3.1 Industrial discharge and mining effluents

Industries such as metal plating, battery manufacturing, mining, textiles, tanneries and electroplating are significant sources of heavy metals such as cadmium, lead, chromium and mercury. Wastewater discharge from these facilities often enters nearby rivers, lakes and coastal waters without adequate treatment. Mining operations release large amounts of tailings and leachates containing arsenic, lead and other metals. Acid mine drainage from exposed rocks can further mobilize metals into adjacent freshwater and marine system.

3.2 Agriculture runoff and pesticides residues

The use of metal based pesticides, fertilizers and manure introduces elements such as copper, zinc and arsenic into agricultural soils. During rainfall, these metals are washed into streams, rivers and estuaries by surface runoff. Storm water from urban areas collects vehicle emissions, paints, construction materials and sewage effluents transporting metals such as nickel, lead and chromium into aquatic system.

3.3 Atmospheric deposition and sediment resuspension

The combustion of fossil fuels and waste incineration releases heavy metals into the atmosphere, which can travel long distances before being deposited into water bodies through wet and dry deposition.

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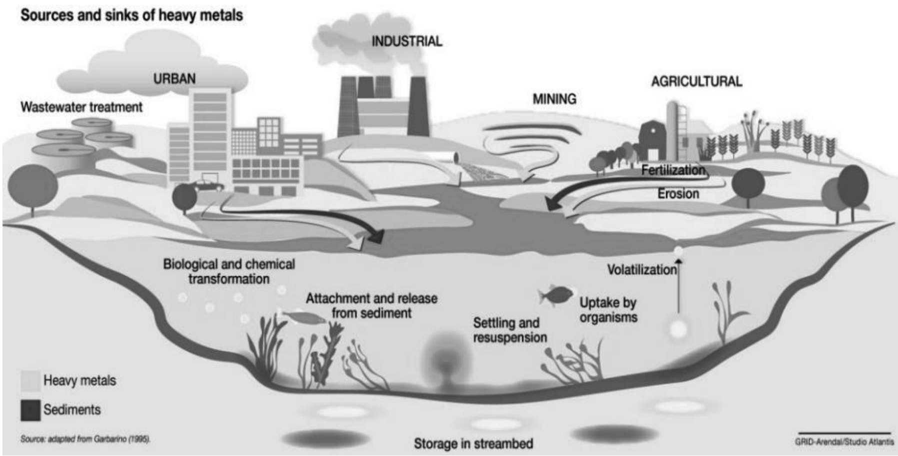

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4. Impact on Aquatic Flora

Aquatic flora such as phytoplankton, algae, submerged plants and macrophytes form the foundation of aquatic ecosystems by driving primary productivity and contributing to oxygenation. However, these plant communities are highly sensitive to heavy metal contamination. Exposure to metals such as cadmium (Cd), lead (Pb) and mercury (Hg) can disrupt cellular metabolism, photosynthesis and nutrient uptake. Heavy metals interfere with chlorophyll content and photosynthetic efficiency, leading to reduced growth and productivity. While metals like copper (Cu) and zinc (Zn) are essential in trace amounts, they become toxic at elevated concentrations, causing oxidative stress and membrane damage in plant cells. This can result in symptoms such as chlorosis, necrosis and reduced reproductive success.

In both freshwater and marine systems, heavy metal toxicity can also lead to shifts in species composition, favoring metal-tolerant species and reducing overall biodiversity. For example, certain cyanobacteria or metal-tolerant algae may dominate, altering food web dynamics and diminishing the habitat value of the ecosystem (Sinha et al., 2007).

5. Impact on Aquatic Fauna

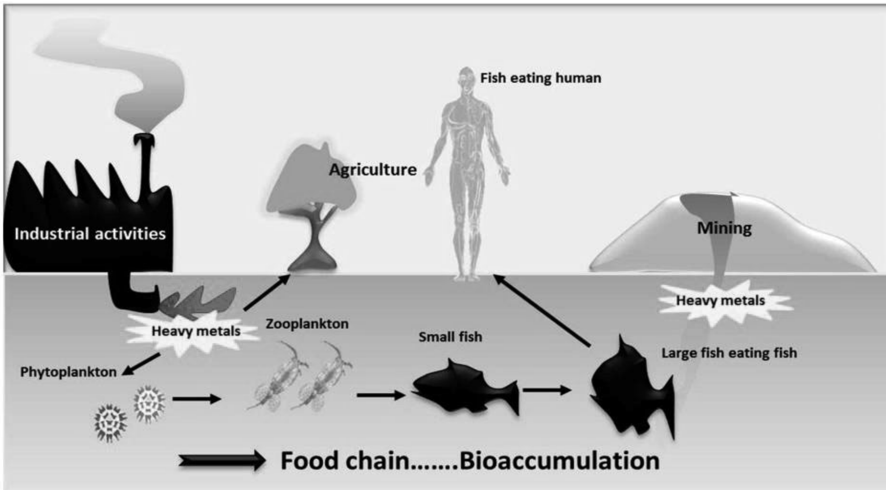
Aquatic fauna such as zooplankton, crustaceans and fish are particularly vulnerable to heavy metal exposure due to direct contact with contaminated water and sediment, as well as through the food chain. Heavy metals tend to bioaccumulate in the tissues and organs of aquatic animals and, in many cases, become biomagnified, affecting predators at higher trophic levels. In both freshwater and marine species, heavy metals can cause a range of toxicological effects, including gill damage and respiratory distress, oxidative stress and mitochondrial dysfunction, reproductive toxicity and immunosuppression.

For example, mercury is particularly harmful due to its transformation into methyl mercury, a highly toxic compound that accumulates in predatory fish and poses serious health risks to both humans and wildlife. Lead exposure can impair neurological development in aquatic vertebrates, while cadmium can damage kidneys and skeletal structures in fish and amphibians (Burger et al., 2002).

6. Assessment Approaches

6.1 Bioaccumulation

Bioaccumulation refers to the gradual build-up of substances, such as heavy metals or chemicals, within living organisms over time. This process can occur through various routes of exposure, including direct contact with contaminated air, water and soil or through consuming contaminated food.



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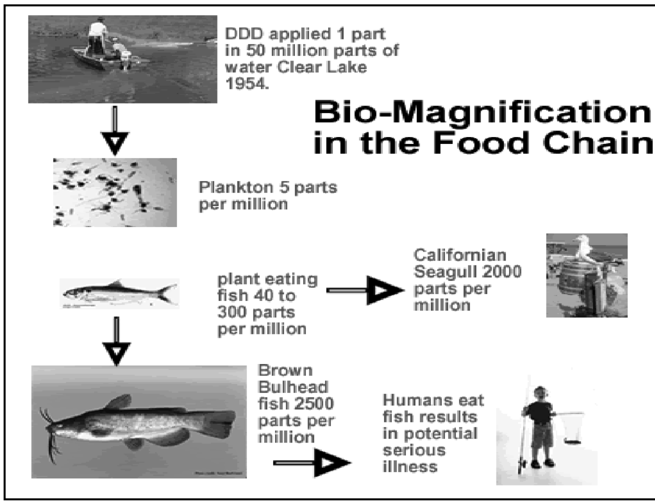
Trophic transfer and biomagnifications

Trophic levels refer to the positions that organisms occupy in a food chain. When a predator consumes prey, substances present in the prey such as mercury or pesticides are transferred to the predator.

6.2 Biomagnification

Biomagnification is the process by which the concentration of certain pollutants increases as they move up through the food chain. Unlike essential nutrients, some toxic substances such as DDT (dichloro diphenyl trichloroethane), PCBs (polychlorinated biphenyls) and mercury are not easily broken down or excreted by organisms. As a result, these pollutants accumulate over time, particularly at higher trophic levels. Top predators often exhibit the highest concentrations of these substances because they consume many prey organisms, each carrying small amounts of the pollutants.

For example, phytoplankton absorbs mercury from the surrounding water. Small fish feed on large quantities of phytoplankton and accumulate mercury in their tissues. Larger fish then consume these smaller fish, further concentrating the mercury. Eventually, humans who consume large predatory fish such as tuna may ingest harmful levels of mercury.



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7. Remediation and Mitigation Approaches

7.1 In Flora

Phytoremediation: Phytoremediation is a plant-based technology that utilizes the natural processes of vegetation to contain, remove, or render harmless contaminants in soil, water and air. It has emerged as a practical and eco-friendly solution for remediating heavy metal-polluted environments due to its cost-effectiveness, environmental compatibility and its ability to improve soil structure and fertility (Salt et al., 1995).

This technique involves the use of green plants and their associated microorganisms to stabilize or reduce contamination in soil, sediments, groundwater, and surface water. Phytoremediation includes various mechanisms depending on the type of contaminant and plant species involved:

- Phytoextraction: Uptake and accumulation of contaminants in plant tissues.
- Phytostabilization: Immobilization of contaminants in the root zone.
- Rhizofiltration: Absorption or adsorption of contaminants by plant roots in water.
- Phytovolatilization: Transformation and release of contaminants into the atmosphere through transpiration.

Case study: Use of sunflowers at chernobyl

Following the Chernobyl nuclear disaster in 1986, one of the most notable applications of phytoremediation involved planting sunflower (*Helianthus annuus*) to extract radioactive cesium and strontium from contaminated water and soil. Sunflowers were chosen for their fast growth, high biomass and strong ability to accumulate heavy metals and radionuclides. Within two weeks, a measurable decrease in metal concentrations was observed in the water and soil. This case study demonstrates the effectiveness of phytoremediation and its potential applicability to other polluted sites.

7.2 In Fauna

Habitat restoration: Habitat restoration plays a crucial role in mitigating the impact of heavy metal contamination on aquatic fauna. It involves rehabilitating ecosystems that have been degraded, fragmented or contaminated, with the goal of supporting the recovery and long-term survival of animal populations.

Key components of this approach include:

- Removal of contaminated sediments to reduce direct exposure to heavy metals.
- Rehabilitation of degraded habitats to promote biodiversity and restore ecological balance.

- Re-establishment of healthy food webs to prevent the biomagnification of toxins.

Habitat restoration helps reduce pollutant exposure, interrupts the trophic transfer of contaminants, and supports the maintenance of essential ecosystem functions and biodiversity.

8. Policy and Conservation Implications

- **Regulation of persistent pollutants:** Implement strict controls on the release of long-lasting toxic substances into the environment.
- **Environmental monitoring frameworks:** Establish and enforce systems to monitor and regulate bioaccumulative substances in ecosystems.
- **Protection of top predators and keystone species:** Prioritize conservation efforts for species that play critical roles in maintaining ecological balance.
- **Restoration of contaminated habitats:** Rehabilitate ecosystems affected by heavy metal and chemical pollution to support biodiversity recovery.
- **Reduction of mercury emissions:** Implement measures to reduce and control mercury use and emissions, thereby preventing its biomagnification in food chains.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-8

Regulation and Global Policies: Environmental Laws, International Treaties and Regulatory Framework

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AUTHOR'S CONTRIBUTION

MP prepared the abstract and introduction, highlighting the significance of environmental governance and its contextual background. They also contributed to the section on important environmental laws by analyzing national and regional frameworks, and concluded the paper by synthesizing key insights and future directions. RA focused on waste disposal methods, evaluating sustainable practices within regulatory contexts, and developed the section on global policies by examining major international treaties and agreements such as the Paris Agreement and Basel Convention. Additionally, she also reviewed and edited the manuscript for clarity, coherence, and academic quality.

ABSTRACT

To regulate the environmental protection and sustainability has become the topic of main concern in global governance with a growing recognition of the need to address transnational environmental challenges. Environmental laws, international treaties and regulatory frameworks had played a crucial role in making the drastic changes in environment less effective in nature. To conserve bio-diversity, and ensuring sustainable development, national environmental laws has been set for local governance, while international treaties like The Paris Agreement, The Kyoto Protocol, The Stockholm Convention on persistent organic pollutants, and the Convention on Biological Diversity targets to create a collective response to environmental degradation. With the help of these treaties co-operation between countries, harmonize standards and binding commitments established to reduce harm on environment. Furthermore, a regulatory framework, within countries as well as globally, are evolving to comprise environmental, social, and governance (ESG) considerations, leading to more imperishable business practice and the incorporation of environmental protection into the global economy. However challenges remain in ensuring amenability, implementing regulations, and reconciling national interests with international goals. This abstract explores the dynamic interaction between national environmental laws, international treaties, and global regulatory frameworks accentuating their importance in addressing the most pressing environmental issues facing the planet today.

Keywords: Environmental laws, bio-diversity, conservation acts, pollution, global policies.

1. Introduction

Environmental laws are regulations and legal principles that targets to protect the environmental laws and promotes sustainability. These laws address a wide range of issues such as air and water quality, waste management, wildlife conservation, land use, and climate change. Global policies on the environment refer to international agreements, treaties, and strategies. Traditionally environmental policies have been associated with controlling pollution, limiting natural habitat loss, managing waste, and reducing the impact of natural hazards (Connely et al.,2012). The major global policies aimed at addressing environmental issues that transcend national borders, such as climate change, biodiversity loss, and pollution. In short, an environmental policy addresses the complex, reciprocal links between modern society, the economy and the environment, making it unique among policy areas (Ingram and Mann, 1983). The recognition that the increased pace, scale, and magnitude of contemporary human activity has pervasively affected the natural environment has been an important deliver of environmental policy since the 1960s. Achieving a harmonious balance between society, the economy, and environmental system is the main aim on sustainable development, the key concept for organizing environmental policy (Jordan and Adger, 2009).

2. Important Environmental laws in India

One of India's first legislation pertaining to environmental protection was the Forest Act of 1865. But it's important to remember that the idea of environmental protection has changed throughout time, and later laws have greatly influenced the development of environmental legislation in India. An early attempt at environmental preservation in India particularly focused on forests was the Forest Act of 1865, also known as Act VIII of 1865 (Sekar, 2024). With varying degrees of resource use limitations, it established the idea of classifying forests into "protected" and "reserved" areas (Venkataraman, 2009). It's important to understand that India's current environmental laws have changed as a result of later laws such as the Environment

(Protection) Act (1986), the Air (Prevention and Control of Pollution) Act (1981) and the Water (Prevention and Control of Pollution) Act (1974). Among other things, these regulations have raised the extent of environmental protection in India (Chand, 2018).

i. **Forest protection act, 1980**: In order to prevent deforestation, the Forest (Conservation) Act, 1980 was passed. According to this Act, forest destruction and the use of forest land for purposes other than forests are unlawful without preceding the Central Government approval. Weak forest governance accelerates deforestation, diverseness loss, injury to ecosystems, and land erosion (Elizalde and Schroeder, 2011). It also roots with loss of revenues, destruction of vulnerable and protected forests, and deterioration of moral values for law and chaos in society. For the benefit of the public; the Act must be firmly enforced with the goal to fulfil its lofty aim. It is evident that India has many laws pertaining to environmental protection. However, the way these laws have been enforced has been far from ideal. The other environmental laws and the constitutional obligation must be enforced successfully and effectively (Dash and Kothari, 2013).

ii. **Wildlife protection act, 1972**: In order to safeguard wild animals, birds, and plants, the Wild Life (Protection) Act of 1972 was passed. It provides legal protection to wild animals, birds and plants by creating six schedules that classify species based on the degree of protection needed. Additionally, the Act forbids the removal, destruction, damage, or selecting of any specific plant from any forest. According to the Act, the State animals Advisory Board is to counsel the State government on the creation of policies for the preservation and conservation of animals and certain flora, as well as the choice of which puts to designate as national parks, sanctuaries, protected areas etc. A director of wildlife preservation, chief wildlife warden, along with other wardens and their staff, supervise the administration of the act. The largest threat to the preservation of wild life is the commerce in wild life. Demands in global markets are the main cause of the widespread poaching of wildlife and its products. The Act has been amended several times to strengthen punishments for violations, address illegal trade, and expand protection to marine ecosystems. Initially, only the state legislature had constitutional authority over wild animals and birds, which were listed in schedule VII. Several state legislatures adopted resolutions under Article 252 of the constitution to address this challenge. These resolutions gave the parliament the authority to pass the necessary legislation for India's wildlife conservation. It remains a crucial tool for India's environmental governance (Choudhary, 2024; Krishnan, 1973). Environmental regulatory agencies in India were developed after the constitution was established. This framework has enabled a system of environmental governance that is regulated at the national level and coordinated at the state level.

iii. **Environment protection act, 1986**: The Environment (Protection) Act (EPA) was passed in the year 1986 in order to protect and improve the quality of the environment, as well as to prevent, regulate, and mitigate environmental pollution. The EPA, 1986 was enforced soon after the Bhopal Gas Tragedy which was a major leak of toxic chemical gases occurred from the Union Carbide chemical plant in the city of Bhopal in 1984 and is considered an umbrella legislation as it fills many gaps in the existing laws. The Ministry of Environment and Forestry (MoEF) was designated as the nodal regulating agency (Malik and Dutta, 2005). Consequently, as the issue started to emerge, more laws were created. The Bhopal disaster underlines the problem governments confront in formulating a response to disaster situations when poverty levels are high and health infrastructures and government resources are severely limited. This brings into focus the need for private multinational (or public) industries to take some responsibility towards the environments and populations (Singh and Mishra, 1996).

iv. **Water (prevention and control of pollution) act, 1974**: Water is the important source of life.The Water (Prevention and Control of Pollution) Act of 1974 is a landmark environmental law enacted by the Indian Parliament designed to combat water pollution and preserve the purity or "wholesomeness"of both surface and groundwater across the country. It empowers the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs) to enforce effluent standards, regulate discharges into water bodies, monitor pollution levels, and impose penalties for violations. To fund enforcement and pollution abatement efforts, the Act was supplemented by the Cess Act of 1977, which imposes a cess on water consumption by industrial users. Since its origin in 1974, the legislation has undergone amendments to strengthen its measures, notably in 1988 and later updates including enhanced enforcement procedures introduced in recent years (Prasad, 2006; Chand, 2018; Central Pollution Control Board).

v. **Biological diversity act, 2002**: In order to encourage the preservation of biological diversity, the sustainable use of its constituent parts, and the fair distribution of advantages resulting from the utilization of biological resources, India approved the Biological diversity Act, 2002. India has passed the Biological Diversity Act, 2002 to promote conservation of biological diversity, sustainable use of its components and equitable sharing of benefits arising out of the use of biological resources. However, a thorough examination shows that the Act would significantly impede biodiversity research in India, particularly in the areas of taxonomy, both statistically and qualitatively (Dar et al., 2012; Venkataraman, 2009).

vi. **National forest policy, 1988**: The national objective should be to have at least one-third of the country's land area covered by forests, according to the current national forest policy. Maintaining two-thirds of the land under such cover in hilly and mountainous areas should be the goal in order to stop erosion and land degradation and to keep delicate ecosystems stable. By conserving and conserving forests, the NFP 1988 also placed a strong focus on preserving environmental stability and re-establishing ecological balance. The preservation of the nation's biological diversity and natural heritage, boosting the productivity of damaged forests, and attending to local needs while promoting participation are the policy's other primary goals. The derivation of direct economic benefit is to be sub-ordinate to this objective (Joshi et al., 2011; Turyahabwe and Banana, 2008).

vii. **3R's Environmental policy and solid waste management**: The disposal of garbage has become a significant environmental problem in the country, one that affects everyone rather than just a single individual. Ignoring the issue will not solve it, and the "out of sight, out of mind" mentality cannot address our nation's ever-increasing waste problem. Effective strategies for recycling, reducing, and reusing materials must be developed to manage this challenge (Figure 1). Educating children, our most valuable resource, about these practices is equally important, as it helps instill sustainable habits they can apply in their homes and communities (Gosh et al., 2021).

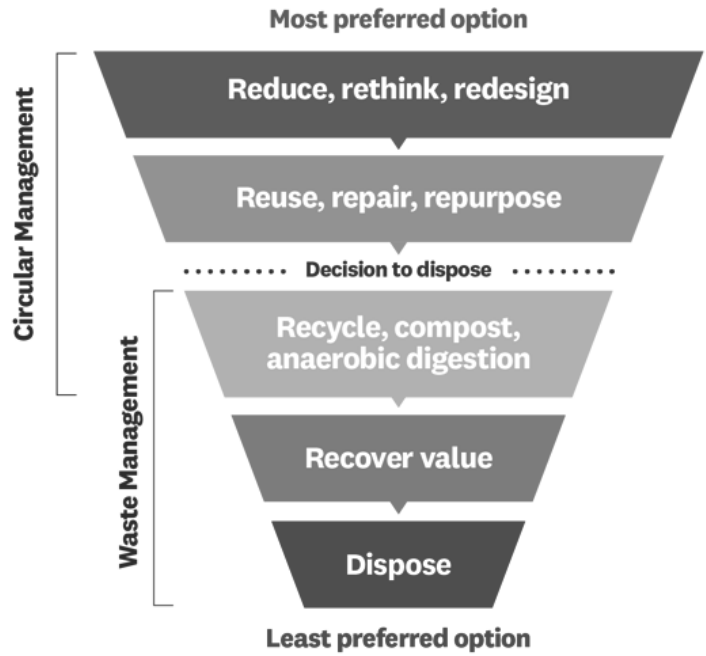

Figure 1: Figure shows the hierarchy of waste management.

(Source: https://www.wastenothing.co.nz/our-zero-waste-journey/waste-hierarchy.)

3. Methods of Solid Waste Disposal in India

i. **Open dumping and non-sanitary landfills:** A dominant yet unscientific practice in Indian cities, especially smaller urban centers which poses grave environmental and health hazards through water, air, and soil pollution. ~70–90% of unsorted municipal solid waste ends up in open dumpsites or inadequately managed landfills (Mor and Ravindra, 2023).

ii. **Scientific or sanitary landfills**: Engineered landfills following guidelines (e.g., CPCB, CPHEEO) are laid for more controlled and safer option, though implementation across the country remains limited (Kulkarni, 2020).

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iii. **Composting (Aerobic decomposition)**: It's an effective way to manage organic waste by turning it into valuable manure, especially suitable in Indian contexts with large volumes of biodegradable wastes (Verma and Bisen, 2020).

iv. **Vermicomposting:** Uses earthworms to accelerate decomposition and produce high-quality compost. The method has proved to reduce nitrogen loss and greenhouse gas emissions compared to standard composting methods (Verma and Bisen, 2020).

v. **Anaerobic digestion / biogas production:** Organic waste is converted into biogas and organic fertilizer through anaerobic processes, an energy-generating and eco-friendly disposal method receiving attention in policy discussions (Verma and Bisen, 2020).

vi. **Refuse-Derived Fuel (RDF) / Waste-to-Energy (WtE):** Waste, or its recyclable fractions, are processed into fuel or energy (e.g., RDF, incineration, pyrolysis), helping reduce landfill dependence and recover energy (Verma and Bisen, 2020; (Mor and Ravindra, 2023; Pujara et al., 2019).

vii. **Plasma gasification (Advanced thermal treatment):** A cutting-edge method that breaks down waste at high temperatures into syngas and inert slag, scientifically efficient but not yet widely adopted in India (Verma and Bisen, 2020).

viii. **Resource recovery & utilization of inert waste:** Inert components (e.g., demolition debris, ash, glass) are repurposed - used in road construction, bricks, tiles, or as aggregates enhancing sustainability (Thakur et al., 2021).

ix. **Integrated Solid Waste Management (ISWM)**: This holistic framework combines several methods such as landfilling, composting, anaerobic digestion, RDF, material recovery facilities etc., to optimize waste treatment and minimize environmental impact (Pujara et al., 2019).

x. **Smart collection, transport and segmenting technologies:** Modern approaches enhance waste handling efficiency e.g., using transfer stations, smart routing, QR code tracking, and door-to-door segregation systems (Singh et al., 2024).

xi. **Life-Cycle Assessments (LCA) for scenario planning:** Analytical studies simulate future waste management conditions (e.g., 2001–2051), demonstrating that treating >60% of waste can reduce landfilling needs by up to 40%, and an 80% treatment scenario could shrink landfill demand drastically (Pujara et al., 2019).

4. Global Policies Related To the Environment

Agreements between nations to solve global environmental problems like pollution, biodiversity loss, and climate change are known as international environmental treaties. These agreements set up structures for international collaboration and nations' dedication to environmental preservation. Some of the important international environmental treaties are**-**

i. **Helsinki Declaration, 1964:** The Helsinki Declaration, initially established in 1964 by the World Medical Association, outlines ethical principles for medical research involving human participants. It highlights the importance of respecting individuals, obtaining informed consent, and prioritizing the well-being of patients over the interests of science or society. This declaration serves as a guide for physicians and researchers around the globe, ensuring that clinical trials and biomedical studies adhere to ethical standards. It has been revised several times to address new challenges such as genetic research, the use of placebos, and the protection of vulnerable groups. The Helsinki

Declaration continues to be a fundamental element of research ethics, reinforcing the need to balance scientific progress with human rights while shaping national regulations, institutional review boards, and international guidelines for medical research (Goodyear et al., 2007).

ii. **Ramsar Convention, 1971**: The Ramsar Convention on Wetlands, established in 1971 in Ramsar, Iran, is an international treaty focused on the protection and sustainable management of wetlands. It highlights the ecological significance of wetlands as essential habitats for diverse species, especially waterfowl, and their crucial function in maintaining water cycles, supporting livelihoods, and combating climate change. The treaty identifies Wetlands of International Importance, referred to as Ramsar sites, which are afforded protection and management assistance from participating countries. With more than 2,400 designated sites worldwide, spanning millions of hectares, it stands out as one of the most effective frameworks for preserving ecosystems. The Ramsar Convention promotes the prudent use of wetlands, merging conservation efforts with sustainable development, and encouraging the involvement of local communities in conservation initiatives (The convention on wet lands).

iii. **The United Nations Environment Program (UNEP), 1972:** The United Nations Environment Programme (UNEP), founded in 1972, is the foremost global authority on environmental issues within the UN framework, based in Nairobi, Kenya.UNEP advocates for environmental sustainability by orchestrating international initiatives focused on climate change, biodiversity, pollution management, and sustainable development. It plays a vital role in formulating international treaties such as the Montreal Protocol and the Paris Agreement. UNEP also aids nations in policy implementation, offers scientific evaluations like the Global Environment Outlook, and mobilizes resources for eco-friendly projects. By encouraging collaboration among governments, NGOs, and the private sector, UNEP acts as a central hub for promoting environmental protection and creating a sustainable future globally.

iv. **Convention on International Trade in Endangered Species (CITES), 1973:** The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), which was adopted in 1973 and implemented in 1975, oversees the global trade of endangered species to prevent jeopardizing their survival. It offers different levels of protection through three appendices, encompassing over 38,000 species of both animals and plants. CITES stipulates that permits and certificates are needed for trading species that are listed, aiding in the fight against illegal wildlife trafficking and excessive exploitation. It is instrumental in maintaining biodiversity by reconciling legal trade with the demands of conservation. By promoting international collaboration, CITES has established itself as one of the key agreements aimed at safeguarding wildlife from unsustainable commercial use (CITES).

v. **Montreal Protocol, 1987**: The Montreal Protocol, established in 1987, is a significant global environmental agreement aimed at safeguarding the ozone layer by phasing out the production and use of substances that deplete it, including chlorofluorocarbons (CFCs) and halons. It is recognized as one of the most effective environmental accords, having received universal approval from all UN member countries. Scientific research has connected ozone-depleting substances to the deterioration of the stratospheric ozone layer, which acts as a shield against harmful ultraviolet radiation. Through the implementation of deadlines and the introduction of alternatives, the protocol has facilitated notable recovery of the ozone layer. The Kigali Amendment (2016) further broadened its scope by addressing hydrofluorocarbons (HFCs), which are powerful greenhouse gases (UNEP, The Montreal Protocol).

vi. **Basel Convention, 1989:** The Basel Convention on the Control of Trans-boundary Movements of Hazardous Wastes and Their Disposal, adopted in 1989 and enforced in 1992, is an international treaty designed to protect human health and the environment from the adverse impacts of hazardous waste. It was developed after growing global concerns about the movement of toxic wastes from developed to developing countries, where regulations were often weaker. The treaty sets guidelines for reducing hazardous waste generation at the source, promoting environmentally sound management, and ensuring that trans-boundary movement of waste occurs only with prior informed consent of the receiving country. It prohibits the export of hazardous waste to nations lacking adequate disposal capacity and emphasizes minimization, recycling, and safe treatment. Over the years, the Basel Convention has been expanded through amendments, including the 1995 "Ban Amendment," which restricts exports of hazardous waste from OECD to non-OECD countries. Despite challenges in enforcement and illegal trafficking, the convention has significantly improved transparency, monitoring, and accountability in global waste trade. It also plays a key role in linking environmental protection with sustainable development, making it one of the most important multilateral agreements addressing global waste management and environmental justice (UNEP, 1989).

vii. **Convention on Biological Diversity (CBD), 1992:** The Convention on Biological Diversity (CBD) was signed by 150 government leaders at 1992 Earth Summit in Rio de Janeiro. It is a legally binding treaty aimed at conserving biological diversity, promoting sustainable use of its components, and ensuring fair sharing of benefits arising from genetic resources. It recognizes the sovereign rights of nations over their biological resources while promoting global cooperation. The CBD has led to important protocols, such as the Cartagena Protocol on Biosafety (2000) and the Nagoya Protocol on Access and Benefit Sharing (2010). Despite challenges in halting biodiversity loss, the 1992 Rio Earth Summit (Convention on Biological Diversity, CBD) enhanced global awareness, strengthened national policies, and fostered initiatives for ecosystem restoration, species protection, and sustainable resource management worldwide.

viii. **Kyoto Protocol, 1997:** The Kyoto Protocol, which was adopted in 1997 and came into force in 2005, is an international agreement under the United Nations Framework Convention on Climate Change (UNFCCC). It mandates industrialized countries to reduce their greenhouse gas emissions, acknowledging that developed nations are mainly accountable for the current elevated levels of emissions. The protocol established market-based strategies like emissions trading, the Clean Development Mechanism (CDM), and joint implementation to promote cost-effective emission reductions. While it succeeded in increasing global awareness of climate change, its overall impact was constrained due to the lack of participation from some key emitters. Nevertheless, it laid the groundwork for subsequent agreements such as the Paris Agreement, marking it as a significant milestone in climate governance (UNFCCC, The Kyoto Protocol, 2012).

ix. **The Stockholm Convention on Persistent Organic Pollutants, 2001**: The Stockholm Convention on Persistent Organic Pollutants (POPs), which was adopted in 2001 and came into effect in 2004, is an international agreement that seeks to safeguard human health and the ecosystem from dangerous chemicals that remain in the environment, build up in living beings, and present significant hazards. It focuses on compounds like polychlorinated biphenyls (PCBs), dioxins, and specific pesticides such as DDT. The convention advocates for the elimination, limitation, and secure disposal of POPs while promoting the development of safer alternatives. Additionally, it tackles unintentional by-products generated during industrial activities. By decreasing exposure to harmful pollutants, the Stockholm Convention has greatly advanced worldwide chemical safety and enhanced international collaboration in the realm of environmental health. The pact has 183 signatory nations (The Stockholm Convention).

x. **Doha Amendment, 2012:** The Doha Amendment to the Kyoto Protocol was adopted in 2012 during the UN Climate Change Conference held in Doha, Qatar. This amendment created a second commitment period (2013–2020) for the reduction of greenhouse gas emissions, following the first period (2008–2012). Under this amendment, developed nations agreed to collectively cut emissions by no less than 18% compared to 1990 levels. However, its impact was hindered by delays in ratification and the departure of several major emitters. Although the Doha Amendment came into effect in 2020, it was largely eclipsed by the 2015 Paris Agreement. Nonetheless, it signifies a transitional stage in global climate policy, linking Kyoto's binding commitments with the broader engagement seen in Paris (UNFCCC, The Doha Amendment, 2012)

xi. **Paris Agreement, 2015**: The Paris Agreement, established in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), represents a significant global pact designed to address climate change and its associated effects. Unlike previous agreements, it creates a universal framework where all participating nations, regardless of their development status, engage in climate action. The primary objective is to curb the global average temperature increase to significantly below 2°C compared to pre-industrial levels, with an aim to restrict it to 1.5°C. To accomplish this, the agreement mandates that countries provide Nationally Determined Contributions (NDCs), which are individual action plans centered on reducing emissions, developing adaptation strategies, and strengthening resilience. Notably, it encourages transparency through consistent reporting and review processes, motivating countries to progressively raise their commitments every five years. The accord also highlights the importance of financial and technological assistance, with wealthier nations committing to provide climate funding to help at-risk countries adapt and move towards clean energy sources. Additionally, it recognizes the principle of "common but differentiated responsibilities," taking into account the differing capabilities of nations. Although it faces criticism for lacking binding enforcement mechanisms, the Paris Agreement represents a pivotal moment in international climate negotiations, encouraging unprecedented collaboration and establishing a ground-work for shared, long-term efforts aimed at achieving sustainable and low-carbon development (UNFCCC, The Paris Agreement, 2015)

xii. **Agenda 2030 for sustainable development, 2015:** The 2030 Agenda for Sustainable Development was adopted unanimously by the United Nations in 2015 as a global initiative to eradicate poverty, safeguard the planet, and guarantee peace and prosperity for everyone by 2030. At the heart of this agenda are the 17 Sustainable Development Goals (SDGs) and 169 related targets, which provide a thorough framework for tackling interconnected global issues (**Figure 2**). These goals encompass the eradication of poverty and hunger, the assurance of quality education and healthcare, the achievement of gender equality, the provision of access to clean water and sanitation, sustainable and affordable energy, the promotion of economic growth and decent work, and the development of resilient infrastructure. Environmental sustainability is also a key component, with objectives aimed at addressing climate change, preserving oceans, protecting land-based ecosystems, and ensuring sustainable consumption and production practices.

Agenda 2030 underscores the importance of inclusivity through the principle of "leaving no one behind," which asserts that development should benefit everyone, particularly the most vulnerable populations. In contrast to previous development models, this agenda combines economic, social, and environmental aspects to foster equitable advancement. It stresses the significance of global collaborations, innovation, technology sharing, and capacity enhancement to meet its goals. Additionally, it encourages active collaboration among governments, civil society, the private sector, and citizens. Essentially, Agenda 2030 is more than just a policy framework; it represents a vision for reshaping the world into a just, equitable, and sustainable environment for both present and future generations. Achieving its goals depends on shared responsibility and the dedication of every country to execute and track advancements toward these ambitious objectives (United Nations Sustainable Development Goals; Bexell and Jönsson, 2017; Lee et al., 2016).

Figure 2: Sustainable Development Goals, AGENDA (2030)

(Source:https://commons.wikimedia.org/wiki/File:Sustainable_Development_Goals.png).

5. Conclusion

In conclusion, India's ability to handle the various and nuanced problems in plan execution is closely related to its path towards sustainable development. A comprehensive and cooperative approach is necessary to overcome the obstacles, which range from political instability and regional inequities to financial constraints and bureaucratic red tape. In addition to deliberate policy changes, addressing these issues calls for a cultural shift that prioritizes openness, community involvement, and flexibility. India must establish a strong and flexible governance framework that can handle the complexities of plan implementation. Crucial actions include bolstering political stability, improving financial resource mobilization, and fortifying administrative procedures. Furthermore, encouraging community involvement, raising public awareness, and making investments in human resources are essential to guaranteeing the sustainability and inclusivity of development projects.

India must see obstacles as chances for innovation and development as it works to meet its developmental objectives. In addition to advancing the country toward sustainable development, putting these obstacles into practice will set an example for other areas dealing with comparable challenges. India can set the path for a future characterized by equitable growth, environmental sustainability, and enhanced quality of life for its diverse people by encouraging a resilient and adaptable approach to plan implementation.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-9

Pesticides and Their Impact on the Environment and Human Health

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AUTHOR'S CONTRIBUTION

Both authors played significant roles in developing the concepts and framework for this research on pesticides and their effects on the environment and human health. VK conducted the main literature review, analysed the data and wrote the initial draft of the manuscript. The MM author offered essential revisions, guidance on valuable insights to enhance the comprehensive analysis.

ABSTRACT

Insects, rodents, fungus, weeds and other nuisance creatures can be controlled or eliminated with the help of pesticides, which are chemical components. Excessive use of pesticides poses major dangers to human and environmental health, despite their usefulness in disease management and boosting crop yields. The persistent pesticide ingredients that have contaminated our air, water, food and soil pose a number of health hazards, including acute and chronic toxicities. Acute toxicity can be caused by inhaling, ingesting, or coming into contact with a high amount of pesticides; chronic toxicity can be caused by sustained or repeated exposure. An assortment of harmful effects, including neurotoxicity, mutagenicity, carcinogenicity, teratogenicity and disturbance of the endocrine system, are caused by pesticides. It is possible for a pesticide's toxicity to be influenced by both the active ingredient and any inert or synergistic chemicals that may be present. To control modern pesticide-induced health dangers, safety concerns must be addressed immediately. Important issues include how well the existing laws protect people and the environment and how well they are put into practice. Pesticides are the subject of this chapter's comprehensive review, which includes discussions of their present impacts on human health as well as the most recent legislative concerns regarding their safety. Legislation, sufficient training, and education are necessary to reduce the negative impacts of pesticide use and promote safer, more ecologically friendly farming practices.

Keywords: Pesticides, toxicity, neurotoxicity, mutagenicity, carcinogenicity, teratogenicity, endocrine disruption

1. Introduction

Pesticides are chemicals that are used to protect plants from insects, weeds and other pests. These compounds can be synthetic or generated from natural sources. According to Khan *et al.* (2023) and Elbialy et al. (2021), these substances are classified based on their chemical structure, mechanisms of action, hazards and applications. Since the mid-1940s, pesticide use has been steadily increasing, mostly due to commercial farming (Elbialy et al., 2021; Umapathi et al., 2022). Contamination of food, environment, farms, and water sources occurred as a consequence of pesticide use that was both excessive and unregulated (Cechet al., 2023). Pesticides can be found in a variety of foods and environments, including freshly produce, processed foods, water, air and dirt. Particularly in underdeveloped nations, the acute and chronic nutritional and environmental impacts of agricultural pesticides pose significant threats to human health. Concerning human health, chemical pesticides have the potential to cause cancer, cell death and mutations. There is no species bias in the way insecticides work, therefore, they can kill or injure creatures other than pests, including human. The majority of the three million poisoned and two hundred thousand dead worldwide are believed to have been exposed to pesticides in developing countries (Boedeker et al., 2020). Reduced antioxidant levels and antioxidant protection against oxidative damage in cells are consequences of pesticide-induced reactive oxygen species generation. Proteins, lipids and nucleic acids all have an impact on cellular signalling pathways because of the imbalance.

The harmful effects on human health over the long term are largely attributed to oxidative stress and the generation of reactive oxygen species (Kaur et al., 2019). Inaccurate pesticide application is linked to several adverse health outcomes, including acute intoxication and chronic diseases such as cancers of the brain, breast, prostate, bladder and colon (Rani et al., 2021; Singh et al., 2018). Pesticide exposure has also been associated with Alzheimer's disease (Sanborn et al., 2007; Frisoni et al., 2019; Wang et al., 2024), infertility (Bhardwaj et al., 2018; Foucault et al., 2021), diabetes (Hernández-Mariano et al., 2022), and Parkinson's disease (Perrin et al., 2021). Nonetheless, pesticides play a significant role in boosting agricultural productivity. They increase crop yields by reducing losses caused by weeds, pests, and diseases (Popp et al., 2013; Tudi et al., 2022). By safeguarding both the quantity and quality of harvested crops, pesticides contribute substantially to global food security.

The public health sector employs pesticides to decrease populations of mosquitoes, fleas, ticks and malaria vectors, which in turn reduce the prevalence of diseases including dengue fever, malaria and Lyme disease (Tudi et al., 2022; Kitchen et al., 2009). Even though agrochemicals contribution to increased crop yields is well-established, there has been a surge in the development and manufacture of eco-friendly pesticides in the developed world's pesticide trade, available in a variety of forms including powder, solution and emulsifiable concentrates (Hazra et al., 2017; Zuma et al., 2023). Still, ethical pesticide techniques such integrated pest management, should be encouraged to guarantee long-term efficacy of pest control strategies, and pesticide use should be balanced with health and environmental concerns. Although intended for use in agriculture and other areas to control pests, pesticides have far-reaching and negative consequences for human health and the natural world. These impacts may manifest immediately (acute) or take time to become apparent (chronic). Pesticides are used to get rid of, discourage or control pests using chemical or biological agents. Pests include anything that can harm crops, cattle, public health or human dwellings, such as insects, rats, fungi, weeds and so on. There are more than a thousand distinct pesticides in use today, and all of them are vital to contemporary farming and public health.

2. Types of Pesticides

Pesticides can be classified based on the type of pests they target, their chemical composition, or their mode of action (Aktar et al., 2009). Among the major categories, **insecticides** are widely used to control insect populations. These include organophosphates and carbamates, which disrupt the insect nervous system; pyrethroids, synthetic analogs of natural pyrethrins derived from Chrysanthemum flowers that also affect the nervous system (Ahamad et al., 2023); and insect growth regulators (IGRs), which interfere with insect maturation (Nauen, 2007). **Herbicides**, also known as weedicides, are employed to manage weeds that compete with crops for nutrients. These may be selective, eliminating only specific weed species without harming the main crop, or non-selective, destroying all plant life they contact. **Fungicides** are applied to control fungal infections such as mildews, blights, and rusts, while **rodenticides** are designed to kill rodents including rats, mice, and gophers. **Nematicides** target plant-parasitic nematodes that damage roots (Chitwood, 2003), whereas **molluscicides** are used against snails, slugs, and other molluscs. Similarly, **algaecides** are applied to inhibit or eliminate algae, particularly in aquatic environments. Beyond agriculture, certain pesticides serve specialized functions; for example, **disinfectants and antimicrobials** are used in hospitals, food processing facilities, and public spaces to control bacteria, viruses, and other microorganisms. Additionally, **wood preservatives** are applied to protect timber from insects, fungi, and other pests, thereby extending its durability.

3. Applications of Pesticides

a. **Agriculture**: This is the largest sector for pesticide use, protecting crops from insects, weeds, and diseases to improve yield and quality (Potts et al., 2010).

b. **Public health**: Used to control vectors of disease, such as mosquitoes (Malaria, Dengue, Zika), ticks (Lyme disease) and rodents (Plague, Hantavirus).

c. **Household and garden**: Used by consumers to control pests in homes, lawns and gardens (e.g., ant sprays, weed killers, cockroach baits).

d. **Forestry**: To protect trees from pests and diseases.

e. **Industrial and commercial**: Pest control in factories, warehouses, food establishments etc.

4. How Pesticides Work

Pesticides exert their effects primarily by interfering with the metabolic processes of target organisms (Pimentel, 2005, 2009).

Depending on their mode of action, they can be classified into several categories. **Nerve poisons**, such as organophosphates and carbamates, disrupt the normal functioning of the nervous system, leading to paralysis and death. **Stomach poisons** act when ingested by pests, damaging internal tissues and impairing vital functions, whereas **contact poisons** kill upon direct exposure by penetrating the pest's outer covering. **Systemic poisons** are absorbed and distributed throughout plant or animal tissues, rendering them toxic to pests that feed on them, while **fumigants** act through inhalation of toxic vapors that interfere with respiratory processes. Overall, pesticides encompass a diverse range of chemical compounds and biological agents, each formulated to target specific pests, with their classification often based on their mode of action and chemical class (Casida, 2009).

5. Insecticides (to control insects) and Their Types

5.1 Organophosphates

Organophosphates (OPs) are highly toxic nerve poisons that act by inhibiting acetylcholinesterase, an enzyme essential for the proper transmission of nerve signals. This disruption in the nervous system leads to paralysis and death in target insects. Among the commonly used OPs, **malathion** is widely applied in agriculture, mosquito control, and even in some over-the-counter treatments for head lice. **Chlorpyrifos** was once extensively used in agriculture and household pest control, but its applications have been restricted or banned in many countries due to health concerns. **Diazinon** served as a broad-spectrum insecticide, though many of its residential uses have now been phased out. **Parathion**, one of the most toxic organophosphates, has also been largely restricted or banned worldwide because of its severe risks to human health and the environment.

5.2 Carbamates

Carbamates act through a mechanism similar to organophosphates, interfering with the nervous system by inhibiting acetylcholinesterase, but their effects are generally more reversible. Common examples include **Carbaryl** (Sevin), widely used as an insecticide in gardens, lawns, and agricultural crops; **Propoxur** (Baygon), often applied in household insect sprays and baits; and **Methomyl**, which is extensively used in agriculture, particularly as bait for controlling flies. **Pyrethroids**, on the other hand, are synthetic analogs of natural pyrethrins derived from chrysanthemum flowers. They disrupt nerve function, causing paralysis and death in insects, while being comparatively less toxic to mammals than organophosphates and carbamates. Notable examples are **Permethrin**, employed in agriculture, mosquito nets, and flea or tick treatments for pets; **Cypermethrin**, commonly used in agriculture and structural pest control; **Deltamethrin**, effective against a broad range of insect pests and widely used in agriculture and public health; and **Bifenthrin**, frequently found in household and garden pest control products. **Neonicotinoids** represent another class of insecticides that target nicotinic acetylcholine receptors in the insect central nervous system. They are systemic in nature, absorbed by plants to make them toxic to feeding insects. Widely used neonicotinoids include **Imidacloprid**, applied in seed treatments, soil drenches, foliar sprays, and also for flea control in pets; **Thiamethoxam**, used as a seed treatment and foliar spray, often in combination with other pesticides; **Clothianidin**, a popular seed treatment for field crops; and **Acetamiprid**, applied to fruits, vegetables, and ornamental plants. In contrast, **Organochlorines** (chlorinated hydrocarbons) disrupt nerve impulse transmission and are highly persistent in the environment, leading to bioaccumulation and widespread bans in many countries (Rafeeinia et al., 2022). Classic examples include **DDT (Dichloro-diphenyl-trichloroethane)**, once extensively used against malaria vectors and agricultural pests but now banned in most nations due to its persistence and ecological damage, though limited use still exists in specific public health contexts (Hernández-Mariano et al., 2022). Other banned organochlorines include **Aldrin/Dieldrin**, known for their persistence and high toxicity, and **Chlordane**, previously employed for termite control but now largely prohibited worldwide.

6. Herbicides (to control weeds) and their types

Commonly used herbicides include **Glyphosate**, the active ingredient in products like Roundup, which is a non-selective, systemic herbicide that kills most plants by inhibiting an essential enzyme pathway for growth and is widely applied with "Roundup Ready" genetically modified crops. **2, 4-D** is a selective systemic herbicide primarily targeting broadleaf weeds in lawns and cereal crops by mimicking natural plant hormones (auxins). **Atrazine**, another selective herbicide, is commonly used in corn, sorghum, and sugarcane fields to control both broadleaf and grassy weeds, though its persistence makes it a frequent water contaminant. **Paraquat** is a fast-acting, non-selective contact herbicide that is extremely toxic if ingested. **Dicamba** serves as a selective herbicide effective against broadleaf weeds, often applied in combination with glyphosate to improve weed control. Additionally, **Pendimethalin** is a pre-emergent herbicide that prevents the germination of annual grasses and certain broadleaf weeds, making it particularly useful in integrated weed management practices.

7. Fungicides (to control fungi) and Their Types

Fungicides are chemicals used to control fungal diseases in crops, and they come in different types depending on their mode of action. **Mancozeb** is a broad-spectrum contact fungicide widely applied to various crops for managing multiple fungal infections. **Azoxystrobin**, a systemic fungicide, is highly effective against numerous fungal diseases and is commonly used in cereals, fruits and vegetables. Another widely used option is **Chlorothalonil**, a broad-spectrum contact fungicide applied to crops, turf, and ornamental plants. **Copper-based fungicides**, such as Bordeaux mixture and copper hydroxide, are among the oldest fungicides and continue to play a role in organic farming, offering protection against both fungal and bacterial diseases. **Tebuconazole**, belonging to the triazole class, is a systemic fungicide frequently used in cereals, fruits, and other crops for reliable disease control.

Rodenticides, designed to control rodent populations, also vary in their action. **Warfarin** is an anticoagulant rodenticide that causes internal bleeding, while **Brodifacoum** is a more potent second-generation anticoagulant with prolonged effects. Non-anticoagulant options like **Bromethalin** act as neurotoxins, causing brain swelling and death in rodents.

Beyond these major categories, there are other important pesticides with specialized uses. **DEET (Diethyltoluamide)** is one of the most widely used insect repellents, technically classified as a pesticide. **Methyl bromide**, once a common fumigant for soil, commodities and structures, has largely been phased out due to its ozone-depleting properties. **Aluminum phosphide** remains in use as a fumigant for controlling pests in stored grains, while **Naphthalene (mothballs)** is employed in enclosed spaces to repel or kill moths and similar pests. Together, these examples represent the diverse world of pesticides, illustrating the range of compounds developed to manage fungi, rodents, insects and other agricultural or household pests.

8. Risks and Concerns

Despite their effectiveness in controlling pests, pesticides are inherently toxic and pose significant risks to both human health and the environment, particularly when misused.

8.1 Human health impacts (Cooper and Dobson, 2007)

Pesticides can cause a range of health issues depending on the level and duration of exposure. Acute effects include nausea, dizziness, headaches, skin and eye irritation, respiratory problems, and in severe cases, seizures or coma. Chronic exposure is associated with long-term health risks such as cancers (leukemia, lymphoma), neurological disorders (Parkinson's and Alzheimer's diseases), reproductive problems, endocrine disruption, immune system dysfunction, and organ damage. Children and agricultural workers are especially vulnerable due to greater exposure and sensitivity.

8.2 Environmental impacts

Pesticides exert wide-ranging effects on ecosystems, threatening biodiversity by harming non-target organisms such as beneficial insects, fish, birds, soil microbes and essential pollinators like bees. They also degrade soil fertility and reduce microbial diversity, leading to long-term soil health concerns. Water resources are contaminated through runoff, leaching, and drift, polluting both surface water (rivers, lakes, oceans) and groundwater. Air quality is affected as well, with pesticide drift and volatilization dispersing toxic chemicals over long distances, contributing to atmospheric pollution. Furthermore, the repeated use of pesticides fosters pest resistance, forcing reliance on stronger or more frequent applications.

The growing awareness of these negative impacts has driven interest in more sustainable pest control methods. Integrated Pest Management (IPM) offers a balanced approach by prioritizing non-chemical strategies such as biological control, cultural practices and habitat management, while reserving pesticide use as a last resort. This approach not only minimizes health and environmental risks but also helps maintain long-term agricultural sustainability.

9. Agricultural Practices

In farming, agricultural practices are the procedures and methods used to grow crops and raise animals. These practices have evolved significantly throughout history, from traditional, manual methods to highly mechanized and technologically advanced approaches. The goal of agricultural practices is to optimize productivity, ensure food security, and manage natural resources. Here's a breakdown of common and modern agricultural practices, along with a focus on sustainable approaches:

9.1 Common/basic agricultural practices (Traditional and Conventional)

These are fundamental steps involved in crop production, regardless of the scale or intensity.

i. **Soil preparation:** Soil preparation is a crucial step in agriculture that ensures healthy crop growth and improved yield. It begins with **ploughing** (tillage), which involves loosening and digging the soil using ploughs or cultivators. This process aerates the soil, enhances water infiltration, and helps in controlling weeds. After ploughing, the field is **levelled** to create an even surface, which ensures uniform distribution of water and facilitates proper seed placement. Finally, **manuring or fertilizing** is carried out before sowing, where organic matter such as manure or compost, or chemical fertilizers, are added to enrich the soil with essential nutrients, thereby improving its fertility and providing a strong foundation for crop growth.

ii. **Sowing (planting):** Sowing, or planting, is the next important step in crop production that directly influences the quality and quantity of yield. It begins with **seed selection**, where only high-quality, healthy, and disease-resistant seeds are chosen to ensure better germination and crop performance. Seeds can then be sown using different methods. **Broadcasting** involves scattering seeds manually or with mechanical tools over a large area, making it a simple but less precise method. For greater accuracy, **drilling** is used, where seeds are placed in rows at specific depths and distances with the help of seed drills, ensuring uniform growth and efficient use of resources. Another common method is **transplanting**, in which seedlings are first raised in a nursery and later carefully transferred to the main field; this technique is especially useful for crops like rice, tomatoes, and peppers, as it promotes healthy plant establishment and better yield.

iii. **Nutrient management (post-sowing):** Nutrient management is essential to ensure healthy plant growth and higher yields after sowing. **Fertilization** provides crops with essential nutrients at regular intervals through organic or chemical sources, applied via methods such as top-dressing, foliar sprays, or fertigation, where fertilizers are supplied through irrigation water. To maintain soil fertility and structure, **manuring** is also necessary, which involves the continuous addition of organic matter. Another important practice is **crop rotation**, where different crops are grown sequentially on the same plot of land. This improves soil fertility, helps in controlling pests and diseases, and enhances soil structure for sustainable farming.

iv. **Irrigation:** Irrigation is vital for supplying adequate water to crops, and it can be sourced from wells, ponds, canals, tube wells, dams, and rivers. Different methods of irrigation are used depending on the crop and region. **Surface irrigation**, such as flooding or furrow irrigation, involves spreading water over the soil surface and is common in rice cultivation. **Sprinkler systems** distribute water evenly over crops in the form of rainfall, making them suitable for a variety of fields. A more efficient modern technique is **drip irrigation**, which delivers water directly to the plant roots, minimizing water loss and ensuring optimal usage.

v. **Weeding (weed control):** Weeds compete with crops for nutrients, water, and light, making weed control a critical step in farming. **Manual weeding** involves uprooting weeds by hand or with simple tools like a khurpi, while **chemical weeding** uses herbicides or weedicides to eliminate unwanted plants. In addition, **biological control** employs natural enemies to manage weed populations sustainably. Another effective practice is **mulching**, where organic or synthetic materials are used to cover the soil surface, preventing weed growth while also conserving soil moisture.

vi. **Crop protection:** Crop protection safeguards plants from pests, diseases, and other harmful organisms that threaten yield. **Pest control** is achieved through various measures, including the application of pesticides or integrated pest management practices. **Disease management** involves identifying, preventing, and treating plant diseases to maintain crop health and productivity.

vii. **Harvesting:** Harvesting marks the final stage of crop production and involves several steps to collect and process mature crops. **Cutting or gathering** is done manually using sickles or mechanically with harvesters. This is followed by **threshing**, which separates the grain from the stalks, and **winnowing**, which removes lighter chaff from heavier grains using wind or mechanical blowers, ensuring clean produce.

viii. **Storage:** Proper storage is crucial to preserve harvested crops and prevent post-harvest losses. **Drying** harvested grains reduces their moisture content, minimizing spoilage risks. **Fumigation** protects stored produce from pests and microorganisms using controlled chemical treatments. Finally, storing crops in proper facilities such as granaries, bins, or godowns ensures long-term preservation and reduces wastage, thereby maintaining food security.

9.2 Modern agricultural techniques (technology-driven)

These practices leverage advanced technologies to enhance efficiency, productivity, and sustainable resource management.

i. **Precision agriculture (satellite farming):** Uses GPS, sensors, drones, and satellite imagery to collect information on soil health, crop conditions, and yield variations across fields. This enables precise application of water, fertilizers, and pesticides, improving input efficiency and minimizing waste.

ii. **Hydroponics:** The cultivation of plants in nutrient-rich water solutions without soil. It allows for year-round production, reduces water usage through recycling, and eliminates soil-borne pests and diseases.

iii. **Aeroponics:** A soil-free cultivation technique where plant roots are suspended in the air and sprayed with a nutrient solution. It provides excellent root aeration and achieves even greater water efficiency than hydroponics.

iv. **Aquaponics:** Integrates aquaculture (fish farming) with hydroponics in a closed-loop system. Plants absorb nutrients from fish waste, which simultaneously purifies the water for the fish, creating a symbiotic relationship.

v. **Vertical farming:** The practice of growing plants in vertically stacked layers within controlled environments such as buildings or shipping containers. It maximizes space utilization in urban areas, enables year-round cultivation, and significantly reduces water use and transportation costs.

vi. **Biotechnology and genetic engineering:** Involves developing genetically modified (GM) crops that are resistant to pests, tolerant to drought, higher yielding, or nutritionally enhanced. Techniques such as tissue culture are also used for rapid propagation of disease-free plants.

vii. **Automation and robotics:** Employs self-driving tractors, robotic harvesters, automated irrigation systems, and drones for monitoring and resource distribution. These technologies reduce labor requirements and increase operational efficiency.

viii. **Smart irrigation systems:** Use soil moisture sensors and weather data to determine exact water requirements, ensuring highly efficient and sustainable water use.

9.3 Sustainable agricultural practices (environmentally focused)

Incorporating these methods into food production has multiple goals: reducing negative impacts on the environment, preserving resources, and maintaining ecological balance in the long run.

i. **Integrated Pest Management (IPM):** Integrated pest management (IPM) is a strategy for controlling pests that makes use of biological, cultural, mechanical, and chemical components. Focuses on preventing problems and implementing non-chemical controls first; pesticides are used selectively and only when absolutely necessary.

ii. **Conservation tillage (No-till/reduced-till)**: It aims at minimizing or eliminating soil disturbance. Leaves crop residues on the soil surface, which reduces soil erosion, conserves moisture, improves soil structure, and enhances microbial life.

iii. **Cover cropping:** Planting non-cash crops (e.g., clover, rye) between main crop seasons or alongside cash crops helps protect soil from erosion, improve organic matter, suppress weeds and in some cases, fix nitrogen.

iv. **Crop diversification/polyculture:** It is growing a variety of crops on the same land or within a field, rather than just one (monoculture). Enhances biodiversity, improves soil health, reduces pest outbreaks and provides economic resilience.

v. **Agroforestry:** Adding vegetation such as trees and shrubs to the farm land is termed as agroforestry. This provides shade, shelters to crops and livestock, reduces erosion, enhances biodiversity and can offer additional income (fruits, nuts, timber).

vi. **Organic farming:** Organic farming is a holistic system that avoids synthetic pesticides, fertilizers, GMOs and antibiotics. Composting, crop rotation and biological pest control are some of the natural processes that are relied upon for pest management and soil fertility maintenance.

vii. **Water conservation techniques:** Wider adoption of drip irrigation, precise scheduling based on soil moisture monitoring, rainwater harvesting, and efficient water storage.

viii. **Soil health management:** Focus on practices that build and maintain healthy soil ecosystems, including increasing soil organic matter, minimizing compaction, and promoting microbial activity.

ix. **Nutrient cycling:** Maximizing the recycling of nutrients on the farm, by composting, manuring and and integrating livestock to return nutrients to the soil. Factors including weather, soil type, technology, money and environmental objectives all play a role in determining which farming methods are best. More and more, contemporary farmers are looking to sustainable practices and technological advancements to solve the problems of food insecurity and environmental degradation.

10. Endocrine Disruptions

Endocrine disruption refers to the interference of certain chemicals, known as endocrine-disrupting chemicals (EDCs), with the body's natural hormone system (the endocrine system). This system regulates vital physiological processes such as growth, development, metabolism, reproduction and mood through chemical messengers called hormones (Singh et al., 2018).

10.1. How EDCs Work

EDCs act through different mechanisms that disturb hormonal balance (Singh et al., 2018). Some mimic natural hormones, like estrogen and bind to receptors to produce false signals, while others block hormone receptors, preventing normal function. They may also disrupt hormone synthesis, metabolism, or transport, leading to imbalances. In addition, EDCs can alter the sensitivity or number of hormone receptors on cells. Beyond these effects, some EDCs induce epigenetic changes that modify gene expression without altering DNA, causing long-term health effects that may pass to future generations.

10.2. Sources of Endocrine-Disrupting Chemicals (EDCs)

EDCs are widespread in the environment and originate from multiple sources. Agricultural chemicals such as pesticides, herbicides and compounds like atrazine, organophosphates and organochlorines are well-known examples (Singh et al., 2020). Industrial and consumer products also contribute significantly, including bisphenol A (BPA) in plastics and can linings, phthalates in packaging, toys, and cosmetics, as well as parabens, triclosan, and synthetic musks in personal care products. Flame retardants like PBDEs, industrial pollutants such as dioxins, PCBs, and PFAS, and heavy metals like cadmium, mercury, lead, and arsenic further add to the burden. Pharmaceuticals, especially synthetic hormones, and even natural compounds like phytoestrogens in soy also exhibit endocrine-disrupting potential, though often to a lesser degree compared to synthetic chemicals.

10.3. Impacts of EDCs on human health

The impacts of endocrine-disrupting chemicals (EDCs) on human health are profound, often dose-dependent, particularly severe during sensitive periods such as fetal development, infancy, and puberty, when even low-level exposures can lead to long-term effects. Reproductive health is especially vulnerable, with men experiencing reduced sperm count and quality, testicular dysgenesis, prostate abnormalities, and infertility, while women may suffer from endometriosis, PCOS, premature ovarian failure, altered menstrual cycles, infertility and early puberty (Richardson, 1993). EDCs also disrupt developmental processes, contributing to birth defects, abnormal breast or gonadal development, and neurodevelopmental disorders including ADHD, autism, and cognitive impairments. In addition, they are strongly linked to metabolic disorders such as obesity, diabetes and metabolic syndrome, as well as hormone-sensitive cancers like breast, prostate, testicular and thyroid cancer. Beyond these systemic impacts, EDCs impair immune function, leading to weakened defenses and autoimmune conditions, and interfere with thyroid hormone synthesis, affecting growth, metabolism and brain development. They may also contribute to respiratory issues such as asthma, wheezing, and chronic irritation, along with dermatological problems like rashes, itching, blisters and burning sensations. Ocular effects-including eye irritation, blurred vision, and even blindness-have been reported, while gastrointestinal issues such as nausea, vomiting, abdominal pain and diarrhea further illustrate the wide-ranging risks of exposure to these chemicals.

10.4. Impacts on the environment and wildlife

Endocrine-disrupting chemicals (EDCs) enter the environment through wastewater, agricultural runoff, industrial discharges, and consumer waste, where their persistence and ability to biomagnify pose serious ecological risks. Aquatic organisms such as fish and amphibians are highly vulnerable, with effects like feminization of male fish, reproductive disorders, and developmental abnormalities. In wildlife, exposure leads to behavioral changes, reduced fertility, and population declines in birds, mammals, and amphibians. Notable examples include masculinization of female snails, eggshell thinning and reproductive failure in birds of prey, and immune as well as reproductive impairments in marine mammals due to bioaccumulation of persistent EDCs.

10.5. Ecosystem disruption

Endocrine-disrupting chemicals (EDCs) and pesticides can disrupt food webs and ecosystem health by affecting key species, with pollinators like bees experiencing severe population declines that threaten crop pollination and biodiversity. Soil contamination from pesticide residues alters microbial diversity, reducing soil fertility and agricultural productivity, while runoff pollutes surface waters, causing algal blooms, and groundwater contamination threatens drinking water supplies. Air pollution also arises from pesticide drift and volatilization, spreading chemicals beyond target areas and contributing to secondary pollutants. Moreover, frequent pesticide use accelerates pest resistance, creating a cycle of stronger chemicals and worsening environmental and health risks. Sustainable practices such as organic farming and integrated pest management (IPM) are therefore essential to reduce dependence on synthetic pesticides and protect ecological balance (Trellu et al., 2021).

11. Conclusion

The pervasive use of pesticides, while offering immediate benefits in pest control and agricultural productivity, endangers people's well-being and disrupts the natural ecological balance in major ways. **For Human Health:** Pesticides present a spectrum of risks, ranging from acute symptoms like headaches, nausea, and skin irritation to severe chronic conditions including various cancers, illnesses affecting the nervous system (including Parkinson's disease and developmental delays in children), troubles with reproduction, and disturbances to the endocrine system. Due to occupational exposure or heightened sensitivity at important developmental phases, vulnerable populations, such as agricultural labourers, children, and pregnant women, experience disproportionately increased risks. **For the Environment:** The intentional release of pesticides into ecosystems leads to widespread contamination of soil, water, and air. This results in critical biodiversity loss, particularly impacting vital non-target organisms like pollinators (bees), beneficial insects, and aquatic life, thereby disrupting essential ecosystem services. Furthermore, pesticide persistence contributes to soil degradation, widespread water pollution, and the concerning development of pest resistance, creating a vicious cycle of increasing chemical dependency. Ultimately, the short-term gains from pesticide use often come at a substantial long-term cost. This comprehensive understanding underscores the urgent need for a global shift towards more sustainable and integrated pest management strategies that prioritize ecological health and human well-being, minimizing reliance on synthetic chemical interventions.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-10

Technological Innovations for Ecotoxicology and Sustainable Environment: Artificial Intelligence, Internet of Things, Renewable Energy and Advanced Pollution Control Technologies

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AUTHORS' CONTRIBUTIONS

The study was conducted by a team of three authors. Author MA supervised the research and reviewed the initial draft of the manuscript. Author ZK prepared the first draft of the chapter and also wrote the final version of the paper. Authors ZK and SF jointly managed the literature search for the relevant sections. Author SF organized and formatted the references according to the guidelines. The final draft was thoroughly checked by MA. All authors read and approved the final manuscript.

ABSTRACT

Rapid technological advancements have revolutionized ecotoxicology and environmental sustainability, offering innovative solutions to mitigate pollution, monitor ecosystems and promote renewable energy. This Chapter explores cutting-edge developments in artificial intelligence (AI), the Internet of Things (IoT), renewable energy systems and advanced pollution control strategies. AI and machine learning enhance predictive modeling for toxicological assessments, enabling more accurate risk evaluations and faster response times. IoT-enabled sensors facilitate real-time environmental monitoring, improving early detection of contamination events and ensuring timely interventions. These technologies support data-driven decision-making, optimizing resource management and regulatory compliance. Renewable energy integration-including solar, wind and bioenergy-is pivotal in reducingcarbon emissions and advancing sustainable development. Additionally, advanced pollution control methods such as nanotechnology-based remediation, electrochemical treatments and bioremediation demonstrate high efficacy in degrading pollutants. These approaches minimize ecological damage while offering scalable, cost-effective soil, water and air purification solutions. This chapter highlights their transformative potential in fostering a cleaner, more resilient environment by integrating these innovations. Interdisciplinary collaboration-merging engineering, biotechnology and data science-is crucial for addressing complex global challenges. Combining AI, IoT, renewable energy, and pollution mitigation strategies underscores a path toward sustainable environmental stewardship, balancing technological progress with ecological preservation.

Keywords: Ecotoxicology, artificial Intelligence (AI), internet of Things (IoT), renewable energy, pollution control.

1. Introduction

Environmental degradation and pollution represent some of the most pressing challenges of the 21st century, threatening ecosystem health, biodiversity, and human well-being (Rockstrom et al., 2009). Ecotoxicology, which examines the harmful effects of chemicals on ecological systems, has evolved significantly in recent decades as technological innovations have transformed our capacity to detect, monitor, and mitigate environmental contaminants (Ankleyet al., 2023). As anthropogenic activities continue introducing new chemicals and stressors into the environment, the imperative for sustainable approaches to environmental management has never been greater.

The convergence of digital technologies, renewable energy systems, and advanced pollution control mechanisms offers unprecedented opportunities to address complex environmental challenges. Artificial intelligence (AI), the Internet of Things (IoT), renewable energy technologies, and advanced pollution control systems represent four interconnected pillars of innovation that are reshaping environmental protection paradigms (Macias-Tapia et al., 2025). These technologies enable more precise detection of pollutants, predictive modeling of ecological impacts, efficient resource management, and targeted remediation strategies (Rosa-Bilbao et al., 2025). This chapter explores how these technological innovations revolutionize ecotoxicological research and environmental management practices.

2. Artificial Intelligence in Ecotoxicology

2.1 Fundamentals of AI in Environmental Science

Artificial intelligence encompasses a range of computational techniques that enable machines to perform tasks that typically require human intelligence. Machine learning, deep learning, and natural language processing represent key subfields of AI with diverse applications in ecotoxicology and environmental science. AI is transforming the way we analyze and make decisions about water quality, utilizing algorithms and models to analyze vast amounts of data, identify trends, and make informed decisions (Dogo et al., 2019).

The integration of AI into ecological research has been facilitated by advances in computational power, big data analytics, and algorithm development, enabling more sophisticated analysis of complex environmental systems. Environmental data present unique challenges for AI implementation, including spatiotemporal variability, data gaps, multiple scales of interaction, and complex causal relationships. Despite these challenges, AI offers transformative potential for processing large environmental datasets, identifying patterns invisible to human observation, and generating insights that inform evidence-based environmental management (Tuia et al., 2024).

2.2 Predictive Modeling of Pollutant Behavior

AI algorithms have dramatically improved our ability to predict the fate and transport of environmental contaminants across different media (Zhang et al., 2019). Machine learning models can incorporate multiple variables, including chemical properties, environmental conditions, and biological factors, to forecast how pollutants will move through air, water, and soil matrices. Deep learning approaches have proven particularly valuable for modeling complex environmental processes that involve non-linear relationships and feedback mechanisms (Wang et al., 2024)

Quantitative structure-activity relationship (QSAR) models enhanced by AI can predict chemical toxicity based on molecular structure, reducing the need for extensive experimental testing and accelerating the assessment of new compounds. These models can identify potential persistent, bioaccumulative, and toxic (PBT) substances before they enter the environment, enabling proactive regulatory approaches (Alves et al., 2015). Environmental fate models incorporating machine learning have demonstrated superior performance in predicting the distribution and degradation of emerging contaminants such as pharmaceuticals, microplastics and perfluoroalkyl substances (PFAS) in complex ecosystems. By accurately forecasting pollutant behavior, these models help prioritize monitoring efforts and inform risk assessment frameworks (Deng et al., 2025).

2.3 Toxicity Prediction and Risk Assessment

Traditional toxicity testing is time-consuming, expensive, and raises ethical concerns regarding animal testing (Hartung, 2019). AI-driven approaches offer alternatives that can rapidly screen thousands of chemicals for potential toxicity through in-silico methods. Deep neural networks trained on existing toxicological data can predict adverse outcomes with increasing accuracy, supporting regulatory decision-making and chemical prioritization efforts. Bayesian networks and ensemble methods have proven effective for ecological risk assessment, incorporating multiple lines of evidence and accounting for uncertainties in exposure and effects data. These probabilistic approaches provide more nuanced risk characterizations that can better inform environmental management decisions under conditions of incomplete information (Luechtefeldand Hartung, 2018).

2.4 Computer Vision for Ecosystem Monitoring

Computer vision algorithms, particularly convolutional neural networks (CNNs), have revolutionized the processing of visual environmental data from satellites, drones, and camera traps. These systems can automatically identify, classify, and quantify environmental features such as vegetation types, land use changes, and wildlife populations at unprecedented scales (Kattenborn et al., 2021).

In aquatic ecotoxicology, computer vision enables automated analysis of behavioral alterations in test organisms exposed to contaminants. Changes in swimming patterns, feeding behaviours, and social interactions can be quantified as sensitive endpoints for toxicity assessment, providing early warning indicators of environmental stress.Remote sensing combined with AI has transformed the detection and monitoring of pollution events such as oil spills, algal blooms, and industrial discharges (Bae and Park., 2014).

2.5 AI for Environmental Data Integration and Analysis

The heterogeneity of environmental data sources presents significant integration challenges that AI methods are uniquely suited to address. To create comprehensive environmental datasets, deep learning frameworks can harmonize data from diverse sources including field measurements, laboratory experiments, remote sensing, and citizen science initiatives (Hampton et al., 2017).

Natural language processing (NLP) techniques enable extracting valuable information from scientific literature, technical reports, and other text sources, facilitating knowledge synthesis across the fragmented ecotoxicological literature. Text mining algorithms can identify emerging contaminants, track evolving research trends, and compile evidence on exposure-response relationships from thousands of publications.Explainable AI approaches are increasingly important for environmental applications where transparency and interpretability are essential for stakeholder acceptance and regulatory compliance. These methods provide insights into the factors driving model predictions, allowing scientists and decision-makers to understand the basis for AI-generated environmental assessments (Wang et al., 2025).

3. Internet of Things (IoT) for Environmental Monitoring

Kevin Ashton first proposed the concept of IoT in 1999, and he referred to the IoT as uniquely identifiable connected objects with radio-frequency identification device (RFID) technology. However, the exact definition of IoT is still in the forming process that is subject to the perspectives taken. IoT was defined as "dynamic global network infrastructure with self-configuring capabilities based on standards and communication protocols" (Gokhale et al., 2018).

The "Thing" in IoT can be any device with any embedded sensor that can collect data and transmit it across the network without manual intervention (AitMouha, 2021).

3.1 IoT Infrastructure for Environmental Applications

The Internet of Things represents a network of interconnected devices embedded with sensors, software, and network connectivity that enables them to collect and exchange data. Environmental IoT deployments typically consist of sensor nodes, communication networks, data storage systems, and analytics platforms that provide real-time environmental intelligence (Das et al., 2025). Low-power wide-area networks (LPWAN) technologies such as LoRaWAN, NB-IoT, and Sigfox have extended IoT capabilities to remote environments with limited infrastructure, enabling monitoring in previously inaccessible locations. These technologies support long-range communication with minimal power requirements, facilitating the deployment of environmental sensor networks in wilderness areas, marine environments, and developing regions (Iqbal et al., 2020; Ramirez et al., 2022).

Edge computing architectures process environmental data closer to its source, reducing latency and bandwidth usage while enabling rapid responses to detected environmental threats. This distributed approach to data processing is particularly valuable for time-sensitiveapplications such as flood warning systems, wildfire detection, and industrial emission monitoring (Mamat et al., 2021).

3.2 Smart Sensor Networks for Pollution Detection

Advances in sensor miniaturization, energy efficiency and wireless connectivity have enabled the development of dense networks of environmental sensors that provide unprecedented spatial and temporal resolution of pollution data. These networks can detect pollutants at concentrations that were previously undetectable using conventional monitoring approaches, revealing subtle patterns of contamination (Rayabharapu et al., 2022). Low-cost air quality sensors have democratized air pollution monitoring, enabling community-based approaches to environmental surveillance and environmental justice initiatives. When calibrated appropriately and integrated with professional monitoring systems, these networks provide granular data on spatial variations in air pollution exposure, supporting epidemiological research and targeted interventions (Velez-Guerrero et al., 2023).

Distributed sensor networks with machine learning capabilities can identify pollution sources. By analyzing the temporal and spatial characteristics of pollution events, these systems can distinguish between industrial emissions, traffic-related pollution, and natural sources, informing more targeted pollution control strategies (Ullo and Sinha, 2020). IoT-enabled water quality monitoring systems continuously measure physical, chemical, and biological parameters, including temperature, pH, dissolved oxygen, turbidity, nutrients, and specific contaminants. These systems enable early detection of water quality deterioration, pollution events, and harmful algal blooms, allowing for rapid management responses. Smart water sensing networks deployed across watersheds can trace pollution from source to sink, identifying point and non-point pollution sources and quantifying their contributions to overall water quality impairment (Islam et al., 2021; Khan et al., 2021).

4. Renewable Energy Technologies and Their Environmental Impact

The convertible currency of technology is energy. The entire structure of civilization would collapse without energy. Energy supply and use issues are linked to environmental issues such as air pollution, acid precipitation, ozone depletion, forest degradation, radioactive material emissions, and global warming. For mankind to have a bright energy future with minimal environmental repercussions, these challenges must be considered at the same time. There is a lot of evidence that if people continue to destroy the environment, it will have a detrimental effect on the future. Increasing renewable energy sources and technology is one way to address the impending energy shortfall (Dincer, 2000).

4.1 Solar Energy

The most plentiful renewable resource on Earth is solar energy. Despite this abundance, 0.04% of the fundamental power consumed by humans comes directly from solar sources (Mohtasham, 2015). Recent solar photovoltaic (PV) technology developments have significantly improved energy conversion efficiency while reducing manufacturing costs and environmental impacts (Mughal et al., 2018). Perovskite solar cells, tandem architectures, and bifacial modules represent promising approaches to exceed the theoretical efficiency limits of traditional silicon PV cells (Lehr et al., 2022).

Life cycle assessment studies indicate that next-generation solar technologies can dramatically reduce carbon footprints and energy payback times compared to conventional energy sources and earlier PV technologies. These improvements address concerns about resource consumption and emissions associated with renewable energy manufacturing. Ecotoxicological considerations in solar technology development include the replacement of toxic materials such as lead and cadmium with more environmentally benign alternatives and the design of panels for eventual recycling and material recovery (Kannan andVakeesan, 2016).

4.2 Wind Energy

Wind power energy is a very simple process. Like other renewable energy sources, wind energy has many advantages. It reduces greenhouse gas emissions by using turbines, which produce energy and electricity when moved by the wind and can reduce electricity costs. Innovation in wind turbine design has addressed key environmental concerns, including wildlife impacts, noise generation, and visual disturbance. Radar-activated shutdown systems, blade painting schemes, and ultrasonic acoustic deterrents have demonstrated effectiveness in reducing bird and bat mortality at wind energy facilities.

Floating offshore wind platforms have expanded the potential for wind energy development in deeper waters, reducing conflicts with coastal ecosystems and fisheries while accessing stronger and more consistent wind resources. These installations present different ecological considerations than fixed-foundation turbines, requiring tailored environmental monitoring and management approaches (Tan et al., 2022). Life cycle assessment of modern wind energy systems demonstrates significant environmental advantages over fossil fuel generation, with continual improvements in energy return on investment and reductions in resource requirements per unit of electricity generated. Developing recyclable blades and sustainable decommissioning protocols further enhances the environmental performance of wind energy systems (Darwish and Al-Dabbagh, 2020).

4.3 Hydroelectric Power

One clean and renewable energy source is hydropower. Most nations prioritize the development of hydropower because of its advantages in terms of economy, technology, and the environment. For instance, with a total theoretical hydropower capacity of 694 GW, China possesses the world's largest hydro resources (Mohtasham, 2015).Advanced hydroelectric designs, including run-of-river systems, enhanced fish passage technologies, and variable-speed turbines, reduce ecological impacts while maintaining energy generation capacity. Environmental flow regimes that mimic natural hydrological patterns can support downstream ecosystem functions while meeting energy production goals.

Small-scale hydropower innovations such as in-pipe turbines, irrigation canal systems, and low-head installations provide distributed renewable energy with minimal additional environmental disruption. These technologies utilize existing water infrastructure, avoiding the significant ecosystem alterations associated with large dam projects. The removal of aging dams, coupled with the installation of more ecologically compatible hydropower systems, represents an emerging approach to river restoration and sustainable energy production. This strategy can reconnect fragmented aquatic habitats while maintaining renewable energy generation through more efficient and environmentally sensitive technologies (Singhania, 2024; Pandey and Karki, 2016).

4.4 Biomass Energy

Biomass energy is a renewable energy source derived from organic materials such as agricultural residues, wood, food waste, and algae. It can be converted into heat, electricity, or biofuels, offering a sustainable alternative to fossil fuels. Recent advancements in biomass energy have significantly improved its efficiency and environmental impact. For example, second-generation biofuels now use non-food biomass like crop residues and forest waste, reducing competition with food production. Algae-based biofuels are gaining attention due to their rapid growth rate, high oil content, and ability to grow on non-arable land. Additionally, technologies like pyrolysis and gasification have enhanced the conversion of biomass into cleaner, more energy-dense fuels. Innovations in anaerobic digestion systems have also boosted biogas production from organic waste, making biomass energy more viable and eco-friendlier than ever (Mohtasham, 2015; Banerjee, 2023).

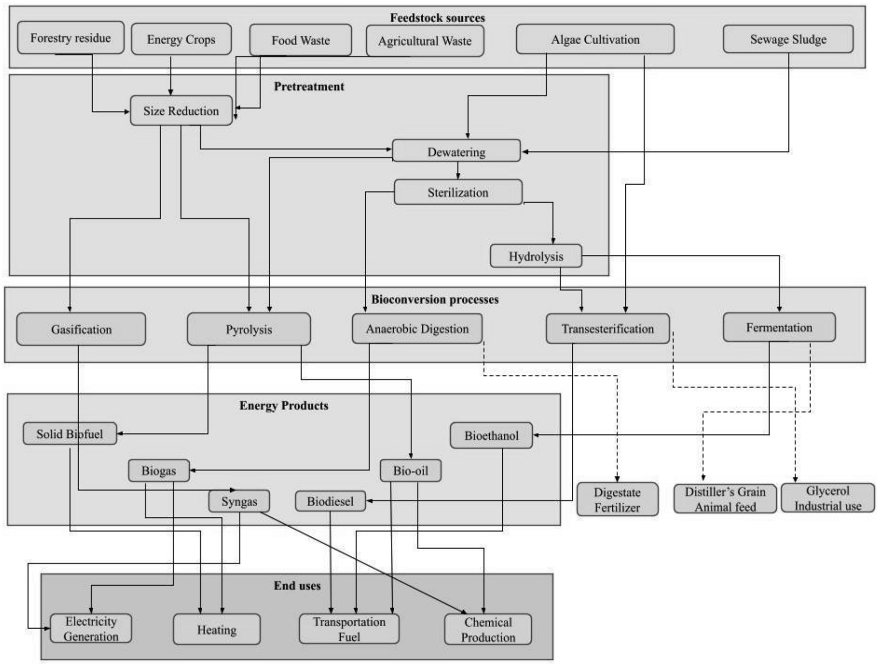

Figure 1: Biomass Energy Conversion.

4.5 Geothermal Energy

Geothermal energy is a renewable source that uses heat from beneath the Earth's surface to generate electricity and provide direct heating. Traditionally, it relies on naturally occurring hot water and steam reservoirs, but recent innovations are expanding its potential. One significant advancement is Enhanced Geothermal Systems (EGS), which create artificial reservoirs by injecting water into hot, dry rock formations-allowing energy extraction in areas without natural geothermal resources.

Another cutting-edge development is closed-loop geothermal systems, where a working fluid circulates through a sealed pipe underground, preventing environmental contamination and improving efficiency. Additionally, lithium extraction from geothermal brine is emerging to supply materials for batteries while generating clean energy. These innovations are making geothermal power more accessible, scalable, and sustainable for a broader range of locations across the globe (Akhigbe, 2025).

Table 1: Renewable Energy-Energy Production, Advancements, Pros and Cons

Energy Type	Basic Info	Energy Production	Advancements	Pros & Cons
Solar	Harnesses sunlight via photovoltaic (PV) panels or solar thermal systems.	~1,000 kWh/kW per year (varies by location). Global capacity: ~1,200 GW (2023).	Perovskite solar cells, bifacial panels, floating solar farms, AI-driven optimization.	Renewable, low operating costs. Intermittent, high initial cost, land use.
Wind	Uses turbines to convert kinetic energy from wind into electricity.	Onshore: ~2,500–5,000 kWh/kW/year. Offshore: ~6,000+ kWh/kW/year. Global: ~900 GW.	Larger turbines (15+ MW), floating offshore wind, hybrid wind-solar systems.	Scalable, low emissions. Noise, bird impacts, intermittent.
Hydro	Generates power from flowing water (dams, run-of-river).	~4,000 TWh globally (largest renewable source). Capacity: ~1,400 GW.	Small-scale hydro, pumped storage hydropower, fish-friendly turbines.	Reliable, high efficiency. Ecosystem disruption, high upfront cost.
Biomass	Burns organic matter (wood, crops, waste) or converts it to biogas/biofuels.	~500 TWh globally (varies by feedstock). Co-firing with coal reduces emissions.	Advanced biofuels (algae), waste-to-energy, carbon capture integration.	Waste utilization, dispatchable. Air pollution, land competition.
Geothermal	Uses heat from Earth's core for electricity (steam turbines) or heating.	~100 GW global capacity (steady output). Supplies ~0.3% of global electricity.	Enhanced Geothermal Systems (EGS), binary cycle plants, low-temperature tech.	Baseload power, small footprint. Location-specific, high drilling costs.

5. Advanced Pollution Control Technologies

Advanced pollution control technologies are innovative solutions designed to mitigate environmental pollution across various sectors, including industrial, automotive, and municipal waste management. These technologies aim to reduce emissions, treat contaminants, and promote sustainable practices.

5.1 Next-Generation Filtration and Separation Technologies

Advanced membrane technologies, including forward osmosis, membrane distillation, and functionalized nanomembranes, offer superior separation performance for complex waste streams. These technologies can remove emerging contaminants, microplastics and other pollutants that challenge conventional treatment systems (Wang et al., 2024).

Electrochemical filtration combines physical separation with oxidation/reduction processes to degrade contaminants while removing them from waste streams. This multifunctional approach is efficient for persistent organic pollutants and other recalcitrant compounds that resist conventional treatment methods (Chen et al.,2005).3D-printed adsorbents with precisely engineered pore structures and surface chemistries enable highly selective removal of target contaminants from air and water. These materials can be designed for specific pollutants, improving removal efficiency while minimizing energy and material requirements (Wang et al., 2022).

5.2 Bioremediation and Phytoremediation Innovations

Synthetic biology approaches to environmental remediation involve engineering microorganisms with enhanced capabilities for pollutant detection, degradation, and transformation. These designer organisms can target specific contaminants or chemical classes andaccelerate remediation processes while minimizing ecological disruption.Plant-endophyte partnerships represent a promising direction in phytoremediation research, where plant hosts and their microbial symbionts work synergistically to remediate contaminated soils. These associations can enhance contaminant uptake, transformation, and tolerance, extending the range of pollutants amenable to plant-based remediation (Malik, 2022).

Metagenomics and other omics technologies have revealed previously unknown biodegradation pathways and organisms with remediation potential in various environments. This knowledge enables more targeted bioremediation approaches and the development of site-specific microbial consortia optimized for contaminant profiles(Techtmann and Hazen, 2016).

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5.3 Carbon Capture and Utilization Technologies

Direct air capture technologies have advanced significantly, with innovations in sorbent materials, process engineering, and energy integration reducing costs and energy requirements. These systems can remove CO^2 directly from ambient air, complementing point-source capture approaches and addressing historical emissions (McQueen et al., 2021).

Biological carbon capture utilizing microalgae, cyanobacteria, and engineered plants offers natural mechanisms for CO^2 fixation with potential co-benefits, including biomass production, wastewater treatment, and ecosystem services. Research in synthetic biology and bioreactor design continues to improve the efficiency and scalability of biological carbon capture systems. Carbon utilization pathways transform captured CO^2 into valuable products, including building materials, chemicals, and fuels, creating economic drivers for carbon capture implementation. Integration of carbon capture and utilization with industrial processes creates synergies that improve overall system efficiency and economic viability (Yang et al., 2024).

5.4 Nanomaterials for Environmental Remediation

Engineered nanomaterials offer unique properties for environmental applications, including high reactivity, large surface area-to-volume ratios, and tunable surface chemistries. These materials can catalyze contaminant degradation, selectively adsorb pollutants, and serve as sensors for environmental monitoring. Reactive nanomaterials such as nanoscale zero-valent iron (nZVI) have demonstrated effectiveness for in situ remediation of contaminated groundwater, transforming chlorinated solvents, heavy metals, and other priority pollutants. Modifying these materials can enhance their mobility, reactivity, and specificity for target contaminants (Yin et al., 2022).

Ecological and human health considerations associated with environmental applications of nanomaterials remain an active research area.Safe-by-design approaches incorporate biocompatibility and transformability into nanomaterial development, reducing potential risks while preserving beneficial properties (Fadeel et al., 2017).

5.5 Advanced Oxidation Processes

Advanced oxidation processes (AOPs) generate highly reactive radical species capable of degrading recalcitrant organic pollutants to harmless end products. Innovations in photocatalysis, electrochemical oxidation and hybrid AOP systems have improved energy efficiency and expanded the range of treatable contaminants (Wang et al., 2022). Solar-driven AOPs utilizing visible light photocatalysts represent sustainable water and air treatment approaches, particularly valuable for remote locations and developing regions. Recent advances in photocatalyst design have extended light absorption into the visible spectrum, improving solar utilization efficiency (Zawadski, 2022). Process intensification strategies combining multiple AOPs or integrating AOPs with biological treatment can overcome the limitations of individual technologies and achieve complete pollutant mineralization. These integrated approaches optimize energy use and treatment performance for complex waste streams containing multiple contaminant classes (Pandis et al., 2022).

5.6 AI-IoT Integration for Environmental Monitoring and Management

The convergence of AI and IoT creates intelligent environmental monitoring systems capable of autonomous operation, adaptive sampling strategies, and real-time data interpretation. These integrated systems shift environmental monitoring from periodic sampling to continuous surveillance with automated detection of anomalies and emerging threats.

Digital twin technologies create virtual replicas of environmental systems that can be used for scenario analysis, predictive modeling and decision support. These digital models, continuously updated with IoT sensor data and refined through AI algorithms, enable a more sophisticated understanding of environmental processes and intervention outcomes (Shah et al., 2024; Suparna et al., 2025).

6. Conclusion

The convergence of artificial intelligence, the Internet of Things, renewable energy and advanced pollution control technologies has created unprecedented opportunities to address complex environmental challenges.These technological innovations enhance our ability to detect, understand, and mitigate environmental threats while supporting the transition to more sustainable production and consumption systems.

Effective integration of these technologies requires interdisciplinary collaboration, responsible innovation practices, and careful consideration of technical and socioeconomic factors.By combining technological advancement with ethical reflection and inclusive governance, we can harness these innovations to support healthier ecosystems and more sustainable societies.The field of ecotoxicology is being transformed by these technological developments, with new approaches to monitoring, assessment, and remediation expanding our capacity to protect environmental health. As we continue to develop and deploy these technologies, maintaining focus on their ultimate purposecreating a more sustainable relationship between human activities and the natural environmentremains essential.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-11

Constitutional and Legal Framework for Environmental Protection

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ABSTRACT

The environment and its degradable challenges are the global issues, with numerous conferences and agreements aimed at safeguarding the planet's health with coterminous targets of development. For which world consensus is high-rated on the table but low-rated on the ground. Environmental law frameworks and policies are dual in nature, existing at both national and international levels. India is a signatory as well as a rectifier of several environmental treaties. The establishment of the UN Charter in the aftermath of World War II led to the evolution of the sound concept and practical approach of sustainable development in the Declaration on Human Rights at Stockholm. International treaties, such as the Montreal Protocol and the Brundtland Commission, exert binding effects on nations, governing their interactions and promoting international law. India's commitment to environmental protection and sustainable development is reflected in its domestic legislation and its development of a worldwide solar alliance. The Earth Summit, held in 1992, was a successful global environmental and development

summit involving over 150 nations. It approved the crucial binding agreement and commitment by the world nation. The United Nations Commission on Sustainable Development (UNCSD) was established to assess the progress made by member nations, aiming to promote collaboration and equitable resource allocation. The Kyoto Conference on global warming in 1997 committed to reducing greenhouse gas emissions, and COP28 in 2023 focused on transitioning to renewable energy solutions, which clearly shows the commitment of nations, at least in frameworks. The international investment law treaties also mention the environmental clause in the bilateral and multilateral agreements, which show the pen work well done but with no men working. As under this study various legislative steps and commitments are being discussed, which are the collective responsibility of the residents of this Earth, which can't be improved without involvement in action, but these last 5 centuries have really made a difference of opinion on prioritizing health over development. Such a law will always be made in the future also, but it's human activities which need to be, well, fair and equitable from the environment's point of view, for which it's the need of the hour to make such a law stricter and more actionable per se.

Keywords: Environment, earth, sustainable development, treaties, legislation

1. Introduction

The environment and the enforcement of environmental legislation are global problems. Numerous conferences of parties have occurred to date; nonetheless, their objectives and accomplishments remain unfulfilled. International legal frameworks and environmental policies are sophisticated, multidimensional systems intended to safeguard our planet, Earth, rich in natural resources, public health, and the environment, from the detrimental impacts of human activities associated with development, research, and warfare. The legal and regulatory frameworks are dual in nature, existing at both national and international levels. India is a signatory to several environmental legislations that include binding treaties. India has enacted domestic legislation and is now developing a worldwide solar alliance to facilitate the accessibility and affordability of renewable energy; hence, substituting non-renewable resources. These rules established a new framework for global change that collectively directs sustainable growth and environmental preservation worldwide (Divan and Rosencranz, 2001)

2. Historical Development of International Environmental laws

In the aftermath of the two world wars, the establishment of the UN Charter marked a significant moment in global history. Under such a charter, numerous organisations have, for the first time, directed their attention on an international scale towards issues pertaining to the environment. Rather than the continuous pursuit of development, the term "sustainable development" has gained prominence, first articulated in the Cocoyoc declaration during the early 1990s, which focused on the interplay between environmental considerations and developmental goals. Despite the numerous discussions and accolades surrounding environmental issues at the United Nations General Assembly, it was in 1967 that the Maltese proposal was ratified, establishing a framework for legal protection aimed at fostering sustainability and development within the international community (Leelakrishnan, 2008). The phrase "rights of future generations" gained significant acknowledgement globally through the Stockholm Declaration on Human Rights, a product of the "United Nations Conference on Human Environment" held in 1972, where the then Prime Minister of India, Mrs Indira Gandhi, was also in attendance. This conference highlights the imperative of safeguarding the environment while establishing a formal agenda for international policy and regulation. The central focus of the conference revolved around the implications of human activity on the environment, particularly addressing the management of anthropogenic pollution and the urgent need to regulate the depletion of natural resources. Secondly, a conflict emerged between nations, characterized by the disparity between developing and developed countries, as the latter engaged in the unrestricted exploitation of natural resources in pursuit of advancement. A total of 26 principles were adopted, which, while not binding on 114 signatory nations, represented an early yet significant framework for environmental law. These principles encompassed a wide array of fundamental freedoms, including equality, health, wildlife habitat, urbanisation, precautionary measures, greenhouse effects, ozone layer depletion, and various human activities that impact the environment.

3. "Treaties" International Binding Agreements

International treaties exert binding effects within the realm of international law, as they represent legally binding agreements among nations that must be adhered to, thereby governing their interactions with one another. We can categorise treaties into two distinct types: bilateral and multilateral. In these agreements, nations commit to binding obligations that pertain to the signatory parties. Furthermore, the Indian Constitution mandates the Indian Parliament to oversee the rectification and regulation of such international treaties, ensuring the establishment of suitable provisions and laws that promote international law (Sands et al, 2018). The majority of environmental legislation is derived from international agreements. The Indian Environmental Protection Act serves as a notable instance of international treaties. In contemporary society, industrialisation is meticulously regulated, taking into account the environmental impact assessments pertinent to specific industrial zones. This regulation is an integral aspect of the act, wherein public participation is of paramount importance (Sathe, 2002).

I. **Montreal (Canada) Protocol:** The Year of 1987 Was this a significant year in environmental history, as this protocol facilitated the consensus among nations concerning the issues related to the ultraviolet ray-reflecting layer, namely, the depletion of the ozone layer? This is the rationale behind the designation of this protocol as the Ozone Treaty. The inception of this treaty occurred on January 1st, 1989. This protocol facilitated a collaborative effort between developed and developing nations to address the critical issue of ozone layer depletion attributed to chlorofluorocarbons. The treaty exerted a compelling influence on developed nations, given that the preponderance of signatory nations were indeed developed. Developing nations, including China and India, opted not to sign due to the high costs associated with alternatives to chlorofluorocarbons and their specific development objectives. These nations continue to use these substances for commercial and research applications. In contrast, developed countries, particularly the United States, are responsible for the majority of emissions, primarily for luxury conveniences such as refrigeration, air conditioning, and entertainment, etc.

II. **Brundtland Commission:** Initially, this commission was known as the World Commission on Environment and Development. In its 1987 report, widely recognised as Our Common Future, it expanded the concept of sustainable development, facilitating its global recognition and comprehension. This commission highlighted the significance of recognising the diverse political, economic, and sociological landscapes that characterise individuals and nations. However, it is imperative to acknowledge our shared resources, environment, and atmosphere, which necessitate a commitment to sustainability (Singh, 2016). The commission emphasises two fundamental aspects:

firstly, the priority of the term "need," as it is imperative that the necessities of the impoverished global population are not overlooked. Furthermore, the constraints imposed on developed nations concerning technology and social organisations serve to prevent environmental exploitation, thereby safeguarding the needs of future generations. This assignment is essential to strike a harmonious balance between economic growth and sustainable development while addressing the essential needs of both the environment and society. This commission acknowledges the paramount importance of fundamental human rights, intergenerational equity, rigorous environmental standards, and monitoring; the necessity of industrialisation coupled with environmental assessments; and the collective obligation of nations to collaborate. Furthermore, it emphasises the conservation of biological diversity and the biosphere, as well as their sustainable utilisation**etc.**

III. **Earth Summit**: Influenced by the Brundtland Commission's report, the earth summit marked a significant achievement in addressing goals related environment and development. In 1992, more than 150 nations at the "UN Conference on Environment and Development" accepted this influence and need, which is more commonly referred to as the Earth Summit 1992. This summit encourages the member states to consider future elements of future demands without sacrificing the needs of today. Additionally, the summit approves and passes a plan for sustainable development that is referred to as Agenda 21. The "Rio Declaration on Development and Environment", the "Forest Principle", and the two legally binding treaties that are connected to "Climate Change" and "Biodiversity" are three other outstanding works that were produced as a result of this summit (Birnie et al., 2009). Considering everything, this summit in 1992 was a truly enlightening and collaborative step towards a deeper understanding of the world's evolving needs and the complex environmental issues. It also established law-backed agreements to address these needs, incorporating accepted principles and conventions such as pollution, poverty, precautionary principles, polluter pay principles, public participation, and governmental plans of action at the national, local and regional levels, etc. (United Nations, 1992).

IV. **United Nation Commission on Sustainable Development**: This commission was established in response to Agenda 21, stemming from the 1992 Summit, as previously noted, to assess the advancements made by member nations of the Earth Summit. The UNCSD serves as the operational entity established pursuant to Article 38 of the UN Charter, functioning under the auspices of the UN Organisation of Economic and Social Council since its inception on February 16th, 1993. The primary objective is to foster collaboration among nations to attain equilibrium between developed and developing countries, as well as to ensure a fair allocation of natural resources. It further advances sustainability across national, regional, and international communities through intergovernmental collaboration to enhance Agenda 21 and the Convention on Biodiversity and Forests. This commission compiles an evaluative report and presents it to the UN General Assembly, detailing the advancements made, the mechanisms of oversight established during the Earth Summit, and addressing issues that were not deliberated or highlighted during the Rio Earth Summit.

V. **“Green fund” conference or Kuala Lumpur Conference**: At this conference, which was held in Kuala Lumpur, Malaysia, in 1992, the ministers of developing nations came together with the idea of a reciprocal arrangement with the developed nation to establish a fund that is known as the

Green Fund. The purpose of this fund is to generate funds that can be used to ensure that the earth and every nation have at least thirty percent of their land covered by forest by the year 2000 (Bodansky, 2010). India was also a participant at such a conference that took place in Malaysia; nevertheless, countries such as the United States of America did not take action to fix such a fund. The most important motivating factor for the establishment of this fund is the fact that nations that plundered the Earth without regard to sustainability are now much more developed and have huge pockets with which they can contribute to the process of regreening the planet again.

VI. **Earth Summit Plus 5**: The actions of the nation's members represented a significant advancement in environmental jurisprudence, occurring subsequent to the five-year interval following the inaugural Earth Summit convened in 1992. The Earth Summit Plus 5 of 1997 exemplifies the dedication of member nations and United Nations organisations to their profound concern and inquiry for an improved planet. During the 1997 summit, the United Nations General Assembly deliberated on a report assessing the progress made by member nations over the past five years in relation to the objectives established at the Rio conference in 1992. The result of this submission indicated a 2% increase in greenhouse gas levels, alongside an estimated 13.7 million hectares of deforestation occurring under the auspices of urbanisation and industrialisation. This summit underscored the imperative of increasing foreign aid to developing nations in order to mitigate greenhouse gas emissions. The delegates of this summit underscored the significance of the global warming challenge and the imperative for solutions at both international and national tiers of environmental jurisprudence to realise the "programme of action" for sustainable development.

VII. **Greenhouse Gas Conference or the Kyoto Conference on Global Warming**: One of the most significant steps that has been taken in the direction of reducing greenhouse emissions was this meeting. The first legally binding promise of its sort was made to members all over the world at the formal meeting of members that took place in Kyoto. This commitment was on the subject of lowering emissions of greenhouse gases and addressing the issue of global warming. At the international climate conference that took place on December 11th, 1997, a total of 159 countries participated and reached an agreement to reduce the amount of greenhouse gases that are used in states that are industrialised. The primary goals of this protocol were, first and foremost, to regulate the emission of greenhouse gases in such a way that the atmosphere would be at a level that would allow the ecosystem to naturally adapt and rejuvenate itself; secondly, to ensure that the global order concerning food security would not be disrupted; and thirdly, to ensure that the economic activities of the nation would proceed in a manner that is both environmentally responsible and sustainable (**UNFCCC, 1992**).

VIII. **Earth Summit Plus 10 (2002):** This event marked the third Earth Summit following the 1992 Rio conference, a ten-day gathering convened in Johannesburg to address issues of sustainable development and environmental stewardship. It is noteworthy that the former UN Secretary-General, the Honourable Kofi Annan, emphasised to the participants the decade-old commitment to environmental protection and sustainability, along with the principles and frameworks of Agenda 21 established in Rio in 1992. The summit culminates in a novel declaration concerning sustainable development (Johannesburg), which further emphasises the necessity of fostering new partnerships and alliances aimed at advancing African development (NEPAD). The Jonesburg declaration embraced a multitude of principles grounded in notions of equity and humanity, addressing issues such as illicit drug challenges, corruption, chronic hunger, disabilities, biodiversity conservation, adequate housing, health care, energy sustainability, fish stock management, global partnerships, organised crime, endemic conditions and armed conflict, among others. The tenets of this conference encompass the engagement and collaboration of the private sector in addressing the challenges articulated during the summit (Redgwell, 2000).

IX. **Copenhagen Climate Summit (COP15) 2009** : The Copenhagen Summit (COP15) This term pertains to the annual conference of parties, which serves as the sole platform for nations to convene, assess the advancement of their objectives, and engage in discussions regarding pertinent environmental issues. This collaborative effort culminated in the Copenhagen Accord (COP 15). During this summit, the member nations of the UN reached a voluntary consensus to diminish emissions of greenhouse gases, opting for commitments rather than a legally binding treaty. In spite of the considerable efforts exerted by the nations involved, the summit culminated in the absence of a legally binding agreement; instead, nations merely "took note" of the COP, resulting in a political statement rather than an enforceable and law-making treaty. Over time, the strategy of nations relying on voluntary pledges devoid of legal enforcement has significantly influenced the development of a "pledge-and-review" framework. This system has garnered attention and prompted concern and discourse within the context of the Paris Agreement, where participating nations establish and periodically revise their commitments to addressing climate change and promoting sustainability.

X. **The Paris Agreement 2010 and the COP 21**: As it achieved a turnout from the previous political pledges and evaluated its pledge system that produced the Paris Agreement 2015 (COP21), the year 2010 became the cornerstone year of the worldwide climate conferences and meetings. All things considered, other initiatives, not the same as before, such as the Copenhagen 2009 or the Kyoto Protocol, which remain political pronouncements merely, one way or the other, lacked legally enforceable objectives or were more focused on blaming only rich nations for exploitation. This COP 2015 drew attention to a historic change. Adopting the "bottom-up" idea meant every nation had to file its own NDC report to lower or cut the greenhouse gas emissions. Every five years, these reports or goals will be enhanced for improved performance. Aiming to bring the planetary temperature to pre-industrial levels, the COP 2015 pledges seek to lower global warming by at least 2°C (Hunter ET AL., 2011). Raising awareness about the often-used term on global concerns of global warming and climate change, the Paris Agreement offers a new path to the continuing conferences and summit. One of the most open, ambitious, and practical mobilising climate finances was the Paris Agreement, which is more centred and fair for the poor countries as well as the affluent ones. As it provides a realistically feasible and universal aim for which actual efforts were well observed internationally, this COP has closed the gap between what is and what should be.

XI. **Conference of United Nations Conference on Sustainable Development:** The commitments of nation continues with the Rio de Janeiro in 2012 conference of United Nations Conference on Sustainable Development which developed the concept of green economy and

Introduce the world with the most basic and fundamental goals based on the basic needs and humanity and welfare development of the nation i.e. sustainable development goals (SDGs), which purposely aiming to adhere the environmental Impact and allowing economic advancement with ecological sustainability. The another remarkable summit of UN Climate Action in 2019 urges the focus on global climate action and an obligation set for all nations without differencing developed and developing nations to net-zero commitments, to achieve net-zero emissions by mid-century. The outcome of COP, conferences, summit and commitments can be well appreciated in 2020s, which results in strengthening global climate targeted goals and Increased encouragement partnership among regional governments, borderless businesses, which is the need of time for the international communities essential for a better sustainable and strong future. The next upcoming development in environmental history was Glasgow Climate Pact (COP26) in 2021 strengthened achievable climate targets for reducing global increasing temperature of the planet, which includes avoiding or reducing the dependence of coal use, and increasing the contribution to climate finance fund, this climate pact emphasized the imminent need for collective efforts in combatting the climate change (UNEP, 2019). In recent years, COP27, which was hosted by Egypt in 2022, emphasised mainly the need for participation, loss and damage sustained by African nations, and the reminder to raise the climate finance by 20% for vulnerable or fundamentally poor nations, which focused on the significance of treating current and ongoing challenges while also planning and preparing for future disaster management through resilience-building and sustainable development initiatives of net zero emissions of CFC and greenhouse gases by 2050. A significant challenging step towards global climate action was approved for the first-ever commitment between world nations to shift away from fossil fuels, which are widely used in every nation from transportation to industry, by farmer to tycoon, at COP28 in 2023, which focused primarily on supporting and innovating the breakthrough technologies and creating more alternative modes of renewable energy solutions for a sustainable future.

4. India and its Environment Legal Framework:

India And its environmental jurisprudence though seem to be new but the environmental knowledge and protection were there from the very ancient time of the Indian civilization the habitats of India were from the ancient time have a religious respect towards the environment and its resources but in a modern time the environmental law in India is basically evolved from the international commitments and the treaties to which India is representing in the United Nations General Assembly. This is crucial to discuss in short what is the impact on Indian environmental jurisprudence after the 1972 Stockholm declaration (Bodansky et al., 2017) till date-

I. **Indian constitution and the environment:** The Indian Constitution did have the provision to protect the basic need and sustainability of the people and the society in 1950 itself when the constitution was enforced. Indian Constitution has three golden articles related to environment these Articles time and time again were interpreted and constructed by the honourable Supreme Court of India for the betterment of life, health, safety, sustainability and progress of the nation.

II. **Article 21:** This article is the part of the fundamental right which means the right to life. The right to life was interpreted and constructed by the Supreme Court in such a way that life means the healthy life, which includes the clean environment, water, air, and land. The right to life does not mean a mere existence like an animal but a better life with dignity where the Supreme Court of India gives it a wider meaning to include the healthy aspects of the environment favouring human health and the biodiversity (Constitution of India, art. 21).

III. **Article 48A:** This article is provided under Part IV, which is DPSP, which means it is a state duty and responsibility to enforce such law, which protects and improves the environment. It casts the duty on the state, and when the time demands, such a law must be there to enforce it (Constitution of India, art. 48A).

IV. **Article 51A(g):** This is the fundamental duty of every citizen provided in Part IV A of the constitution, which was not mandatory but declaratory as a duty to always be remembered as a citizen of India to protect and make efforts to improve the natural environment and resources of the nation (Constitution of India, art. 51Ag).

5. Major Acts Passed by Indian Parliament After Stockholm 1972

I. **The Environment (Protection) Act, 1986**: This Act is a comprehensive coverage of many environmental aspects like air pollutants and pollution, water pollutants and pollution in water, land and soil pollution, human health effecting pollutants, and hazardous. The Act was introduced by the Parliament of India as a cautious response to catastrophic incidents such as the Bhopal gas tragedy, which had devastating consequences for society at large. Aimed at fixing liability and ensuring the protection of both the environment and public health, the legislation also served to fulfill India's international commitments. Under this Act,

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the central government was empowered to regulate environmental protection by setting specific targets for pollutants and hazardous substances. It vested authority in the central government to measure, control, and prescribe standards for environmental quality. Notably, the Act is commendable for recognizing the importance of local residents' voices in affected areas, thereby promoting sustainability and pollution reduction through public participation. Unlike soft laws, this legislation enforces accountability by imposing strict liability on polluters, with provisions for imprisonment and substantial fines for violations (The Environment (Protection) Act, 1986).

II. **The Air (Prevention and Control of Pollution) Act, 1981:** The Air (Prevention and Control of Pollution) Act, 1981 was enacted to define and regulate air pollutants, with the objective of controlling industrial emissions that contribute to air pollution and balancing industrial development with public health concerns arising from industrialization. The Act established a two-tier regulatory framework consisting of the Central Pollution Control Board (CPCB) and State Pollution Control Boards (SPCBs). While the CPCB is responsible for regulating overall air quality and setting the Air Quality Index (AQI), which categorizes pollution levels as good, bad, or severe, the SPCBs oversee and monitor industrial activities that release hazardous and toxic pollutants at the state level. The Act extends to all activities contributing to air pollution, including emissions from automobiles, factories, industries, and construction sites. Additionally, it mandates that industries obtain prior approval from the state authority before commencing operations likely to cause air pollution (The Air Prevention and Control of Pollution Act, 1981).

III. **The Water (Prevention and Control of Pollution) Act, 1974:** The objective of the Act is to restore clean drinking water for the population and to regulate pollutants, harmful substances, and untreated waste discharged into water bodies. It emphasizes the preservation, storage, and conservation of water in both quality and quantity for the nation. The Act also establishes permissible limits for industries to conduct trade and business without causing water pollution, while empowering authorities to inspect and collect samples to ensure proper implementation of the law. Furthermore, it provides for stringent punishment, which may extend to six years of imprisonment and a fine, in cases of violation of permissible limits. Notably, any complaint regarding the violation of this Act is cognizable and triable by a Judicial Magistrate (The Water Prevention and Control of Pollution Act, 1974).

IV. **The Forest Conservation Act, 1980**: The Act, 1980, is the new legal framework in independent India; it is designed not only to regulate the conversion of forest land for non-forestry purposes but also to foster the preservation of biodiversity and the forest ecosystems. The key objectives of the act are to save forests and endangered species of trees and manage and control the deforestation for which the role of central and state government is specially mentioned under the act. Act aims to balance the industrial, infrastructural, and agricultural expansion with that of forestation and its needs (The Forest Conservation Act, 1980). Pre-approval is Essential: Areas which are covered with forest should not be exploited unnecessarily for the human activities and wants, which include highway projects, mining sites, industrial areas, or agriculture land, without prior approval from the central government for which central bodies appoint the special advisory bodies on that basis. The role of central authority is prioritised over the state governments for the de-reservation or allocation of forests or the repurposing or redeveloping of forest land.

The act also clears the expected alternative goals for the use of land: it does acknowledge the development and need of the civilisation, for which forest land is acquired for agriculture, building, or development that happens without including regeneration and related measures. Above all, the Act prioritises forest conservation measures. Violations of the Forest Act may lead to serious repercussions, which include imprisonment and financial penalties. It seeks to attain a balance which is coterminous between development, progress and the protection and preservation of our ecological belt. It protects the fundamental welfare of the society and the communities and the human dependence on forests and their ecosystems for their survival.

V. **The Wildlife Protection Act, 1972**: It is not the most important law, but it has a significant impact on the environment and the conservation of wildlife animals and birds, including mammals and reptiles, as well as the eggs of such wildlife. The Wildlife Protection Act of 1972 also includes the two most well-known initiatives undertaken by the government of India. These initiatives are the project tiger, which aims to preserve the breeding and increasing population of Bengal Tigers, and the project that is related to the conservation and protection of elephants, which are primarily endangered in the widely accepted area of their habitats that are located in South India. In addition to focusing on the protection of wildlife, the Wildlife Protection Act also aims to make the habitat or the area that is demographically and geographically able to support life more hospitable and liveable for animals. This is done in order to ensure that animals are able to reproduce and survive in the environment that they fundamentally require. It is the responsibility of this act to provide wild animals with the necessary resources and sustenance that they need in order to survive or to get from their surroundings. It is a great accomplishment in and of itself because the Act clearly defines in its schedules which species are in danger and need urgent conservation and preservation. This is a big achievement. It also makes it illegal to hunt animals that are in risk of extinction. It is clearly provided for in the Act that the penalty for hunting animals that are included in schedules one and two is particular. In and of itself, the act is a promising piece of law that will contribute to the production of animals and to the preservation of environmental biodiversity (The Wildlife Protection Act, 1972).

VI. **The National Green Tribunal Act, 2010:** The National Green Tribunal (NGT) is a judicial body or aquatic judicial body which is constituted under the National Green Tribunal Act 2010. The main purpose of the NGT is to give award orders and directions in all cases related to environmental protection and environmental regulations which are purely civil in nature and to give such orders which fulfil the wide range of environmental laws with an expedient and expert award. The order degree or award passed by the NGT is only challenged before the Supreme Court. NGT is one of the most important environmental courts in India, second only to the Supreme Court. The National Green Tribunal has both appellate and advisory jurisdictions. The principal branch of the NGT is in Delhi; to have easy and affordable justice, it has regional branches in Bhopal, Chennai, Kolkata, and Pune (**The National Green Tribunal Act, 2010)**.

6. Conclusion

In conclusion, the evolution of international environmental law and India's environmental jurisprudence reflects a growing recognition of the need for sustainable development and the protection of natural resources. Despite numerous global conferences and treaties aimed at addressing environmental issues, significant challenges remain, particularly in balancing economic growth with ecological sustainability. India's commitment to international environmental treaties has led to the establishment of a robust legal framework, including key legislation such as the Environment (Protection) Act, the Air and Water (Prevention and Control of Pollution) Acts, and the Wildlife Protection Act. The National Green Tribunal further enhances India's capacity to address environmental concerns through specialized judicial oversight. As global climate initiatives continue to evolve, the emphasis on collaborative efforts among nations, public participation, and the integration of environmental considerations into development policies will be crucial for achieving long-term sustainability and protecting the rights of future generations.

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Chapter-12

Microplastics Pollution of Water Bodies: A Review

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AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration between all three authors. Author PYN guided the study and improved the first draft of the manuscript. Author VY prepared the table and wrote the final draft of the paper. Both authors managed the literature search of the relevant portions. Author NH wrote the first, rough draft of the paper and formatted the references in the format of the journal. All authors read and approved the final manuscript.

ABSTRACT

The durability and affordability of plastics have led to a steep increase in their production year after year. Plastic waste is generated as a result of the excessive production and use of plastics, which break down into microplastics. Plastic particles that are between 0.1 μm and 5 mm in diameter are termed microplastics (MPs). Over the past ten years, MPs have drawn considerable attention and are currently regarded as one of the most alarming new pollutants in natural habitats. This article reviews the existing research on the presence of MPs in water bodies and in both freshwater and marine water fish. It lays emphasis on identifying potential causes of MP ingestion and the resulting effects on fish.

Keywords: Microplastics, water bodies, microplastics in fish, plastic particles

1. Introduction

Plastics offer multiple health care, social and technical advantages due to their resistance to heat and cold, durability, affordability and portable nature (Jacob et al., 2020). Global plastic production has risen steeply from two million tons (Mt) in 1950 to 368 Mt in 2019 (Plastic Europe, 2020) and is expected to reach 12 billion tonnes by the year 2050 (UNEP, 2018). Year after year, a staggering increase in global plastic production and application has been observed due to the incredible versatility of these anthropogenic agents (Plastics Europe, 2022). The dramatic rise in plastic production and use has led to an increasing amount of plastic waste released into the environment and consequent ubiquitous plastic pollution of all ecosystems (Barnes et al., 2009). The problem becomes all the more pertinent in a highly populous country like India because our per capita plastic consumption is about 20kg (Shaikh and Shaikh, 2021) and the country ranks fourth for improper handling of plastic waste (Ahmed et al., 2021; Shanker et al., 2022).

In the environment, physical, biological and photo degradation of plastics results in slow fragmentation into smaller particles (Miller, 2020). This degradation of plastics takes hundreds to thousands of years (Gallo et al., 2018; Sathish et al., 2020). Aquatic ecosystems are extremely vulnerable to plastic pollution as an estimated 2 million tons of plastic waste flows from rivers to oceans every year (Lebreton et al., 2017). Though corrective measures are underway to control plastic pollution, the emission of plastic wastes in the environment is ever increasing and is likely to do so in the coming years (Borrelle et al., 2020), raising concerns about its impact on different life forms.

2. What Are Microplastics?

On the basis of its size, plastic debris in the environment are categorized as macroplastic (more than 2.5cm in size), mesoplastics (between 5mm and 2.5cm), microplastics (between 0.1 μm and 5 mm) and nanoplastics (less than 0.1 μm) (Lusher et al., 2017). Thompson et al. (2004) coined the term 'microplastic' (MP) to refer to a heterogenous mixture of plastic fragments in the range of 0.1 μm to 5 mm. Microplastics (MPs) that are less than 1 mm in size are called small MPs and those that are between 1-5 mm in size are called larger MPs (Lim et al., 2022).

Depending on their source of origin, MPs are classified as primary and secondary (Arthur et al., 2009). Primary MPs such as microbeads and fibres (Katzenberger and Thorpe, 2015; Napper et al., 2015) are either manufactured intentionally as in body washes, cleansers etc. or are formed during the production process or recycling process of plastics. Secondary MPs are formed when larger plastics undergo extended periods of degradation and fragmentation due to environmental factors (Svedin, 2020).

3. How Do Microplastics Reach Water Bodies?

Plastic pollution is of significant concern in aquatic ecosystems. Studies show the presence of MPs in aquatic ecosystems on all seven continents (Barnes et al., 2009). These may be in the form of fibres, pellets, spheres and foam (Cowger et al., 2020). There are several ways in which MPs can get into water bodies. Terrestrial plastic wastes in litter dumps, landfills, sewage sludge, dredge piles etc. are carried to water bodies by wind, erosion or surface run off. Grey waters i.e. water from kitchen sinks, wash basins, showers, washing machines etc. also contribute MPs to aquatic ecosystems (D'Avignon et al., 2022). Large plastic wastes such as fishing nets or gear in water bodies undergo fragmentation, bioerosion and photooxidation over several years. This results in the formation of secondary MPs (Jacob et al., 2020). MPs constitute 92.5% plastic debris in the marine environment. Their contribution to plastic litter in other aquatic ecosystems is likely to be similar because most of the plastic waste in water bodies originates from terrestrial sources such as sewage and land run off (Lim et al., 2022).

4. Characteristics of Microplastics

MPs in the aquatic environment can be in the form of fibres, films, fragments, foam and pellets. Several studies show that of all shapes of MPs, fibres are the most common in aquatic environment (Chen et al., 2021). Of all the MPs ingested by fish, the largest percentage of plastics is in the form of fibres, followed by fragments. Fibres are typically mono or polyfilaments, microfibres and threads. Major sources of these fibres are wastewater treatment plants (Napper and Thompson, 2016) and fishery activities (Lim et al., 2022). Flakes, particles, chips etc. constitute MP fragments (Lim et al., 2022).

MPs are chemically constituted by different types of plastics. Different plastic varieties such as polyethylene (Shivasharana et al., 2019), Poly vinyl chloride (PVC), High density polyethylene (HDPE), Low density polyethylene (LDPE) (Shivasharana et al., 2019), Polystyrene (PS), Polycarbonate (PC) (Chatterjee et al., 2019), Polypropylene (PP) and Polyethylene terephthalate (PET) (Shah et al., 2008) can form MPs. However, amongst different plastic varieties polypropylene holds the majority share in the market, and its increasing usage contributes to pollution in the environment (Chatterjee et al., 2019). A survey of global data shows that PE, PS, PP and PA are the most prevalent polymers ingested by fish, probably because they account for almost 80% of the plastic waste generated (Lim et al., 2022).

5. How Do Microplastics Reach Fish?

MPs are ubiquitous in all kinds of aquatic ecosystems. The presence of plastic particles has been well documented in a number of aquatic organisms such as aquatic birds (Kuhn and Franeker, 2012), crustaceans (Iannilli et al., 2018), cetaceans (Lusher et al., 2015) and fish (Foekema et al., 2013) etc. MPs are known to accumulate in various organs such as alimentary canal, muscles, brain, liver, gills and skin of fish (Collard et al., 2018; Ding et al., 2018; Daniel et al., 2020) where they have detrimental effects on the growth and survival of fish. Though several studies pertain to the levels of MPs in fish gut and their consequent effects, complete details of how MPs are taken up by fish are still not very clear. Three major uptake mechanisms are usually described (Roch et al., 2020). Firstly, MPs may be mistaken for food or prey by the fish, constituting primary ingestion (Ory et al., 2017). Secondly, MPs may be ingested passively or accidentally by the fish. Passive ingestion occurs if microplastics are taken up while breathing or if MPs are sticking to the body of the prey and are ingested along with the prey (Hoss and Settle, 1990). Thirdly, MPs may be transferred via the food chain (Jovanovic, 2017). Another possible uptake route is the ingestion of very small MPs along with water. This route becomes highly significant in case of marine fish vis a vis freshwater fish as the former drink water almost continuously to maintain homeostasis (Roch et al., 2020).

Table 1. Studies on presence of microplastics in water bodies of India

S. No	Location	Types of Microplastics	Polymers of Microplastics	Level of Microplastics	References
1.	Vellayani Lake, Kerala	Fibres, fragments, foam	HDPE, LDPE, PET, PP	65 particles/m^3 in monsoon & 49 particles/ m^3 in summers in surface waters	Mahidev et al., 2024
2.	Ponds in Chhatisgarh	Fragments, films and foam	Polyethylene and Polystyrene	2.52 ± 1.28 particles/L for bucket samples and 2.93 ± 1.34 particles/L for net samples.	Upadhyay and Bajpai, 2024
3.	Nainital Lake, Uttarakhand	Fibres were dominant	HDPE was most abundant	8.6–56.0 particles L−1 in surface waters of lake, 0.4–10.6 particles g−1 in sediment	Jain et al., 2024
4.	Upper River Ganga	Mainly fibres ranging from 100 μm to 1 mm in size	PE, PP, PET, PS	118.5 $\pm$ 49.65 particles/1000L in water & 131.5 $\pm$ 53.60 particles/kg	Badola et al., 2023

				dry weight in sediment.	
5.	River Ganga (Rishikesh to Farakka)	Filament	Polyester and Nylon	92.85 ± 50.69 particles m^{-3} (0.1 particle L^{-1}) of surface water.	Rajan et al., 2023
6.	River Jhelum, Kashmir	Flakes, filaments, fragments and spherules	PE, PVC and PP	1474 ± 1026 particles/m^3 in surface waters	Farroq et al., 2023
7.	River Godavari, Karnataka	Fibres, foam, fragment and film	PP,HDPE, LDPE etc	3900 items/m^3 in surface waters	Sekar and Sundaram, 2023
8.	Subarnarekha River &Kharkai River, Jharkhand	Fragments, films, foams and fibres	Polyester, PP, PVC, PS etc.	9.55 ± 4.87 items/L in surface water and 270.88 ± 105.89 items/kg in sediment samples.	Patidar et al., 2023
9.	Vembanad Lake, Kerala	Mainly fibres	Polyamide and PP	26.79 ± 3.74 items L−1 in subsurface waters and 52.70 ± 5.43 items L−1 in bottom waters	Anagha et al., 2023
10.	Chilika	Fragments	PP and PS	Maximum	Singh et

	Lake, Odisha	and foams		110.7 ± 35.6 items/100L in surface waters, Maximum 25.2 ± 9.8 items/kg in sediment	al., 2023
11.	Rewalsar Lake, Himachal Pradesh	Pellets and fragments	PS, PE and PP	13–238 particles L−1 in surface water and 750 to 3020 particles kg−1 dry weight in sediments.	Bulbul et al., 2023
12.	Kumaraswamy Lake, Tamil Nadu	Fibres, fragments and fims	LDPE, HDPE and PP 8.77 ± 0.27 particles per liter	8.77 ± 0.27 particles per litre	Ephsy and Raja, 2023
13.	River Sharavathi	Fragments, films, foams & fibres	PE, PET & PP	2.5 to 57.5 pieces/kg (premonsoon) in sediment 0 to 15 pieces/kg (postmonsoon) in sediment	Amrutha et al., 2023
14.	Anchar Lake, Jammu	Fibres, fragments, films and	PA, PET, PS, PVC,	606 particles/ kg	Neelavannan et al.,

	and Kashmir	pellets	and PP	in sediment	2022
15.	Pangong Lake (A), Tsomoriri Lake (B)and Tsokar Lake (C), Ladakh	Fragments and fibres	PE, PP, PS, PA, PET, PMMA	160-1000 MP/kg (A) 960-3800 MP/kg (B) 160-1000 MP/kg (C) in sediment	Tsering et al., 2022
16.	Kodaikanal Lake, Tamil Nadu	Fibres and fragments	PE &PP	24.42 ± 3.22 items/L in surface water 1728.31 ± 5.29 items/kg in sediment	Laju et al., 2022
17.	Manipal Lake, Karnataka	Fibres, fragments, pellets, films & foams	PET & Cellulose	0.423 particles/L (monsoon) 0.117 particles/L (postmonsoon) in surface water	Warrier et al., 2022
19.	Noyyal River, Tamil Nadu	Fragments, films, fibres and sheets	PP, PET, PS, LDPE, and PVAC	500 to 6500 n/m3 in dry sediments	Ayyamperumal et al., 2022
20.	Kaveri River	Fragments, films, foams and fibres	PA, PE, PET, PP and PS	386.07 ± 84.5 items/kg in river sediments	Maheswaran et al., 2022

21.	Brahmputra River and Indus River	Fragments, fibres and beads	PP and PE	Sammler MPs: 531–3485 MP/kg in the Brahmaputra River and 525–1752 MP/kg in the Indus River. Larger MPs: 20–240 MP/kg in the River Brahmaputra and 60–340 MP/kg in the River Indus	Tsering et al., 2021
22.	Ganga River (Central and Lower Stretch)	Film shaped were dominant	PE was dominant	17- 36 items/kg dry weight in sediment, 380- 684 items/1000 m3 in surface water	Singh et al., 2021
23.	Yamuna River, Delhi	Fragment, pellet, fibre, foam & film	HDPE, LDPE, PS. PP & PET	1.78×10^3 MPs/m^3	Vaid et al., 2021
24.	Renuka Lake, Himachal Pradesh	Fibres, fragments, pellets, films & foams	PE, PP & PS	21 ± 13 particles/L in surface water 180 ± 143 particles/kg dw in	Ajay et al., 2021

				sediment	
25.	Veernam Lake, Tamil Nadu	Fibres, fragments, pellets & films	Nylon, PE, PP, PS & PVC	28 items /km^2 in surface water 309 items/ kg in sediment	Bharath et al., 2021
26.	Alaknanda River	Fibers, fragments, films & pellets	PET, HDPE, PVC, PP, LDPE, PS	955 MPs-566 in water, 389 in sediment	Chauhan et al., 2021
27.	Red Hills Lake, Tamil Nadu	Fibres, fragments, films & pellets	PE, PP, HDPE, LDPE	5.9 particles /L in water & 27 particles /kg in sediment	Gopinath et al., 2020
28.	Netravathi River	Fibres, films and fragments	PE and PET were most abundant	288 pieces/m3 in surface water and 96 pieces/kg in sediment.	Amrutha and Warrier, 2020
29.	Lower Ganga River	Fibres, monofilaments, films, fragments, foams and beads	PET, PE, PP, PS	11.48–63.79 ng/g sediment	Sarkar et al., 2019
30.	Vembanad Lake, Kerala	Foam, fiber, film, filament	HDPE, LDPE, PP, PS	252.80 $\pm$ 25.76 particles/ m^2 in sediment	Sruthy and Ramasamy, 2017

HDPE = High Density Polyethylene, LDPE = Light Density Polyethylene, PET=Poly Ethylene Terephthalate, PP = Polypropylene, PS= Polystyrene, PA= Polyamide, PVC= Poly Vinyl Chloride, PMMA = Polymethylmethacrylate

6. Conclusion

Microplastics (MPs) are ubiquitous in all kinds of ecosystems across the globe. Due to the increasing demand for plastic goods and mismanagement of plastic wastes, an exponential increase in the release of MPs into the environment is noted year after year. This coupled with the pervasive nature of plastics makes them pollutants of serious concern. Increasing number of studies show the ingestion of MPs by fish and other aquatic organisms. Moreover, microplastics act as carriers for transmission of pathogens and other pollutants like heavy metals. The presence of MPs in fish is well documented. A number of studies have highlighted the effects of MPs on fish in the natural marine environment. Studies of presence and effects of MPs in the fresh water and culturable environment are fewer and these areas need to be seriously assessed. Laboratory studies have brought to light the ecotoxicological effects of MPs on various parameters of fish. However, there is a need to look into the environmental relevance of these studies so as to gain a realistic understanding of the risks associated with MPs pollution in aquatic environment. Fish constitute a very important source of dietary protein for humans. Therefore, there is serious concern about transfer of MPs across trophic levels and the consequent exposure of humans to MPs. A realization of the potential threat to humans is likely to lead to better management of plastic waste and policies for reducing the use of plastics.

COMPETING INTERESTS

The authors have declared that no competing interest exists.

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Chapter-13
Green Chemistry: A Sustainable Future Framework

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ABSTRACT

The fields of chemistry and industrial processes have experienced a significant shift in response to growing environmental concerns and the urgent need for sustainable growth. Green chemistry refers to the design of chemical products and processes that minimize or eliminate the use and generation of hazardous substances. Green chemistry encompasses all aspects of a chemical product's life cycle, including design, production, use and eventual disposal. Given their potential to innovate and enhance chemistry to aid in the achievement of global sustainable development goals, the concepts of green and sustainable chemistry have attracted a lot of attention worldwide. The present chapter explores the 12 Principles of Green Chemistry that provide foundation for sustainable chemical innovation, their implementation in various industries and their benefits as well as despite its benefits, green chemistry faces several challenges that were also discussed here. Addressing both environmental and economic issues while ensuring a healthy planet for future

generations will require continued research and the widespread application of green chemistry practices.

Keywords: Green chemistry, sustainable chemistry, 12 principles, healthy planet

1. Introduction

Green chemistry, sometimes referred to as sustainable chemistry, is a cutting-edge methodology that aims to create chemical processes and products that minimize or completely eradicate dangerous materials (Mukherjee, 2021). It emphasizes on social well-being, economic feasibility and environmental responsibility. Green chemistry seeks to reduce pollution, save resources and provide safer substitutes in the production of chemicals by using sustainability concepts.

Green chemistry goes beyond conventional environmental chemistry by actively creating materials and procedures to reduce risks throughout a product's life cycle. This covers the procurement of raw materials, production, utilization and disposal.

In contrast to traditional approaches that often address pollution after it has been generated, green chemistry emphasizes efficiency, prevention, and the use of non-toxic or biodegradable materials (Wale et al., 2023).

The growing need for sustainable solutions to address climate change, resource depletion, and environmental deterioration has fueled the development of green chemistry. Global regulatory bodies have pushed businesses to use green chemistry techniques in order to abide by environmental regulations and lessen their environmental impact. Businesses are also realizing the financial benefits of sustainable operations, including lower waste disposal expenses, energy savings and improved brand recognition.

Green chemistry is an interdisciplinary field of study and industry that combines environmental science, engineering and chemistry concepts to create safer, more sustainable materials and procedures. The development of green chemistry is greatly aided by developments in nanotechnology, biotechnology and catalysis, which open up new avenues for cleaner industrial processes.

Green chemistry can help enterprises strike a balance between sustainability and production while guaranteeing long-term economic and environmental gains. In order to solve urgent global issues and build a more sustainable future for future generations, green chemistry must be adopted.

2. Principles of Green Chemistry

The 12 Principles of Green Chemistry, which were created by Paul Anastas and John Warner, offer a framework for environmentally friendly chemical innovation (Kumar et al, 2025) (Fig.1):

i. **Prevention:** Waste prevention is preferable to waste treatment or cleanup after it has been produced.

   Example: Maximizing the use of nitrogen and hydrogen in ammonia synthesis through atom-efficient processes such as the Haber-Bosch process.

ii. **Atom economy:** Chemical processes ought to be planned to incorporate as much of each material as possible into the finished product while reducing waste.

   Example: Addition reactions like ethene bromination: $C_2H_4 + Br_2 \rightarrow C_2H_4Br_2$ ensure full atom utilization.

iii. **Less hazardous chemical synthesis:** Human and environmental dangers should be minimized by designing chemical processes to be as non-toxic as possible.

   Example: Instead of chlorine, using hydrogen peroxide (H_2O_2) for paper bleaching: $H_2O_2 \rightarrow H_2O + [O]$

iv. **Creating safer chemicals:** Chemical products should be made to be as safe as possible while still fulfilling their intended purpose.

Example: Ibuprofen green synthesis (BHC Process) reduces waste while increases yield.

v. **Safer auxiliaries and solvents:** Whenever possible, auxiliary materials such as solvents and separation agents should be used minimally and in an environmentally responsible way.

Example: Instead of hazardous organic solvents, using water or supercritical CO^2 in extractions and reactions is best alternative.

vi. **Energy efficiency:** The design of chemical processes should prioritize ambient temperature and pressure conditions in order to reduce energy consumption.

Example: Enzyme-based biocatalysis, like lipase-catalyzed esterification, does not require high temperatures.

vii. **Use of Renewable Feedstocks:** Whenever feasible, renewable raw materials should be used in place of depletable ones.

Example: Using maize starch to make polylactic acid (PLA) instead of polymers derived from petroleum.

viii. **Reduce derivatives:** In order to cut down on waste and extra reagents, unnecessary derivatization (blocking groups, protection/deprotection) should be avoided.

Example: Using direct amination rather than multi-step transformations to get amines from alcohols: $R-OH+NH_3 \rightarrow R-NH_2+H_2O$

ix. **Catalysis:** Because catalytic reagents increase efficiency and decrease waste, they are better than stoichiometric reagents.

Example: Palladium-catalyzed Suzuki coupling reaction: $Ar-B(OH)_2+Ar'-X \rightarrow Ar-Ar'+HX$

x. **Design for degradation:** Chemical products should be made to decompose into harmless compounds after use to avoid building up in the environment.

Example: Biodegradable plastics (PHA, PLA) decompose naturally rather than non-biodegradable plastics: $(C_3H_4O_2)n+H_2O \rightarrow CO_2+H_2O$

xi. **Real-Time analysis to prevent pollution**: In order to prevent the production of hazardous compounds, analytical techniques that enable real-time monitoring and control should be established.

Example: Using spectroscopy to track CO emissions in catalytic converters: $2CO+O_2 \rightarrow 2CO_2$

xii. **Better chemistry to prevent accidents:** Chemical process materials should be selected to reduce hazards including fires, explosions, and unintentional discharges.

Example: Reducing the risk of fire in industrial settings by using water-based paints instead of solvent-based ones.

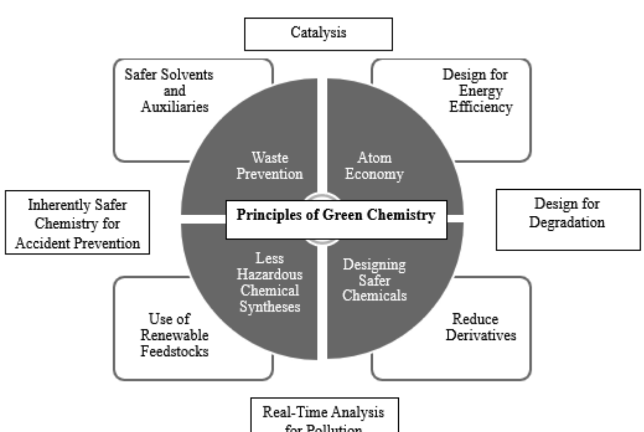

Figure 1. Twelve Principles of Green Chemistry

3. Applications of Green Chemistry

Many industries have effectively adopted the concepts of green chemistry:

1. **Pharmaceuticals:** By using enzyme catalysis for synthesis and embracing green chemistry to develop biodegradable medicine formulations, the pharmaceutical sector has improved efficiency and reduced hazardous waste. To improve sustainability, solvent-free reactions and continuous production techniques have also been incorporated.
2. **Agriculture:** Compared to conventional chemical pesticides, bio-based insecticides that are less detrimental to ecosystems have been developed as a result of green chemistry. Additionally, by offering soil-enhancing compounds and organic fertilizers that have a lower environmental impact, it has encouraged the elimination of synthetic chemical fertilizers.
3. **Textiles:** By creating sustainable fabric treatments and eco-friendly dyes that require less energy and water, the textile industry has embraced green chemistry. Textile wastewater contamination has dramatically decreased as a result of moving to non-toxic, plant-based dyeing techniques. The development of biodegradable polymers and bio-based plastics is a significant accomplishment in the field of green chemistry. Natural decomposition of these materials lowers landfill trash and ocean and ecosystem microplastic pollution.
4. **Energy:** The development of green batteries with less harmful components, biofuels made from renewable resources, and solar cells with eco-friendly manufacturing processes are just a few examples of how green chemistry

advances energy. Cleaner, renewable energy sources are supported by these developments for a sustainable future.

4. Benefits of Green Chemistry

Green chemistry offers a wide range of benefits across environmental, economic, health and regulatory domains:

1. **Environmental impact reduction:** Green chemistry encourages cleaner production practices, which lessen pollution, greenhouse gas emissions, and the need for natural resources. Using sustainable materials and reducing hazardous waste contributes to the preservation of ecosystems and biodiversity (Gupta, 2020).
2. **Economic benefits:** By lowering energy, waste disposal and raw material usage, sustainable operations save money. By increasing efficiency and adhering to environmental standards, businesses that invest in green chemistry frequently obtain a competitive advantage.
3. **Health and safety:** By limiting exposure to harmful chemicals, green chemistry improves worker safety and lowers consumer hazards. Reduced rates of environmental contamination and chemical-related illnesses are the results of safer chemical development.
4. **Regulatory compliance:** By lowering legal risks and liabilities, the adoption of green chemical methods assists industries in adhering to strict environmental rules and regulations. Adherence to sustainability guidelines improves brand reputation and corporate social responsibility.
5. **Market expansion and innovation:** Market expansion and technological breakthroughs have been fueled by the desire for greener alternatives. Growing consumer demand for eco-friendly alternatives leads to new revenue streams

and investment opportunities for businesses creating sustainable products and processes.

5. Examples of Green Chemistry

i. **Biodiesel-oil:** The process of transesterification, in which the oil combines with methanol in the presence of potassium hydroxide, is used to turn the seeds of plants such as *Jatropha curcas* into biodiesel (Fig. 2).

Figure 2. Jatropha curcas

This procedure yields glycerine as a by-product, which is useful in the production of soap. A few advantages of biodiesel are that they comes from renewable resources, doesn't produce sulfur pollutants and helps keep the balance of carbon dioxide in the atmosphere by absorbing CO_2 during plant growth and compensating for combustion emissions. To improve sustainability, supercritical fluids (SCFs) are being utilized in chemical reactions more and more.

ii. **Carbon dioxide as a Solvent:** In addition to being a naturally occurring component of the atmosphere, carbon dioxide is also produced by burning fuels and industrial processes such as the manufacture of ethanol, hydrogen and ammonia. To reduce greenhouse gas emissions and comply with environmental standards, CO_2 can be caught and used for other purposes instead of being discharged into the environment. CO_2 is a solvent that is harmless for the environment and non-toxic. Even though it can independently break down tiny molecules, the development of specific surfactants was necessary for its commercial use to become feasible. Supercritical CO_2 is especially helpful for dissolving polar solvents such as methanol, acetone and fluorocarbons. In its early applications, it was used to decaffeinate tea and coffee.

iii. **Hydrazine Production (Peroxide Process):** The Olin Raschig process, which uses ammonia and sodium hypochlorite (found in bleach) to create hydrazine, has historically produced sodium chloride as a byproduct:$NaOCl+2NH_3 \rightarrow H_2N\text{-}NH_2+NaCl+H_2O$

The peroxide method, in which hydrogen peroxide acts as the oxidant and water is the only byproduct, offers a more environmentally friendly alternative:

$NH_3+H_2O_2 \rightarrow H_2N\text{-}NH_2+2H_2O$

By eliminating the need for additional extraction solvents, this method aligns with Principle 4 of Green Chemistry. The separation process is further simplified because methyl ethyl ketone carries hydrazine in an intermediate ketazine phase.

iv. **Lactide and polylactic acid (PLA) Polymers:** The manufacture of polylactic acid (PLA) polymers, which are made from lactic acid produced by fermenting grain, was enhanced by Cargill Dow (now NatureWorks). Food packaging, cutlery, and textiles all use these polymers. Lactic acid undergoes catalytic cyclization to produce lactide, a cyclic dimer ester. Biodegradable polymers are then produced by distilling and polymerizing the L,L-lactide enantiomer in the melt phase. The manufacture of PLA removes the requirement for dangerous organic solvents and substitutes renewable resources for petroleum-based feedstocks. PLA-based packaging has been used by major merchants such as Wal-Mart.

6. Key Areas of Green Chemistry Advancement

a) **Green nanochemistry:** It is the development of ecologically friendly processes through the use of nanotechnology.

b) **Supramolecular chemistry:** Creating less hazardous self-assembling molecular structure.

c) **Combinatorial green chemistry:** Reducing waste and speeding up the synthesis ofcompound.

d) **Sustainable oxidation reagents and catalysts:** Removing hazardous materials from industrial operations.

e) **Biometric multifunctional reagents:** Cutting down on dangerous byproducts while increasing efficiency.

7. Challenges

Despite its benefits, green chemistry faces several challenges (Quazi et al., 2020):

a) **Cost and initial investment:** Research, technological advancements and changes in processess can make the development of green alternatives expensive. These expenses can be compensated for over time by long-term savings from decreased waste and improved energy efficiency.

b) **Industry resistance:** Many industries are hesitant to transition from conventional processes due to the high capital investment, implementation challenges and disruption to existing supply chains associated with green chemistry. This resistance to change can significantly slow the adoption of sustainable practices.

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c) **Limited awareness and education:** The widespread adoption of green chemistry is hindered by the lack of awareness among industry professionals, educators and policymakers. Bridging this gap requires increased educational initiatives, industry collaborations and targeted training programs.

8. Future Perspectives

- **Government incentives**: Policies such as tax breaks, grants and subsidies can encourage companies to adopt green chemistry.
- **Technological innovations**: Advances in catalysis, nanotechnology and biotechnology can lead to more efficient and cost-effective green solutions.
- **Public awareness and demand**: Increasing consumer preference for sustainable products can drive companies to invest in green chemistry.
- **Collaboration and research**: Joint efforts between academia, industries and governments can accelerate the development and commercialization of green technologies.

A sustainable future will be shaped in large part by green chemistry as environmental consciousness and sustainability legislation grow. To completely integrate green chemistry into international businesses and overcome these obstacles, government incentives, industry cooperation and ongoing research are essential (Factor, 2020). The shift to green chemistry will improve industrial efficiency and economic growth in addition to improving environmental protection. The widespread adoption of green chemistry is increasingly becoming a necessity rather than a choice, driven by stricter environmental regulations and growing consumer demand for sustainable products. To ensure its effectiveness and long-term viability, sustained investment in research, education, and policymaking is essential (Parvez et al., 2023).

9. Conclusion

Green chemistry, which prioritizes safety, efficiency and innovation, is a significant step towards sustainability. Societies may move closer to a cleaner, more sustainable future by upholding its tenets and encouraging cooperation across sectors. Green chemistry's broad adoption will have a significant impact on protecting the environment, lowering pollution, preserving our limited natural resources and slowing down climate change. Furthermore, as consumer preferences shift toward more ecologically friendly products, companies that use green chemistry will gain a competitive edge. Ensuring a shift to more environmentally friendly chemical processes will require the cooperation of industries, scientists and legislators. To encourage sustainable activities, governments must set up robust regulatory structures and offer financial incentives. Academic institutions must to keep investigating novel approaches and businesses ought to make sustainability as top priority in all facets of their operations. In the end, the advancement of creative and sustainable solutions will depend on the combined efforts of people, businesses and legislators. We can ensure a healthier planet for coming generations and provide the foundation for a more sustainable global economy by investing in green chemistry now.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-14

Heavy Metal Contamination in Aquatic Ecosystems: Implications for Fish Health and Human Toxicity

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AUTHOR'S CONTRIBUTION

RA conceptualized the chapter framework, collected the data, conducted the literature review, and prepared the Abstract and Introduction. FA contributed in writing Mechanism of Toxicity, analysis and writing the Conclusion section. Both authors were equally involved in revising the manuscript for intellectual content, approved the final version, and agree to be accountable for all aspects of the work.

ABSTRACT

Heavy metal contamination in aquatic ecosystems has emerged as a serious environmental and health hazard. Industrial effluents, agricultural runoff and urban discharges release toxic metals like chromium, lead, mercury, cadmium and arsenic into water bodies, where they accumulate and disrupt aquatic life. Fish, as key indicators of water quality, bioaccumulate these metals, leading to altered hematological, biochemical and histopathological responses. These toxic effects impair fish health, reproductive capacity, and survival, thereby threatening aquatic biodiversity. Moreover, the transfer of heavy metals through the food chain to humans raises significant public health concerns. Chronic exposure is linked to neurological disorders, renal dysfunction, carcinogenicity and genotoxicity. This review summarizes the toxicological impacts of various heavy metals on fish physiology and human health, with a particular focus on chromium (VI). It also highlights the mechanisms of toxicity and the need for effective monitoring and regulatory measures. The study underscores the urgency of adopting eco-friendly remediation techniques and stricter enforcement of effluent standards to curb metal pollution. Comprehensive strategies involving scientific research, public policy and community awareness are critical for preserving aquatic ecosystems and safeguarding human health.

Keywords: Heavy metals, aquatic toxicity, bioaccumulation, fish physiology, hematological biomarkers

1. Introduction

Heavy metals are metals and metalloids with atomic densities above 4000 kg/m^3 (Liu et al., 2018; Li, 2019). Even at low metal ion concentrations, most heavy metals are harmful to humans such as Copper, cadmium, zinc, chromium, arsenic, boron, cobalt, titanium, strontium, tin, vanadium, nickel, molybdenum, mercury and lead (Muchuweti et al., 2006; Verkleij et al., 2009; Deniz et al., 2017).. Copper, zinc, nickel, boron, iron and molybdenum are essential plant nutrients. For plants and animals, too much concentration is harmful. However, non-essential heavy metals like lead, mercury, cadmium, and arsenic may harm plants and animals. Industrial effluent, sewage sludge, fertilizers, and treated water often pollute soil with heavy metals. Heavy metals have atomic numbers above 20. Volcanoes and mining and refining emit heavy metals into the land (Suedel et al., 1994). These heavy metals spread across the food chain. Due to aquatic bioaccumulation, Hg and Se are highest in the food chain. Fish gills absorb metals from phytoplankton and zooplankton. These produce nutritional deficiencies, illnesses, problems, and malfunctions in fish and their consumers. The pace of heavy metal intake and detoxification determines their effects.

Human toxicity limits of certain metals are: Cobalt, Aluminium, Chromium, Lead, Nickel, Zinc, Copper, Cadmium, Mercury (Mansourri and Madani, 2016). Concentration, emission rate, and exposure duration influence metal toxicity in humans. Non-biotic environment includes these (Mitra et al, 2022; Cardwell et al., 2013). Lead, iron, nickel, cadmium, arsenic, chromium and copper are serious problems in India, particularly in river systems. **Figure 1** shows the areas on Indian map from where the heavy metals are extracted. According to the Centre for Science and Environment, three out of four Indian river monitoring stations have excessive levels of heavy toxic metals, including lead, iron, nickel, cadmium, and arsenic in the Ganga River (Koshy, 2022). Andhra Pradesh, Gujarat, and Maharashtra contribute most to India's heavy metal pollution, and fruits and vegetables are often the cause of heavy metal exposure (Mawari et al, 2022). Heavy metals in products, especially in urbanized areas like Sholapur, Maharashtra also pose health concerns. Major districts and states polluted with heavy metals such as Pb, Hg, Cr, Ar and Cu are shown in **Table 1.**

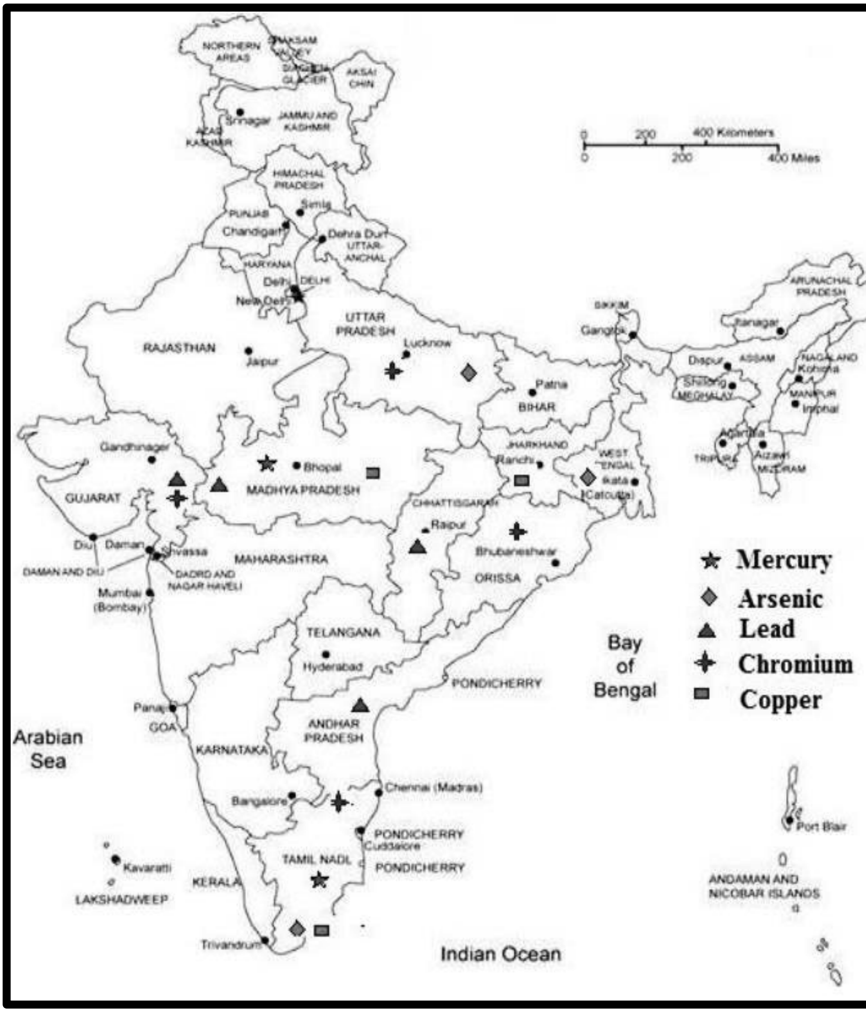

Figure 1. Location of heavy metals found in India (Zaidi and Pal, 2017)

Table 1. Major heavy metal polluted states in India (Zaidi and Pal, 2017)

Chromium	Lead	Mercury	Arsenic	Copper
Ranipet, Tamilnadu	Ratlam, Madhya Pradesh	Kodaikanal, Tamil Nadu	Tuticorin, Tamil Nadu	Tuticorin, Tamil Nadu
Kanpur, Uttar pradesh	Bandalamottu Mines, Andhra Pradesh	Ganjam, Orissa	West Bengal	Singhbhum Mines, Jharkhand
Vadodara, Gujarat	Vadodara, Gujarat	Singrauli, Madhya Pradesh	Ballia, Uttar pradesh	Malanjhkhand, Madhya Pradesh
Talcher, Orissa	Korba, Chattisgarh	-	-	-

2. Sources of Lead, Mercury and Chromium

Human and environmental factors contribute to heavy metals, including chromium, lead, and mercury, according to the UN Environment Program. These metals may enter the environment from mining, industrial production, smelting, oil refining, petrochemical facilities, pesticide manufacture, chemical industry sludge, metal pipelines, untreated traffic, and coal-burning power station combustion products (**See Figure 2**).

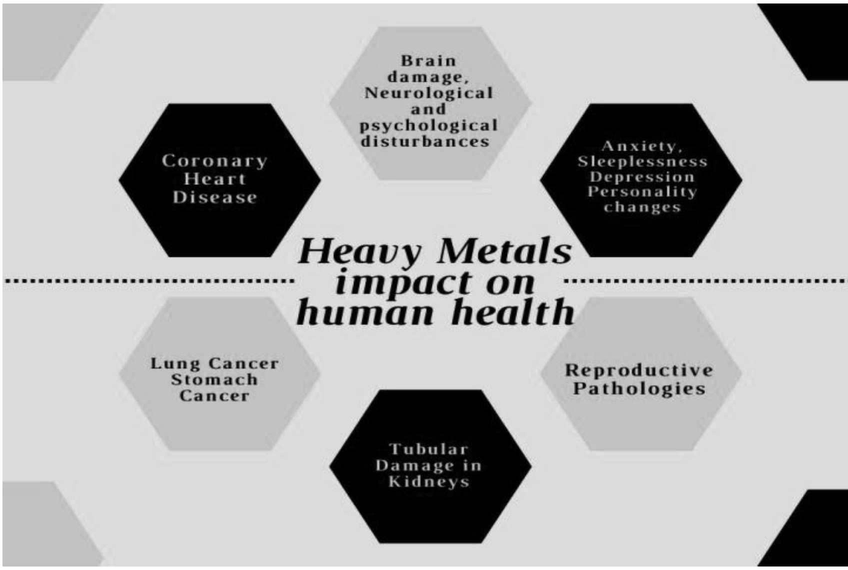

Figure 2. Sources of heavy metals in the environment

Figure 3. Adverse effects of heavy metals on the human body (Mitra et al, 2022)

3. Lead

Lead (Pb^{+2}) is found in freshwater as lead hydrogen carbonate, lead sulfate, lead chloride, lead hydroxide, and lead carbonate. These stick to sediments and organic materials. Changes in pH or ionic composition may remobilize sediment-bound Lead for aquatic species. Lead bioaccumulation has been suggested, but a new study demonstrates otherwise. Terrestrial and freshwater food chains have consistent lead concentrations (Gao et al., 2021). Burning fossil fuels, making ceramics, chemicals, paints, glass, lead batteries, and metal ores contributes to lead pollution. Paints may deposit 20 microgram/dL or more lead in children (Charney, 1980). Adverse effects of heavy metals on humans are shown in **Figure 3**.

3.1 Lead toxicity in humans

Lead toxicity may occur by inhalation of dust particles, food, water, and paints. Children absorb 50% or more of drinking water, whereas adults absorb 35–50%. Absorption depends on age and physiology. Lead absorption is greatest in the kidney, then in the heart, liver, brain, nervous, endocrine, reproductive and skeletal systems (CDC, 2001). Lead poisoning may cause headaches, irritability, memory loss, speech issues, handicaps, growth inhibition, antisocial behaviour and low IQ (USEPA, 2002). **Table 2** shows modified LD50 values for lead in various organisms.

Table 2: Lethal dose of Lead (National Institute for Occupational Safety and Health)

Species	Toxicant	Reference	Route	LD_{50} (mg/ kg)	LD_{Lo} (mg/ kg)	Adjusted LD	Derived value
Dog	PbO	Flury and Zernik, 1935	Oral	-----	1,400	9,114 mg Pb/m^3	911 mg Pb/m^3
Dog	$PbC_4H_6O_4$	Flury and Zernik, 1935	Oral	-----	300	1,344 mg Pb/m^3	134 mg Pb/m^3
Pig	$PbCl_2G$	Budavari, 1989	Oral	-----	1,500	7,770 mg Pb/m^3	770 mg Pb/m^3
pig	$Pb(NO_3)_2G$	Casteel et al., 1996	Oral	-----	500	2,205 mg Pb/m^3	221 mg Pb/m^3
Rat	$Pb(CN)_2$	NRC, 1953	intra-peritoneal	-----	100	560 mg Pb/m^3	56 mg Pb/m^3

3.2. Lead toxicity to fish haemoglobin

Lead (Pb) is a non-essential, non-beneficial, and extremely poisonous heavy metal even at low doses. ATSDR (2007) found that this hazardous element disrupts the hematological system by blocking heme-producing enzymes. Pb is a long-lived environmental danger (Sfakianakis et al., 2015). Numerous authors have found that contaminants like Pb accumulate in many fish species, affecting their physiology, behavior, biochemistry and vital systems like the CNS, PNS, hematopoietic system, cardiovascular system, liver, and kidney (Guo and Hsu, 2002).

Chronic Pb exposure decreases Hb and Hct in *Oncorhynchus mykiss* (Johansson-Sjobeck and Larsson, 1979) and *Barbus conchonius* (Tewari et al., 1987). Ciftci et al. (2008) examined the Hct level of *Anguilla anguilla* over 360 and 720 hours at two Pb dosages, 0.06 mg/L and 0.12 mg/L, comparable to 5% and 10% of the 96 h LC50 value (1.17 mg/L). They discovered that 0.06 mg/L Pb enhanced Hct levels but 0.12 mg/L did not. A toxicological investigation on *Oreochromis niloticus* exposed to 0.1 mg/L Pb for 240 and 480 hours found no significant changes in Hct and Hb count after 240 hours (Cogun and Sahin, 2013). After 480 hours, these hematological markers decreased. Allen (1994) found that 19 mg/L Pb decreased Hct in *Oreochromis aureus*. Martinez et al. (2004) found no hematological alterations in *Prochilodus lineatus* following 96 hours of acute Pb LC50 exposure. Khalesi et al. (2017) found similar results in *Cyprinus carpio* exposed to sub-lethal Pb (6.2 mg/L) for 360 hours. Despite gill lesions, *P. lineatus* and *C. carpio* exposed to Pb concentrations did not experience internal hypoxia as their Hct levels did not alter.

Abdel-Warith et al., (2020a) found that *O. niloticus* exposed to sub-lethal Pb concentrations for 720 hours had greater Hct and Hb levels than the control group, although these values decreased with Pb concentration. The similar tendency was seen for *Clarias gariepinus* (Abdel-Warith et al., 2020b). Fish species' heavy metal exposure may cause hemodilution, hemorrhagic anemia, hemolytic anemia and hypoplastic anemia (poor erythropoiesis), which lower Hb and Hct readings. Erythrocytes released from erythropoietic organs after Pb stimulation may increase hematocrit. It has also been discovered that *Nile tilapia*, *Oreochromis niloticus*, grown with sub-lethal Pb levels had lower Hb levels than those raised without Pb at varied salinity levels (Zainuddin et al., 2017). At salinities of 0, 5, and 10 ppt, Pb-exposed fish had lower Hct than controls.

3.3. Toxicity mechanism (Balali-Mood et al., 2021)

It inhibits protein-calcium interactions. Lead binding to sulfhydryl amide groups inhibits biological molecule activity. Lead also inhibits other metal cations, affecting their enzymatic activity and calcium transport. Lead generates ROS, which harm cells, according to several studies (Hermes-Lima, 1991). Malondialdehyde and antioxidant enzymes rise. Many studies believe lead affects neuronal signaling by affecting Calcium activity. Mitochondrial and endoplasmic reticulum are affected by intracellular calcium cycling (Goldstein, 1993). Lead causes tumors and cancer. Lead may also induce gene mutation, DNA synthesis inhibition and repair and cell morphology abnormalities (Dipaolo, 1978).

4. Mercury

Freshwater mercury commonly exists as Hg(II) bound to ligands. Its elemental, inorganic, and organic forms differ significantly in toxicity. Elemental mercury remains liquid at room temperature and releases mercury vapour due to its high vapour pressure. Both +1 and +2 oxidation states are found (Guzzi, 2008). In soil and aquatic systems, microorganisms can methylate inorganic mercury, producing methylmercury, the most toxic and widespread organic form (Dopp, 2004). This compound bioaccumulates in tissues, causing severe health effects in humans and animals.

Mercury has widespread applications in the electrical industry, dentistry, caustic soda production, pharmaceuticals (as a preservative), wood processing, and nuclear reactors (Tchounwou, 2003). It has also been used in paints and insecticides. Human exposure in the range of 5.61–35.7 ppm may lead to sensory disturbances, ataxia, visual field constriction, and fetal poisoning. A tragic example is the Minamata incident in southern Japan (1956), where, out of 2,252 recognized patients, 1,043 died due to mercury poisoning.

Table 3: Lethal dose data of organic alkyl mercury

Species	Toxicant	Reference	Route	LD_{50} (mg/kg)	LD_{Lo} (mg/kg)	Adjusted LD	Derived value
Rat	HgC_4H_{10}	Izmerov et al., 1982	oral	51	-----	278 mg Hg/m^3	28 mg Hg/m^3
Mouse	HgC_4H_{10}	Izmerov et al., 1982	oral	44	-----	240 mg Hg/m^3	24 mg Hg/m^3
Rat	$HgC_4H_6O_4$	Grin et al., 1973	oral	40.9	-----	180 mg Hg/m^3	18 mg Hg/m^3
Mouse	$HgC_4H_6O_4$	Grin et al., 1973	oral	23.9	-----	105 mg Hg/m^3	11 mg Hg/m^3
Rat	$HgC_6H_{12}O_6$	Frear, 1969	oral	200	-----	742 mg Hg/m^3	74 mg Hg/m^3
Mouse	HgC_6H_{14}	NRC, 1952	intra-peritoneal	-----	1.9	9.3 mg Hg/m^3	0.9 mg Hg/m^3

4.1. Mercury toxicity in humans

Mercury exposure comes from accidents, pollution, food, agriculture, industries, and jobs. Dental amalgams and fish eating cause low-level exposure (Sarkar, 2005). Mercury leaches into the water from the crust and is methylated by algae and microorganisms. Bioaccumulation of methyl mercury occurs in the food chain. Mercury can have detrimental effects on health in the long run, significantly impacting the healthcare system and presenting a considerable public health risk. It can cause various diseases such as cancers, endothelial dysfunction and damages most major organs including the brain (Charkiewicz et al., 2025). The absorbable forms of Hg are HgO and MeHg (Zahir, 2005). Mercury absorbed via the lungs and mouth enters the circulation, penetrates the cell membrane (placenta and brain barriers), and oxidizes to Hg^{+2} within the cell. MeHg is lipid-soluble and absorbed in the gut. It accumulates in kidneys, liver, and neurological tissue and is excreted poorly. Hg is hazardous in all forms.

4.2. Mercury toxicity to fish haemoglobin

Mercury (Hg) may injure people and animals depending on its chemical composition. Sorenson (1991) and Hong et al. (2012) found that organic methylated mercury is more hazardous than organic mercury. In fish, mercury is mostly methylmercury (CH_3Hg) (Spry and Wiener, 1991; Li et al., 2010). Fish may obtain CH_3Hg from the water (where sulfate-reducing bacteria convert elemental mercury into an organic form) or by eating other species (owing to biomagnification throughout the food chain). Anaerobic bacteria convert inorganic mercury to CH_3Hg best in aquatic conditions (Ullrich et al., 2001; Bravo and Cosio, 2019). Mercury has no biological purpose and may have serious metabolic and physiological effects (Calabrese et al., 1975; Jarup, 2003; Rajeshkumar and Li, 2018). Fish blood parameters are affected by mercury exposure. In Tench (*Tinca tinca*), Shah and Altindag (2004) evaluated the effects of acute fatal (1.0 mg/L Hg/48 h) and chronic sub-lethal (0.25 mg/L Hg/3 weeks) mercury exposures on blood-related parameters. Their results showed that greater acute fatal and chronic sub-lethal treatments decreased Hb and Hct levels, but lower acute sub-lethal therapy (0.1 mg/L Hg/24 h) increased Hct. Maheswaran et al. (2008) found that *Clarias batrachus* treated to varied $HgCl_2$ concentrations for 840 hours had lower Hb levels. Hedayati and Ghaffari (2013) found that Silver Carp, *Hypophthalmichthys molitrix* treated with low (10% LC50) and high (50% LC50) $HgCl_2$ for 96 hours had lower Hb and Hct values. (Cyriac et al., 1989) found that mercury exposure increased Hb and Hct levels in *Oreochromis mossambicus* after 120 and 168 hours. Following three mercury treatments (one acute fatal and two chronic sub-lethal), *Tinca tinca* fish had considerably decreased Hb and Hct levels (Lal Shah, 2010). In *Oreochromis niloticus*, Hb and Hct levels did not vary at mercury concentrations of 0.02–0.002 mg/L Hg (Ishikawa et al., 2007). In the first two weeks following $HgCl_2$ exposure, grass carp, *Ctenopharyngodon idella*, had lower Hb and Hct levels (Shakoori et al., 1994). *Cyprinus carpio, Aphanius dispar*, *Channa punctatus,* and *O. aureus* (Beena and Vishwaranjan, 1987; Allen, 1994) exposed to sub-lethal concentrations of $HgCl_2$ (0.30 mg/L, 0.034 to 0.136, and 0.5 mg/L, respectively) showed similar results.

4.3. Toxicity mechanism (Balali-Mood et al., 2021)

Mercury poisoning involves oxidative stress. Hg and MeHg degrade antioxidants via binding to protein cysteines. ROS buildup causes oxidative damage (Shenker, 2000). Inorganic Hg enhances ROS in mitochondria by disrupting ETC and oxidative phosphorylation at the Ubiquinone cytb5 step (Palmeira, 1997). Calcium homeostasis is affected by oxidative stress. Mercury exposure causes organ MDA levels to rise, hepato-nephrotoxicity, and lipid peroxidation. Vit E and Selenium suppress $HgCl_2$-induced lipid peroxidation by scavenging ROS and preventing oxidative stress. ROS regulate cell responses and cancer (Magos, 2006).

5. Chromium

Its +2 to +6 oxidation states affect living things including humans. The most stable is trivalent, followed by hexavalent. Cr (0) does not exist naturally (Patlolla, 2009). Tanneries, metal processing, stainless steel, welding, chromic pigment and chromate manufacture release chromium into the environment. ATSDR's toxicological profile for chromium lists Cr^{+6} as hazardous and carcinogenic (ATSDR, 2008). Cr^{+3} occur naturally in air, water, and soil. WHO limits drinking water chromium +6 to 50 micrograms (Velma, 2009). This substance is anticorrosive. **Table 4** summarises the LD50 and exposure limits of Cr (III) and Cr (VI) in various medium.

Table 4: Limits of Cr (III) and Cr (VI) (ATSDR, 2008; Graham, 1999; Zhang et al., 2016; ACGIH, 2013)

Defined limit	Cr (III)	Cr (VI)	References
LD50*	185-615 mg/kg bw	20-250 mg/kg	WHO
Safe daily doses**	0.03-0.13 microgram/kg bw/d	-	WHO
Normal level	20-30 microgram/L(blood)	<10 microgram /L	ATSDR
Limit, water***	50 microgram/L (total Cr)	0.02 microgram/L	WHO
Limit, air****	0.05 mg Cr/m3	0.05 mg Cr/m3	ACGIH
Limit, toys*****		0.0002 µg/Kg bw/d	On Health and Krätke, 2015

* Oral exposure. Per kg body weight, estimated acute effect from *in vitro* tests

**per kg body weight per day, corresponding to2-8 microgram per day for a 60 kg person

***for drinking water, public health goal (PHG) for Cr (VI)

*****per kg body weight corresponds to 0.0002 mg/kg liquid released

WHO- World Health Organization

ATSDR- Agency for Toxic Substances and Disease Registry

ACGIH- American Conference of Government Industrial Hygienists (US)

5.1. Chromium toxicity in humans

Chromium affects almost 300,000 workers yearly. Cr^{+3} improve insulin action and glucose and protein metabolism in humans and animals (Goyer, 2001). Food and water exposure causes nonoccupational inhalation. Workers in cement factories use the lungs as their major organ. In saltwater, Cr content is 5 to 800 microgram/L, whereas rivers and lakes have 26 to 5.2 (Jacobs and Testa, 2005). Organ toxicity, asthma, kidney damage, allergy, and respiratory tract cancer result from Cr^{+6} exposure. Inhaling high quantities of Cr^{+6} causes small intestine ulcers, reproductive system damage, and anemia (Shelnutt et al., 2007). Cr^{+6} or Cr^{+3} exposure caused edema and skin redness in some persons. Ingesting excessive amounts of Cr^{+6} may cause respiratory, cardiovascular, gastrointestinal, hepatic, renal, neurological and mortality (ATSDR, 2008).

5.2. Chromium toxicity to fish haemoglobin

Chromium (Cr) occurs naturally as trivalent Cr (III) and hexavalent Cr (VI). Cr^{+6} is the most dangerous because it rapidly penetrates biological membranes and converts to the trivalent form, where it interacts with macromolecules, including genetic material, generating toxic and mutagenic consequences (Velma et al., 2009; Ahmed et al., 2013). Chromium mostly enters aquatic ecosystems through effluents from metal finishing, dyeing, printing, leather tanneries, mining, photography, pharmaceuticals, electroplating, ceramics, textiles, etc. Inadequate effluent treatment may raise Cr^{+6} levels in surrounding waterways, endangering fish (Li et al., 2011; Bhatia, 2017; Lellis et al., 2019). Chromium values in seawater are 0.005–0.8 mg/L and in rivers and lakes are 0.026–5.2 mg/L (Jacobs and Testa, 2005). Total Cr, including Cr^{+6}, in drinking water should not exceed 0.1 mg/L, according EPA recommendations. Cr toxicity in aquatic habitats depends on age, species, developmental stage, pH, temperature, Cr concentration, oxidation state, water hardness, and alkalinity. Cr poisons fish by causing hematological abnormalities, morphological and histological alterations, ROS production, growth suppression, and immunological dysfunction.

After 24 and 96 hours of exposure with 39.4 mg/L Cr^{+6}, *Labeo rohita* showed a significant drop in hemoglobin and total erythrocyte count (Vutukuru, 2005). Wepener et al., (1992) found that *Tilapia sparrmanii* treated to 0.098 mg/L Cr^{+6} had significantly lower blood Hb levels. Hb and Hct levels in rainbow trout increased significantly after 504 hours of 2.0 mg/L Cr^{+6} exposure (Van Der Putte et al., 1982). Hb and Hct levels increased significantly in *L. rohita* after 96 hours of Cr^{+3} and Cr^{+6} exposure (Venkatachalam and Natarajan, 2014). Gill and Pant (1987) found polycythemia and increased Hb and Hct levels in abruptly inebriated *Barbus conchonius*, but prolonged exposure caused erythropenia and decreased Hb and Hct. *Salmo gairdneri* treated to Cr (20 mg/L) showed comparable Hb and Hct changes (Schiffman and Fromm, 1959). After 360 hours of 10 mg/L Cr^{+6} exposure, some fish species have increased hematological indices (Strik et al., 1975). (Svobodova et al., 1994) found comparable Hb and Hct levels in *C. carpio* following short-term and long-term Potassium dichromate exposure, while *Oncorhynchus mykiss* increased Hb content-dependently after long-term Cr exposure from 4.2 to 0.125 mg/L. Hb and Hct levels decreased in *Saccobranchus fossilis* subjected to Cr^{+6} concentrations of 0.1, 1.0, and 3.2 mg/L for 672 hours (Khangarot et al., 1999). In another study Cr doses of 30, 40, and 60 mg/L substantially lowered Hb and Hct levels in *Pangasianodon hypothalamus* after 96 hours (Majharul Islam et al., 2020). Mallesh et al., (2015) subjected *Cirrhinus mrigala* to sub-lethal Cr concentrations, causing anemia via lowering Hb and Hct. *L. rohita* exposed to sub-lethal Cr concentrations had considerably lower Hb and Hct levels (Praveena et al., 2013). *C. carpio* exposed to Cr had reduced Hb and Hct levels (Shaheen and Akhtar, 2012). Hematological indices decrease in fish, suggesting that heavy metals damage red blood cells, lowering their oxygen-carrying capacity and causing anemia (Javed et al., 2016).

5.3. Toxicity mechanism (Balali-Mood et al., 2021)

Chromium toxicity depends on solubility, charge, physical properties, and particle size and oxidation state. Cr^{+6} is more poisonous and corrosive than Cr^{+3} (Connett and Wetterhahn, 1983; De Flora et al., 1990). Cr^{+6} passes through the cells better than Cr^{+3}. If Cr^{+6} can be converted to Cr^{+3} outside the cell, toxicity diminishes and it is not absorbed. Cr^{+6} may enter any cell and be reduced by H2O2, Glutathione reductase, and ascorbic acid to Cr^{+5} and Cr^{+4}. These compromise DNA, proteins, and cell processes (De Mattia et al., 2004). In rats, subcutaneous Cr transfusion causes renal injury, proteinuria, urea nitrogen, creatinine, serum alanine aminotransferase and liver lipid peroxide production (Kim and Na, 1991). Cr^{+6} oral consumption increases urine lipid excretion and mitochondrial and lipid peroxidation. Cr inhalation causes worker cancers (Gambelunghe et al., 2003). Cr^{+6} is cytotoxic and damages DNA and chromosomes (Patlolla et al., 2008). Permissible limits of various heavy metals in drinking water are shown in **Table5**.

Table 5. Permissible limit of heavy metals in drinking water (Kumar and Puri, 2012)

Heavy Metals (Mg / L)	WHO	USEPA	ISI	CPCB	ICMR
Lead	0.05	-	0.10	No Relaxation	0.05
Mercury	0.001	0.002	0.001	No Relaxation	0.001
Chromium	0.1	-	0.05	No Relaxation	-

6. River wide Heavy Metal Concentration of Pb, Hg and Cr

The Ministry of Environment, Forest and Climate Change (MoEFCC) is a nodal agency under the Government of India responsible for planning, promoting, coordinating, and overseeing the implementation of environmental and forestry policies and programs. It is also the apex body for regulating matters related to the environment, wildlife, biodiversity, and climate change in the country. Key functions of MoEFCC include formulation of environmental policies and laws, protection and conservation of forests, wildlife, and biodiversity, regulation of activities that affect air, water, and soil quality, implementation of international conventions on environment and climate change (e.g., UNFCCC, CBD, CITES), granting environmental clearances for developmental projects and promoting sustainable development and addressing climate change adaptation and mitigation. Central Pollution Control Board (CPCB) informed that MoEFCC has not set primary water quality requirements for bathing water under the Environment Protection Act 1986 to examine rivers for heavy metals. **Table 6** shows Cr, Hg and Pb concentrations in the key rivers across India. In all States and UTs, CPCBs network consists of approximately 4484 water quality monitoring stations on rivers, lakes, and wells, while the Central Water Commission (CWC) monitors water quality at around 552 locations on major river basins, utilizing a three-tier laboratory system for analyzing various physico-chemical and bacteriological parameters. Water quality is assessed based on physico-chemical and bacteriological parameters. The CWC's higher-level laboratories analyze parameters including heavy metals, total dissolved solids, dissolved oxygen, pH, odour, temperature etc. (https://cwc.gov.in/en/water_quality).

Table 6. Rivers and the concentration of lead, Mercury and Chromium in mg/L (https://cwc.gov.in/sites).

Name of the river	Lead mg/L		Mercury mg/L		Chromium mg/L	
	Min	Max	Min	Max	Min	Max
Baitrani	0.002	0.008	0.0006	0.00057	-	-
Beas	BDL	BDL	0.001	BDL	BDL	BDL
Brahmani	0.004	0.011	0.00006	0.00083	-	-
Brahaputra	BDL	BDL	BDL	BDL	BDL	BDL
Cauvery	0.006	0.1	0.001	0.003	0.05	0.06
Chambal	BDL	0.039	-	-	BDL	0.015
Ganga	0.00031	0.01	0.0001	0.0001	0.00056	0.42
Ghaggar	0.00031	0.419	BDL	0.001	0.00056	0.6
Godavari	0.001	0.09	0.09	0.09	0.005	0.09
Krishna	0.00002	0.009	0.00024	0.09	0.00026	0.09
Mahanadi	0.001	0.199	0.00006	0.001	0.008	0.06
Mahi	BDL	0.013	BDL	BDL	BDL	0.003
Narmada	BDL	BDL	BDL	BDL	BDL	BDL
Pennar	0.00209	0.041	0.00315	0.00315	0.0011	0.043
Sabarmati	0.012	0.012	BDL	BDL	0.005	0.06
Satluj	0.00031	0.1	0.001	0.001	0.00056	0.2
Tapi	BDL	BDL	BDL	BDL	BDL	BDL
Yamuna	0.00031	0.31	BDL	BDL	0.00056	0.56

7. Human Heavy Metal Pharmacology

7.1. Lead pharmacokinetics (Balali-Mood et al., 2021; Chan et al., 2021)

According to the 1976-1980 National Health and Nutrition Examination Survey (NHANES), 88% of children aged 1-4 have

BLLs > 10 μg/dl. The percentage dropped to 4.4% between 1991 and 1994, 1.6% between 1999 and 2002, and 0.8% between 2007 and 2010. The national geometric mean (GM) of blood lead content (BLC) for 1–5-year-olds has decreased significantly from 15μg/dl in 1976-1980 to 0.82μg/dl in 2015-2016 (Holstege, 2020). In the gut, lead absorption changes tremendously. Kids are more lead-sensitive than adults. Lead absorption depends on lead form, particle size, GI transit time and diet. Reduction in the particle size increases lead absorption. Lead paint chips absorb less lead than lead dust. The muco-ciliary tree may inhale or ingest lead, which is absorbed by the gut. Particle size, patient respiratory volume, lead deposition, and muco-ciliary lead clearance also affect respiratory lead absorption. The lungs absorb most lead pollutants. Renal or biliary feces can also remove lead. Many factors affect lead excretion percentage and timing.

7.2. Mercury's pharmacokinetics (Balali-Mood et al., 2021)

Mercury exists in three forms:

(1) Elemental mercury

(2) Inorganic salts

(3) Organic compounds

Mercury vapour is absorbed by 69% – 85% of individuals. Adults absorb 0.04% elemental mercury from mercury amalgam. When exposed to mercury vapour, adults may absorb mercury via the skin. Full-body mercury vapour immersion causes 2% systemic skin absorption compared to inhalation. Mercury vapour is distributed throughout the body after inhalation, with the kidneys having the greatest quantities. Mercury vapor inhalation affects the heart and brain first, owing to their closeness to blood arteries and low HgO oxidation rate. Mercury from inhalation may pass via breast milk to foetuses and babies. Accidental inhalation of mercuric oxide (HgO) may cause systemic mercury absorption, with detection in the brain, kidneys, pelvis and legs.

Adults absorb 1–16% of inorganic mercury. Rodent studies show younger rats absorb more than adults. In isolated human and pig skin, inorganic mercury is absorbed. After consumption, inorganic mercury is distributed throughout the body, with the kidneys and liver having the greatest quantities. Human cord blood, placenta and breast milk contain inorganic mercury, suggesting possible transmission to the foetus and nursing newborn.

Metabolism: Mice show exhaled HgO after mercuric chloride doses, suggesting Hg^{2+} reduction to HgO.

7.3. Chromium pharmacokinetics (Balali-Mood et al., 2021; Chan et al., 2021)

Environmental Health and Medicine Education reports the chromium pharmacokinetics. Chromium is mostly absorbed in the gut. Cr^{+6} is absorbed faster than Cr^{+3}. The body converts Cr^{+6} to Cr^{+3} after absorption. Erythrocytes quickly absorb Cr^{+6} and convert it to Cr^{+3} in the circulation. The body distributes Cr^{+3} broadly. Bone marrow, lungs, lymph nodes, spleen, kidney, and liver absorb most of it. After absorption, Cr^{+6} is converted to Cr^{+3}. This decrease in the oxidation state mostly affects erythrocytes but may also affect other organs. Urine excretes most absorbed chromium. Within 8 hours of intake, 60% of Cr^{+6} is excreted as Cr^{+3}. Plasma chromium removal is faster than tissue removal.

8. Conclusion

Heavy metal pollution in aquatic ecosystems represents a pressing environmental and public health concern. The accumulation of toxic metals such as chromium, lead, mercury, cadmium, and arsenic in fish leads to physiological, hematological and biochemical disturbances, ultimately affecting aquatic biodiversity and ecosystem health. More importantly, the biomagnification of these metals through the food chain poses significant risks to human health, including neurotoxicity, organ damage, and genotoxicity. Immediate attention is required to regulate industrial discharge, enhance water quality monitoring, and promote eco-friendly remediation strategies. An integrated approach combining scientific research, policy intervention, and public awareness is essential to mitigate the harmful effects of heavy metals and ensure the sustainability of aquatic life and food safety.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-15

Ecotoxicology in the Anthropocene: Assessing the Effects of Pollutants on Biodiversity and Ecosystem Health

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ABSTRACT

The Anthropocene era, marked by rapid industrialization and human activities, has significantly contributed to environmental pollution, posing severe threats to biodiversity and ecosystem health. Ecotoxicology, the study of toxic substances and their effects on living organisms, plays a crucial role in understanding and mitigating these impacts. This review explores the major pollutants such as heavy metals, pesticides, pharmaceuticals, and microplastics, focusing on their sources, biological effects and ecological consequences. Pollution-induced biodiversity loss results in disrupted food webs, habitat degradation, and ecosystem instability. Advances in biomonitoring, including molecular biomarkers, bioindicators, and remote sensing technologies, provide valuable tools for assessing ecotoxicological risks. Sustainable mitigation strategies, such as green chemistry, bioremediation and policy interventions, are essential for pollution control and environmental restoration. This review emphasizes the urgent need for integrated approaches to minimize pollutant exposure and protect ecosystem integrity in the Anthropocene. Future research should focus on innovative remediation techniques and enhanced regulatory frameworks to combat ecotoxicological threats effectively.

Keywords: Ecotoxicology, anthropocene, biodiversity loss, heavy metals, pesticides, pharmaceuticals, microplastics

1. Introduction

The Anthropocene, a period characterized by extensive human influence on the environment, has led to unprecedented levels of pollution, threatening global biodiversity and ecosystem stability. Rapid industrialization, urbanization and agricultural expansion have significantly increased the release of toxic substances into air, water, and soil. Ecotoxicology, the study of the effects of environmental contaminants on living organisms, has become essential in understanding the consequences of pollution on ecological health.

Various pollutants, including heavy metals, pesticides, pharmaceuticals and microplastics, have far-reaching impacts on ecosystems. Heavy metals such as mercury, lead, and cadmium accumulate in biological systems, causing neurological, reproductive, and physiological disorders in wildlife. Pesticides and agrochemicals, though intended to protect crops, often have unintended consequences. They can disrupt endocrine functions and reproductive health, particularly in pollinators and aquatic organisms, while also negatively impacting soil microbiota and disturbing natural food webs. Pharmaceutical residues, including antibiotics and hormones, alter microbial communities and contribute to the growing issue of antimicrobial resistance. Similarly, personal care products contaminate water bodies, adversely affecting aquatic life. Microplastics and nanoparticles, now widespread in both marine and freshwater ecosystems, pose additional risks. These particles are often ingested by aquatic organisms, leading to bioaccumulation, ingestion-related toxicity and cellular damage.

The decline in biodiversity due to pollutant exposure has profound ecological consequences, including altered species interactions, habitat degradation and weakened ecosystem resilience. Understanding these impacts through biomonitoring techniques, such as bioindicators and molecular assays, is crucial for assessing environmental risks. Sustainable pollution mitigation strategies, including stricter regulations, green chemistry approaches and public awareness initiatives, are necessary to minimize environmental damage. This review explores the sources and effects of major pollutants, recent advances in ecotoxicological research and potential strategies to protect biodiversity and ecosystem health in the Anthropocene.

2. Literature Review

The Anthropocene has ushered in an era of unprecedented environmental challenges, driven by human-induced pollution that threatens biodiversity and ecosystem health. Lewis and Maslin (2015) formally defined the Anthropocene as a period of human-driven environmental transformation. Several researchers have worked on assessing the impact of pollution on biodiversity and ecosystem health. Based on their research, they have provided important insights for advancing our understanding of ecotoxicology. Rockström et al. (2009) introduced the concept of planetary boundaries, emphasizing pollution as a key factor disrupting ecosystem balance.

Water pollution constitutes a critical component of ecotoxicology, as approximately 70% of the Earth's surface is covered by water, which plays an essential role in sustaining life and maintaining ecological balance. Schwarzenbach et al. (2010) highlighted global water pollution as a major health risk. Halpern et al. (2019) focused on cumulative human impacts on marine biodiversity, identifying pollution as a key driver of aquatic ecosystem decline while, Malaj et al. (2014) evaluated freshwater ecosystem vulnerability to chemical pollutants, identifying pesticides and industrial chemicals as key stressors. Rochman et al. (2016) highlighted the emergence of microplastics as an ecological threat, demonstrating their impact on aquatic food webs. Moreover, Lavoie et al. (2013) studied heavy metal bioaccumulation in aquatic food chains, emphasizing biomagnification risks. The ecotoxicological risks associated with emerging contaminants in aquatic ecosystems have gained increasing attention, particularly due to their potential to disrupt ecological balance. For instance, pharmaceutical pollutants such as antibiotic residues have been shown to significantly alter microbial community structures in water bodies, posing serious environmental concerns (Vijver et al., 2022; Arnold et al., 2014).

The role of biodiversity in enhancing ecosystem resilience to chemical pollution has been increasingly recognized, alongside the promotion of ecosystem-based approaches as effective strategies for mitigating such pollution and supporting sustainable environmental management (Baensch et al., 2023). Sanchez-Bayo and Goka (2014) investigated the effects of neonicotinoids on pollinators, linking pesticide exposure to declining insect populations while Giesy and Kannan (2001) identified perfluorinated compounds (PFOS) as persistent pollutants bioaccumulating in wildlife. Singh et al. (2010) provided an Indian perspective on industrial pollution, linking chemical exposure to ecosystem and human health deterioration. Vighi and Villa (2013) discussed the risk assessment of chemical pollution, emphasizing the need for stricter regulations.

Recent research underscores the complex interplay between pollution, climate change, and biodiversity loss, emphasizing the urgent need for integrated environmental management strategies. The interaction between climate change and pollution has been shown to intensify ecological risks, as rising temperatures can exacerbate the toxicity of environmental contaminants (Bernard et al., 2020; Dasgupta et al., 2020). Microplastic pollution has emerged as a significant concern, particularly in wastewater treatment systems where removal remains a challenge, posing persistent ecological risks (Sun et al., 2019; Syberg et al., 2015). Similarly, nanomaterials in aquatic environments present unresolved ecotoxicological issues, revealing gaps in current risk assessment frameworks (Dudas et al., 2017). The bioaccumulation and biomagnification of heavy metals in aquatic food chains further highlight the potential for long-term ecological harm (Lavoie et al., 2013), while neonicotinoids have been associated with adverse effects on non-target organisms (Chagnon et al., 2015). Biodiversity plays a pivotal role in enhancing ecosystem resilience to chemical pollutants, and ecosystem-based approaches are increasingly advocated for sustainable pollution mitigation (Baensch et al., 2023). Global biodiversity loss linked to pollution is a growing concern, with studies emphasizing the need for resilience-building strategies and urgent policy responses (Peñuelas and Sardans, 2021; Su et al., 2023). The catastrophic effects of persistent pollutants, such as polychlorinated biphenyls (PCBs), are exemplified by population declines in apex species like killer whales (Desforges et al., 2018). In response to these environmental threats, advancements in bioremediation and sustainable remediation technologies offer promising solutions (Wang et al., 2022). Ultimately, addressing the ecological challenges of the Anthropocene demands a sustainability-driven approach that integrates pollution control, climate adaptation, and biodiversity conservation (Steffen et al., 2015).

From early research on persistent pollutants to contemporary studies on climate-pollution interactions, ecotoxicology has evolved significantly. Addressing pollution-driven biodiversity loss requires an integrated approach combining scientific research, policy development and sustainable conservation strategies.

3. Major Classes of Pollutants and Their Ecotoxicological Impacts: Environmental pollution has become a significant challenge in the Anthropocene, leading to widespread ecological disturbances and biodiversity loss. Various pollutants originate from industrial, agricultural, and domestic sources, affecting terrestrial and aquatic ecosystems. This section explores the major classes of pollutants, their sources, and their ecotoxicological effects on living organisms and ecosystem health as explained by table 1.

Table 1. Major classes of pollutants and their ecotoxicological impacts

Pollutant class	Sources	Ecotoxicological impacts
Heavy metals (Pb, Hg, Cd, As)	Industrial discharge, mining, fossil fuel combustion, agricultural runoff	Bioaccumulation in plants and animals, neurological disorders in fish, developmental defects in amphibians and birds, reduced crop yields, carcinogenic effects in humans and wildlife
Pesticides and agrochemicals	Agricultural runoff, excessive pesticide use	Pollinator decline (colony collapse disorder), disrupted soil microbial diversity, amphibian developmental abnormalities, reproductive failures in predatory birds.
Pharmaceuticals and Personal Care Products (PPCPs)	Wastewater discharge, improper drug disposal, veterinary antibiotics	Antibiotic resistance, endocrine disruption in fish, vulture population declines due to renal toxicity, physiological changes in aquatic organisms
Microplastics and nanoparticles	Plastic waste, synthetic fibers, cosmetics, industrial applications	Ingestion causing digestive issues, cellular damage in aquatic species, increased bioavailability of pollutants, biodiversity loss

Air pollutants and greenhouse gases (CO, SO_2, NO_x, CO_2, CH_3)	Vehicle emissions, industrial processes, biomass burning	Acid rain harming plants and aquatic life, ozone depletion affecting food chains, respiratory issues in wildlife, climate change leading to habitat loss

Pollutants in the Anthropocene pose severe risks to biodiversity and ecosystem stability. Heavy metals, pesticides, pharmaceuticals, microplastics and air pollutants disrupt ecological functions, leading to population declines and habitat degradation.

4. Effects of Pollutants on Biodiversity and Ecosystem Health: Various pollutants, including heavy metals, pesticides, pharmaceuticals, microplastics and air contaminants, significantly impact species survival, population dynamics and ecological interactions. These pollutants alter physiological functions, disrupt reproductive processes and contribute to habitat degradation, leading to biodiversity loss and ecosystem imbalances as represented in Table 2.

Table 2. Effects of pollutants on biodiversity and ecosystem health

Category	Pollutants involved	Effects on biodiversity and ecosystem health
1. Terrestrial biodiversity		
Heavy metals and soil contamination	Lead (Pb), Mercury (Hg), Cadmium (Cd)	Reduces microbial diversity, affecting nutrient cycling.
		Bioaccumulation leads to physiological stress and increased mortality.
Pesticides and agrochemicals	Insecticides, herbicides, fungicides	Pollinators (bees, butterflies) experience neurotoxicity and colony collapse.
		Herbicides alter plant communities, affecting herbivores.

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		Birds and mammals consuming contaminated prey suffer reproductive failure.
Air pollution and acid rain	SO_2, NO_x, ozone, particulate matter	Causes respiratory issues in birds and mammals.
		Acid rain depletes soil nutrients, harming plant and forest ecosystems.
		Ground-level ozone reduces photosynthesis and crop productivity.
2. Aquatic biodiversity		
Heavy metals and water contamination	Mercury, lead, cadmium	Neurological disorders and reproductive failure in fish.
		Bioaccumulation affects apex predators (sharks, seabirds).
		Osmoregulation issues in freshwater species.
Pesticides and eutrophication	Fertilizers, agricultural runoff	Fish kills and reduced biodiversity in lakes and rivers.
		Algal blooms deplete oxygen, causing mass fish mortality.
		Disrupts predator-prey relationships in aquatic food webs.
Microplastics and marine pollution	Plastic fragments, Persistent Organic Pollutants (POPs)	Ingested by marine organisms, causing digestive blockages.
		Accumulates toxins, leading to endocrine and immune disruption.
		Coral reefs suffer damage and increased vulnerability to disease.
3. Food chain disruption		
Bioaccumulation and biomagnification	Heavy metals, pesticides	Top predators (raptors, marine mammals) experience toxicity.
		Mercury in fish affects birds like eagles and otters.

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		Organochlorine pesticides cause eggshell thinning in birds.
Antibiotic resistance in microbes	Pharmaceutical residues	Leads to antibiotic-resistant bacteria in water bodies.
		Alters microbial diversity, disrupting nutrient cycling.
4. Habitat degradation and loss		
Deforestation and soil degradation	Industrial waste, mining activities	Depletes soil fertility and forest regeneration.
		Airborne toxins weaken trees, making them prone to pests and diseases.
Coral reef degradation	CO_2, plastic waste, oil spills	Ocean acidification weakens coral skeletons, leading to bleaching.
		Chemical pollution suffocates marine life.
		Warmer ocean temperatures further stress corals.
Wetland and freshwater ecosystem disruption	Industrial and agricultural pollutants	Wetlands lose filtration capacity, increasing downstream pollution.
		Declining bird populations due to habitat destruction.
5. Climate change and ecosystem instability		
Greenhouse gas emissions	CO_2, methane (CH_3)	Alters species distribution and migration.
		Climate shifts increase competition and disrupt food webs.
		Extreme weather events threaten species survival.
Ocean acidification	CO_2 absorption in Oceans	Reduces calcium carbonate for shell-forming marine organisms.
		Weakens marine food webs, affecting fisheries and human livelihoods.

Pollution in the Anthropocene has profound consequences for biodiversity and ecosystem health, leading to species extinctions, habitat degradation, and ecological imbalances. The accumulation of toxic substances in terrestrial and aquatic environments disrupts physiological functions, reproductive success, and trophic interactions. Urgent action is required to implement pollution control strategies, strengthen environmental policies, and promote sustainable practices to mitigate the harmful effects of pollutants.

5. Advances in Biomonitoring and Ecotoxicological Assessment: The increasing threat of environmental pollution necessitates the development of advanced biomonitoring techniques and ecotoxicological assessments to evaluate the impacts of contaminants on biodiversity and ecosystem health. Traditional monitoring methods are being supplemented with cutting-edge technologies, including bioindicators, molecular biomarkers, and remote sensing tools. These advancements allow for early detection of pollution, precise risk assessment, and effective mitigation strategies. This section explores the latest developments in biomonitoring and ecotoxicological assessment as shown in Table 3.

Table 3. Biomonitoring techniques for environmental pollution

Category	Method	Application	Advantages
Bioindicators and sentinel species	Lichens and Mosses	Air pollution monitoring (heavy metals, toxins)	Sensitive, long-term indicators
	Macro-invertebrates and Fish	Water quality assessment	Reflects ecosystem health
	Amphibians	Detection of chemical contaminants	Highly responsive to pollution

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Category	Method	Application	Advantages
Biochemical and physiological biomarkers	Enzyme activity assays (e.g., acetylcholinesterase inhibition)	Pesticide and neurotoxin exposure	Specific and measurable responses
	Oxidative stress markers (catalase, superoxide dismutase)	Heavy metal toxicity	Indicates cellular damage
	Hormonal biomarkers	Endocrine disruption	Detects pharmaceutical pollution effects
Genetic and molecular biomonitoring	Comet assay and Micronucleus test	Genotoxicity assessment	Evaluates DNA damage
	Gene expression (transcriptomics)	Pollution stress response	High sensitivity
	Environmental DNA (eDNA)	Non-invasive species and pollution monitoring	Detects rare/endangered species

6. Future Directions and Sustainable Pollution Management: The integration of advanced biomonitoring and ecotoxicological assessment tools paves the way for sustainable pollution control strategies (table 4). Future research should focus on:

- Developing multi-species biomonitoring frameworks for holistic ecosystem assessments.
- Enhancing non-invasive and real-time monitoring technologies for rapid pollutant detection.

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- Strengthening international collaborations for standardized ecotoxicological research and policy-making.
- Promoting green chemistry to design eco-friendly alternatives to hazardous pollutants.

Table 4. Ecotoxicological Assessment of Pollutants

Category	Method	Application	Advantages
In vivo and in vitro toxicity testing	Daphnia magna and Zebrafish embryo tests	Aquatic toxicity screening	Standardized and widely used
	Cell-based in vitro models	Chemical screening	Reduces animal testing
	Organo-on-a-chip	Simulated physiological response	Human-relevant models
Omics technologies	Proteomics	Toxicant-induced protein changes	Identifies stress pathways
	Metabolomics	Pollutant-induced metabolic shifts	Detects biochemical disruption
	Epigenomics	DNA methylation and gene regulation	Reveals long-term effects
High-throughput and computational toxicology	In silico models	Predicts toxic effects of chemicals	Reduces need for lab tests
	AI and Machine Learning	Large-scale risk assessments	Efficient and data-driven
	QSAR models	Ecotoxicological risk assessment	

Advancements in biomonitoring and ecotoxicological assessment have significantly improved our ability to detect, analyze, and mitigate pollution effects on biodiversity and ecosystem health. The integration of bioindicators, molecular tools, omics technologies, remote sensing and AI-driven analytics enhances the precision of environmental assessments.

7. Mitigation Strategies and Future Perspectives: Environmental pollution poses significant threats to biodiversity and ecosystem health, necessitating robust mitigation strategies to minimize ecological damage. Effective pollution control involves regulatory measures, technological advancements, bioremediation techniques, and public awareness programs. This section explores contemporary and emerging approaches to mitigating ecotoxicological impacts and ensuring a sustainable future.

I. Regulatory frameworks and policy interventions

Governments and international organizations have established stringent environmental regulations to control pollutant emissions and ecological degradation. Key strategies include:

- **Legislative actions**: Policies such as the Clean Air Act, Clean Water Act, and Basel Convention regulate hazardous waste management and emissions.
- **Environmental standards and monitoring**: Agencies like the Environmental Protection Agency (EPA) and European Environment Agency (EEA) set permissible pollutant limits and enforce compliance.
- **Sustainable industrial practices**: Implementing circular economy principles reduces waste generation and enhances resource efficiency.

II. Technological innovations in pollution control

Recent advancements in environmental technologies have revolutionized pollution mitigation:

- **Green chemistry**: Designing eco-friendly chemicals and biodegradable materials minimizes the ecological footprint.
- **Advanced filtration systems**: Nanotechnology-based filters effectively remove heavy metals and microplastics from water bodies.
- **Renewable energy adoption**: Reducing fossil fuel dependence lowers air pollution and greenhouse gas emissions.
- **AI and machine learning in environmental monitoring**: Predictive models enhance pollution tracking and mitigation strategies.

III. Bioremediation and eco-friendly restoration approaches

Bioremediation employs natural organisms to detoxify polluted environments:

- **Microbial bioremediation**: Bacteria and fungi degrade hydrocarbons and heavy metals in contaminated soils.
- **Phytoremediation**: Hyperaccumulator plants, such as *Brassica juncea*, absorb pollutants from soil and water.
- **Mycoremediation**: Fungi, including *Pleurotus ostreatus*, break down industrial toxins and petroleum waste.
- **Bioaugmentation**: Introducing specialized microbial strains enhances the degradation of persistent pollutants.

IV. Sustainable urban and industrial development

- **Smart cities and green infrastructure**: Urban planning integrating green roofs, rain gardens and bio-swales mitigate air and water pollution.
- **Sustainable agriculture**: Reducing pesticide and fertilizer use prevents soil and water contamination.

- **Eco-friendly waste management**: Implementing recycling, composting, and waste-to-energy programs reduces landfill pollution.
- **Public awareness and community participation:** Encouraging active community envolvement and awareness programs.

Educating communities on environmental conservation fosters long-term sustainability:

- **Citizen science initiatives**: Public involvement in pollution monitoring enhances data collection and policymaking.
- **Educational programs**: Schools and universities incorporate environmental science curricula to promote awareness.
- **Corporate Social Responsibility (CSR)**: Industries adopt sustainability goals and eco-friendly practices.

8. Future Perspectives

Emerging research and technological breakthroughs offer promising avenues for ecotoxicology and environmental conservation:

- **CRISPR-based genetic engineering**: Enhancing microbial efficiency for bioremediation.
- **Biosensors for real-time pollution detection**: Early warning systems using genetically engineered bacteria.
- **Blockchain for environmental data transparency**: Ensuring accountability in pollution reporting.
- **Nature-based solutions**: Restoring wetlands and mangroves for natural filtration and carbon sequestration.

Collaborations between governments, researchers, industries, and the public are crucial to achieving environmental resilience. Integrating scientific innovation with policy reforms will shape a cleaner, sustainable future.

9. Conclusion

Ecotoxicology plays a pivotal role in understanding and mitigating the impacts of pollutants on biodiversity and ecosystem health. This review highlights the significance of regulatory frameworks, technological advancements, bioremediation techniques, and public engagement in pollution control. Future research should focus on developing cutting-edge solutions such as genetic engineering, AI-driven monitoring, and sustainable urban planning to combat pollution effectively. Implementing holistic and interdisciplinary approaches will be critical in safeguarding environmental health in the Anthropocene era.

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Chapter-16

Ecotoxicology in the Era of Sustainability

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This work was carried out by two authors. Author SKSC prepared the manuscript. Both authors reviewed the relevant literature. Author VC organized and formatted the references according to the guidelines. Both authors read and approved the final manuscript.

ABSTRACT

Ecotoxicology is the scientific study of the effects of toxic chemicals on living organisms and their environments. It integrates principles from ecology and toxicology to assess the movement of pollutants through air, water and soil, and their impact on biodiversity and human health. This chapter explores the fundamental concepts of ecotoxicology, including bioaccumulation, biomagnification and contaminant degradation. It also examines the relationship between ecotoxicology and sustainable environmental practices, emphasizing pollution control, conservation and eco-friendly technologies. Key themes include the impact of environmental pollution, risk assessment methodologies

and the role of international policies in mitigating ecological harm. The chapter delves into the critical subfields of ecotoxicology, highlighting how pollutants move through environmental compartments and the resulting ecological consequences. Additionally, the chapter discusses the influence of climate change on ecotoxicology, including the synergistic effects that alter pollutant toxicity and ecosystem resilience. By integrating advanced risk assessment techniques and environmental monitoring strategies, ecotoxicology provides valuable insights into managing ecological risks. Technological innovations such as artificial intelligence, bioremediation, and environmental DNA monitoring offer new opportunities for pollution detection and ecosystem restoration. Furthermore, international regulatory frameworks and environmental policies play a crucial role in addressing transboundary pollution and fostering global collaboration. This chapter also highlights the importance of public involvement and community-led initiatives in enhancing environmental monitoring and fostering sustainable practices.

Keywords: Ecotoxicology, bioaccumulation, pollution control, climate change, risk assessment

1. Introduction

Ecotoxicology is a multidisciplinary science that studies how toxic substances affect living organisms and ecosystems. It bridges the gap between toxicology and ecology by examining how pollutants enter and interact with various environmental components (Newman, 2015). In an age marked by rapid industrialization and agricultural expansion, pollutants such as heavy metals, pesticides and microplastics have become ubiquitous (Walker et al., 2012). These substances not only threaten biodiversity but also pose serious risks to human health. The origins of ecotoxicology can be traced back to the mid-20th century when concerns about pesticide use and industrial pollution began to surface (Walker et al., 2012). Rachel Carson's ground breaking work, "Silent Spring" (1962), brought public attention to the dangers of chemical pollutants on ecosystems and laid the foundation for modern ecotoxicological research. Over time, the field has evolved to encompass a broad range of pollutants, including heavy metals, organic contaminants, and emerging substances like microplastics and pharmaceuticals (Gavrilescu, 2022).

A sustainable environment emphasizes the responsible use of natural resources, maintaining ecological balance, and promoting long-term environmental stability (Gavrilescu, 2022). Sustainability is rooted in the principle that human activities should not compromise the ability of future generations to meet their needs. Achieving this requires an integrative approach that balances economic development with environmental protection. Ecotoxicology supports sustainability by identifying and mitigating the effects of toxicants, thereby preserving ecosystem services and ensuring public health.

Pollution is one of the most significant threats to environmental sustainability. Industrial processes, agricultural practices, and urbanization release various pollutants that disrupt ecological balance (Seinfeld and Pandis, 2016). For instance, heavy metals from mining activities accumulate in soils and water bodies, leading to toxic effects on plants, animals, and humans (Tchounwou et al., 2012). Similarly, pesticides used in agriculture can leach into groundwater and surface water, harming non-target species and reducing biodiversity (Aktar et al., 2009). Understanding the sources, pathways, and impacts of these pollutants is essential for designing effective environmental protection strategies.

The integration of ecotoxicology with sustainable practices involves the application of advanced scientific methods to monitor and reduce pollution. Technologies such as bioassays, remote sensing, and environmental DNA (eDNA) offer innovative ways to assess and mitigate ecological risks (Chapman, 2002). Moreover, regulatory frameworks and international policies play a vital role in controlling pollutant emissions and safeguarding ecosystems (UNEP, 2009). Collaborative global efforts are required to address transboundary pollution issues and ensure a coordinated response to environmental challenges. Climate change further complicates the ecotoxicological landscape. Rising temperatures, altered precipitation patterns, and ocean acidification influence the behavior and toxicity of environmental pollutants (Noyes et al., 2009). For example, warmer climates can enhance the bioavailability of certain metals, increasing their toxicity to aquatic organisms (Munday et al., 2019). Addressing these synergistic effects requires adaptive management strategies that consider the dynamic interactions between climate change and pollution.

Ecotoxicology and sustainable environmental management are deeply interconnected. By studying pollutant impacts and implementing sustainable solutions, ecotoxicologists contribute to the preservation of ecosystems and the protection of human health. This chapter explores the core principles of ecotoxicology, the effects of environmental pollutants and the role of technological innovations and regulatory frameworks in fostering a sustainable future. Through interdisciplinary collaboration and proactive policies, ecotoxicology provides the scientific foundation needed to mitigate pollution and promote ecological resilience.

2. Fundamentals of Ecotoxicology

2.1 Definition and scope

Ecotoxicology is the study of pollutants, their sources, and their impacts on ecosystems. It primarily investigates three areas: pollutant sources, their pathways through environmental compartments, and their biological effects on living organisms (Van Straalen and Laskowski, 2005). The scope of ecotoxicology includes both acute and chronic toxicity, the cumulative effects of pollutants, and the variations in responses across species and ecosystems.

2.2 Sources and movement of pollutants

Pollutants enter the environment through both natural processes and human activities. Natural sources include volcanic eruptions and wildfires, while anthropogenic sources encompass industrial discharges, agricultural runoff and urban waste (Seinfeld and Pandis, 2016). The movement of pollutants occurs through different environmental media:

Air: Transported via atmospheric currents, reaching distant ecosystems.

Water: Carried by surface runoff and groundwater flow, impacting aquatic organisms.

Soil: Accumulated in terrestrial ecosystems, affecting plants and animals.

As pollutants move, they undergo complex physical and chemical transformations, which influence their toxicity and bioavailability (Walker et al., 2012).

2.3 Bioaccumulation and biomagnification

Bioaccumulation refers to the gradual buildup of chemicals within an organism, while biomagnification describes the increasing concentration of these substances as they move up the food chain (Newman, 2015). These processes cause significant ecological disruptions and pose health risks to humans who consume contaminated food (Walker et al., 2012). Persistent organic pollutants (POPs) are of particular concern due to their environmental persistence and strong tendency to biomagnify.

3. Toxic Effects on Ecosystems

3.1 Impact on biodiversity

Pollutants negatively impact biodiversity by altering reproductive patterns, reducing species populations, and disrupting food webs (Gavrilescu, 2022). For example, pesticides can harm pollinators such as bees, leading to decreased crop yields and reduced ecosystem stability (Blaustein et al., 2011). The decline of keystone species may trigger cascading ecological effects, ultimately threatening the integrity of entire ecosystems.

3.2 Bioindicators in ecotoxicology

Bioindicator species, such as amphibians and fish, serve as important signals of environmental health and pollutant exposure (Blaustein et al., 2011). Monitoring these organisms provides valuable insights for assessing ecological risks and guiding management strategies. Recent advances in genetic and molecular bioindicators enable early detection of sub-lethal effects, thereby enhancing the accuracy of ecotoxicological risk assessments.

4. Environmental Pollution

4.1 Heavy metals

Heavy metals such as mercury and lead are highly persistent in ecosystems and tend to bioaccumulate in living organisms. These metals can impair neurological functions, cause reproductive toxicity, and disrupt overall ecosystem health (Tchounwou et al., 2012). Industrial discharges and mining activities are among the primary sources of heavy metal contamination.

4.2 Pesticides

Although pesticides are designed to protect crops, they frequently leach into soils and waterways, where they harm non-target species and interfere with ecological processes (Aktar et al., 2009). Persistent pesticide residues can remain in the environment for long periods and may enter the human food chain, posing additional health risks.

4.3 Microplastics

Microplastics, originating from industrial and consumer products, accumulate extensively in aquatic environments. They pose ingestion risks to marine organisms and have been linked to physiological stress and reduced survival (Galloway et al., 2017). Furthermore, microplastics can act as carriers for other pollutants, thereby amplifying their ecological impacts.

4.4 Industrial contaminants

Industrial processes release a variety of hazardous pollutants, including polychlorinated biphenyls (PCBs). These substances are highly persistent, capable of long-range transport, and known to disrupt endocrine systems (Erickson, 2015). Their effects span multiple trophic levels, impairing ecosystem functions and threatening biodiversity.

5. Risk Assessment and Monitoring

5.1 Toxicity testing

Toxicity testing, including bioassays and chemical analyses, is used to measure the effects of pollutants on living organisms (Chapman, 2002). These tests provide critical data for evaluating environmental risks. While acute toxicity tests reveal short-term impacts, chronic toxicity studies are essential for understanding long-term effects that may otherwise be overlooked.

5.2 Bioindicators and environmental monitoring

Bioindicators serve as effective tools for detecting environmental pollution at an early stage. Organisms such as lichens, amphibians, and fish provide valuable insights into ecosystem health and pollutant exposure (Blaustein et al., 2011). In addition, modern techniques such as remote sensing and environmental DNA (eDNA) analysis offer non-invasive approaches to monitor biodiversity and pollutant impacts.

5.3 Environmental risk evaluation

Environmental risk assessments quantify potential ecological harm by analyzing pollutant exposure and biological responses (Walker et al., 2012). These assessments provide policymakers with evidence-based tools to regulate emissions and mitigate ecological risks. Emerging frameworks, such as Adverse Outcome Pathways (AOPs), enhance the mechanistic understanding of toxicant impacts, thereby strengthening predictive ecotoxicology.

6. Ecotoxicology and Human Health

Human health is directly influenced by exposure to environmental pollutants through air, water, and food sources. Persistent organic pollutants, heavy metals, and other contaminants are associated with chronic health conditions, including cancer, neurotoxicity, and endocrine disruption (Landrigan and Fuller, 2015). Ecotoxicological research thus plays a vital role in linking environmental contamination to human disease burden and guiding preventive policies.

7. Climate Change and Ecotoxicology

7.1 Synergistic effects of climate change and pollution

Climate change amplifies the effects of pollutants by altering their chemical behaviour and increasing the vulnerability of organisms (Noyes et al., 2009). Rising global temperatures can enhance the toxicity of certain chemicals and accelerate the degradation of pollutants, sometimes producing secondary toxic by-products. Climate-induced habitat loss and extreme weather events also intensify exposure to hazardous substances, particularly in aquatic ecosystems where pollutants tend to accumulate.

7.2 Ecosystem resilience and adaptation

Shifts in temperature and precipitation patterns influence pollutant distribution, creating new challenges for ecosystem resilience and adaptation (IPCC, 2021). These changes alter ecosystem functioning, reduce the capacity of species to recover from pollutant stress, and increase the risk of population declines.

7.3 Climate-driven ecotoxicological risks

Climate change affects species metabolic rates and physiological processes, which in turn alters their sensitivity to toxicants. For example, ocean acidification increases the bioavailability of heavy metals, thereby intensifying their toxicity to marine organisms (Munday et al., 2019). Such synergistic effects increase risks to biodiversity, particularly for species with limited adaptive capacity. Addressing these challenges requires integrated strategies that combine ecotoxicological knowledge with climate change mitigation and adaptive policies to safeguard ecosystems and human health.

8. Sustainable Environmental Management

8.1 Green chemistry

Green chemistry focuses on minimizing the production and use of hazardous substances through sustainable practices and by designing safe chemicals (Anastas and Warner, 1998). By integrating environmental considerations into chemical production, this approach reduces ecological risks and promotes cleaner technologies.

8.2 Bioremediation

Bioremediation employs microorganisms and plants to detoxify polluted environments by breaking down or immobilizing hazardous substances. This eco-friendly technology is widely applied in treating contaminated soils, sediments, and wastewater (Singh et al., 2004).

8.3 Sustainable waste management

Efficient waste management systems, including recycling, composting, and hazardous waste treatment, play a critical role in reducing environmental contamination and conserving resources (Wilson et al., 2009). Adopting sustainable practices ensures long-term protection of ecosystems and human health.

9. Conservation and Biodiversity Protection

9.1 Sustainable agriculture

Eco-friendly agricultural practices minimize chemical inputs, reduce soil degradation, and enhance biodiversity. Approaches such as organic farming, crop rotation, and integrated pest management contribute to both food security and environmental sustainability (Pretty, 2008).

9.2 Habitat restoration

Habitat restoration through methods such as reforestation, wetland recovery, and controlling invasive species helps rebuild ecological functions and strengthen biodiversity resilience (Suding, 2011). Such efforts are essential for mitigating the impacts of habitat loss and environmental degradation.

10. Regulations and Global Policies

Effective regulations and global policies are essential for managing ecotoxicological risks and advancing sustainable environmental practices. International treaties, such as the “Stockholm Convention”, aim to reduce or eliminate persistent organic pollutants (UNEP, 2009). Similarly, the “Basel Convention” regulates the transboundary movement of hazardous waste to prevent environmental degradation (UNEP, 1992). At the national level, the “Clean Water Act” in the United States establishes standards for water pollution control (EPA, 1972), while the “European Union’s REACH regulation” ensures the safe use of chemicals through comprehensive registration and evaluation (ECHA, 2006).

Global cooperation is critical to address transboundary pollution and emerging environmental threats. Initiatives such as the "United Nations Sustainable Development Goals (SDGs)" emphasize pollution reduction, biodiversity conservation, and sustainable resource management (UN, 2015). Strengthening international agreements and enforcing local regulations remain vital strategies to safeguard ecosystems and human health.

11. Technological Innovations

Artificial Intelligence (AI) and Internet of Things (IoT) are transforming ecotoxicology and advancing sustainable environmental management. Artificial intelligence (AI) and the Internet of Things (IoT) facilitate real-time environmental monitoring and risk assessment. AI algorithms can process large datasets to predict pollution trends, identify ecological risks, and optimize remediation strategies (LeCun et al., 2015; Roland et al., 2020). IoT devices monitor environmental parameters, such as air and water quality, enabling early detection of pollutants and rapid response (Perera et al., 2014).

12. Future Challenges and Solutions

12.1 Addressing emerging pollutants

New pollutants, including pharmaceuticals, nanomaterials and microplastics, pose significant ecological and human health risks. These substances require advanced detection techniques, innovative remediation approaches, and updated regulatory frameworks (Boxall, 2012).

12.2 Community engagement

Community education and public participation are essential for promoting sustainable behaviors and ecological stewardship.

Involving local communities in decision-making enhances awareness, supports conservation efforts, and fosters long-term environmental management.

12.3 Integrated approaches for future challenges

Future challenges in ecotoxicology include managing emerging pollutants, mitigating the effects of climate change, and strengthening global cooperation. Adaptive strategies that integrate technological innovation, policy enforcement and community engagement are essential to safeguard biodiversity and human well-being.

13. Conclusion

Ecotoxicology plays a vital role in understanding and mitigating the harmful effects of pollutants on ecosystems and human health. By studying the sources, distribution, and biological impacts of toxic substances, ecotoxicology provides the foundation for effective environmental management. Integrating ecotoxicological research with sustainable practices enhances pollution control, biodiversity conservation, and the development of eco-friendly technologies. Addressing contemporary challenges demands interdisciplinary collaboration, robust regulatory frameworks, and the adoption of advanced monitoring tools. A sustainable future depends on our ability to balance human development with ecological stewardship. Through international cooperation, community involvement, and technological innovation, ecotoxicology can play a pivotal role in maintaining environmental balance and safeguarding the planet for future generations.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-17

Impact of Heavy Metal Pollutants on Soil Health and Agricultural Productivity

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AUTHOR'S CONTRIBUTION

SK developed the study concept, created the framework, and wrote the first draft of the manuscript. MY conducted the literature review, gathered data, and contributed to the critical analysis of heavy metals' effects on soil health. PS took charge of editing, enhancing the discussion on agricultural productivity, and ensuring academic consistency and proper referencing. All authors examined and endorsed the final version of the manuscript.

ABSTRACT

Heavy metal pollution is a serious environmental concern affecting soil health, agriculture productivity and ecosystem stability. Pollutants like lead (Pb), arsenic (As), mercury (Hg), cadmium (Cd) and chromium (Cr) originate from industrial activities, mining, agricultural chemical fertilizer, pesticides, herbicides and improper waste disposal. These metals disrupt soil chemical balance by altering pH, reducing nutrient availability and decreasing cation exchange capacity. Additionally, they negatively impact microbial diversity, inhibit essential biochemical process and bio-accumulate in plants, causing risks to the food chains. These toxic elements alter soil structure and its water retention property, leading to erosion and reduced fertility. Heavy metals adversely affect soil physico-chemical properties, disrupt microbial communities and impair enzymatic activities important for nutrient cycling and organic matter decomposition. Various remediation strategies, including phytoremediation, soil amendment, bioremediation and physical remediation can mitigate heavy metal toxicity. Understanding and managing heavy metal contamination is crucial for preserving soil productivity, ensuring agricultural sustainability and protecting human and environmental health. Soil is an essential natural resource that supports plant growth, regulate biogeochemical cycles and sustain biodiversity.

Keywords: Microbial diversity, pesticides, bioaccumulation, phytoremediation, agricultural sustainability

1. Introduction

Soil is an important natural resource that supports plant growth, regulates biogeochemical cycles and sustains biodiversity. The organic matter formed by the decomposition of plant and animals is called humus. Soil consists of approximately 45% mineral, 5% organic matter, 20-30% water and 20-30% air. Soil formation process is very slow. It is formed by decomposition of organic matter and breaking up of rocks by different agents like water, air, glaciers etc. (Angelovicova and Fazekasova, 2014). The anthropogenic activities such as industrialization, mining, urbanization and intensive agriculture has led to widespread soil contamination, particularly with heavy metals like lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As) and chromium (Cr). These persistent environmental pollutants pose significant threats to soil health and ecosystem stability (Nagajyoti et al., 2010). Heavy metal pollutants enter the soil through natural and anthropogenic pathways. Natural sources are weathering of rocks, volcanic eruptions and soil erosion, while anthropogenic activities like industrial effluent, mining, excessive use of pesticide and fertilizers and improper waste disposal contributes significantly to soil contamination (Gao et al., 2020).

These metals enter the soil through various ways like irrigation with contaminated water, industrial wastes, chemical fertilizers and atmospheric deposition (Alloway et al., 2013). These metals are naturally present in soil ecosystem and play an important role in biochemical cycling. When soil contaminated with heavy metals, restrict the growth and survival of the plants it poses nutritional, ecological and evolutionary challenges. Heavy metals generally produces common toxic effects on plants, such as low biomass accumulation, chlorosis, inhibition of growth and photosynthesis and nutrient assimilation. Prolonged overuse of fertilizers leads to the accumulation of heavy metals in agricultural soils, which diminishes soil fertility and subsequently hampers plant growth and productivity (Li et al., 2020). Some organic pollutants and heavy metals do not degrade over time and tend to accumulate in the soil, leading to long term environmental and agricultural consequences. Their presence affects the physic-chemical properties such as pH, nutrient availability and exchange capacity in soil and also they have negative impact on plant growth and microbial diversity (Kabata-Pendias, 2011). Soil micro-organisms are essential for organic decomposition and nutrient cycling resulting in reduced microbial diversity and disrupted ecosystem functions (Giller et al., 2009). The presence of heavy metals reduces soil fertility, potential contamination and microbial toxicity of crop.

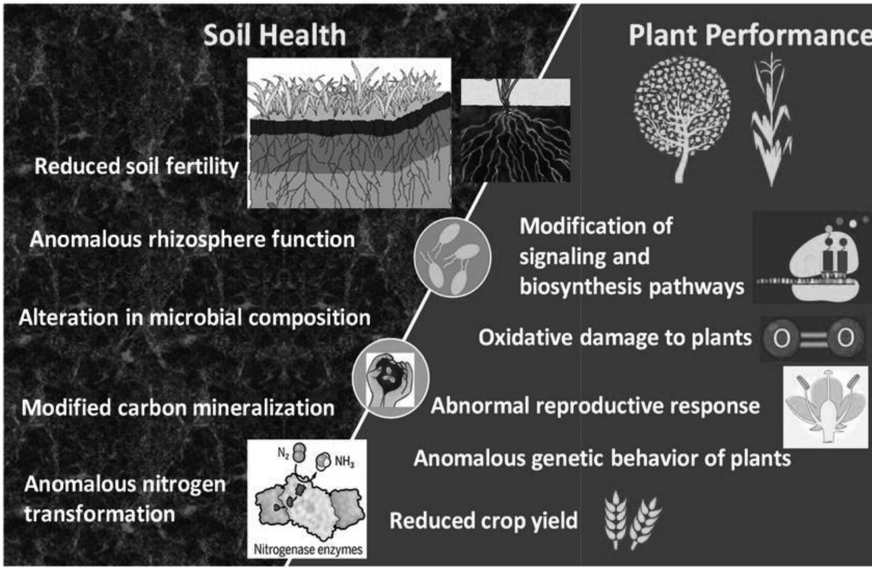

Figure 1: Agro-ecological consequences of heavy metal contamination (Adapted from Rizvi et al., 2020)

Furthermore heavy metals can bio-accumulate in plants, leading to their entry into the food chains and posing serious health risks to animals and humans (Ali et al., 2019). Some organic pollutants are non-biodegradable and tend to accumulate in soil, leading to toxicity and degradation of soil quality over time (Zhou et al., 2020). Contaminated soils also suffer from reduced water retention capacity and structural degradation, making them more susceptible to erosion and desertification (Adriano, 2001). Soil health is mainly determined by the abundance and diversity of microbes present in the rhizosphere. Bacteria fix atmospheric nitrogen into organic forms, which is used by plants. Given the reliance on high yield agriculture to meet growing population demands, it is critical to understand the extent to which heavy metal contamination impairs crop productivity. Many studies focuses on exploring the impact of heavy metals on agricultural output, focusing on physiological stress response in plants and the implications for sustainable crop production (Rizvi et al., 2020). **Figure 1** shows the impact of heavy metals on the agricultural productivity and the environment.

2. Sources and Effects of Heavy Metal Contamination in Soil

Heavy metal contamination arises from both natural processes such as weathering of rocks and anthropogenic activities including industrial discharge, mining and agricultural practices. These metals, when accumulated in soil and water, pose serious risks to ecosystems and human health by entering the food chain. The following table provides a concise overview of major heavy metals, their common sources and associated effects (**Table 1**).

Table 1. Major heavy metals, their sources and associated effects

S. No.	Heavy metal	Sources	Effect in soil health	Impact on microbial
1.	**Lead (Pb)**	Industrial discharge, mining	Alters soil pH, reduce organic matter decomposition	Reduce microbial diversity, inhibit nitrogen fixing bacteria
2.	**Cadmium (Cd)**	Phosphate fertilizers	Reduces enzymatic activity	Toxic to soil microbes, reduce crop productivity
3.	**Arsenic (As)**	Pesticides, mining, coal combustion	Increase soil toxicity, alters nutrient cycles	Inhibits microbial respiration, beneficial fungi
4.	**Mercury (Hg)**	Coal combustion, industrial effluents, fungicides	Disrupt microbial metabolism, bioaccumulates in soil	Kill beneficial bacteria, affect organic matter breakdown

5.	**Chromium (Cr)**	Tannery waste	Reduce water retention capacity	Destroys soil fungi, reduce essential nutrient
6.	**Nickel (Ni)**	Stainless steel industries, Electroplating industries	Toxic to plants, alters cation exchanged capacity	Inhibits microbial respiration, disrupts nitrogen cycle
7.	**Zinc (Zn)**	Fertilizers, smelting	Excessive Zn can lead to nutrient imbalance	Interferences with microbial enzymatic activity, reduce plant growth
8.	**Copper (Cu)**	Pesticides, industrial discharge	Reduces organic matter decomposition	Inhibits root associated microbial communities

3. Effect of Heavy Metals on Soil Fertility

Soil fertility is a crucial factor for sustainable crop production, depending on a balanced availability of nutrients, microbial activity and favourable physic-chemical conditions. However, the accumulation of heavy metals in soil such as Cd, Hg, Pb, As and Cr can significantly disrupt these parameters, reducing both soil quality and productivity. Heavy metals are toxic for soil microbes such as phosphate solublising bacteria, nitrogen fixing bacteria and mycorrhizal fungi. These microbes are important in nutrient cycling and inorganic matter decomposition (Chibuike and Obiora, 2014). Irreversible changes in soil structure, poor aeration, compaction and reduced water holding capacity is attributed to prolonged exposure to heavy metals (Tchounwou et al., 2012). **Figure 2** represents various sources of heavy metal pollution (Akhtar et al., 2023).

4. Concussion of Heavy Metals on Crop Productivity

Heavy metals such as Cd, Cr, Hg, As and Pb, even when present in least amounts, can exert harmful effects on agriculture. Their accumulation in soil and uptake by crops adversely affects plant growth, physiological functions and crop yield. These heavy metals disrupt seed germination by impairing water uptake and enzyme activation. Toxic concentrations of heavy metals can delay or inhibit seedling establishment (Yadav, 2010).

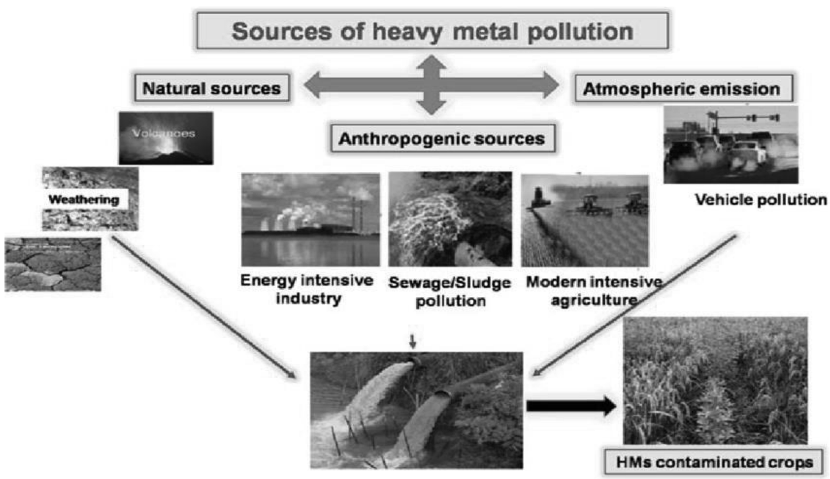

Figure 2: Sources of various heavy metal pollutants (Adapted from Akhtar et al., 2023).

5. Risk to Food Safety and Human Health

Heavy metal contamination in agriculture causes a serious issue to food safety and human health. The major concern with heavy metals arises from their non-biodegradable nature, long term persistence in the environment and accumulation across food chains. These harmful metals accumulate in edible parts of plants, making their way into the human diet (Chibuike and Obiora, 2014).

6. Soil Remediation Strategies for Heavy Metal Pollution

i. **Phytoremediation:** Phytoremediation is a plant based technology that uses the natural processes of vegetation to remove harmless contaminants in soil, water and air. Due to its low cost, eco-friendly nature and capacity to enhance soil structure and fertility. Phytoremediation has gained recognition as an effective strategy for the remediation of heavy metal contaminated soils. This approach utilize green plants along with their associated microorganisms to immobilize, extract or degrade pollutants present in the soil, surface water, sediments and ground water (Salt et al., 1995). A variety of phytoremediation methods currently being employed are depicted in **Figure 3**.

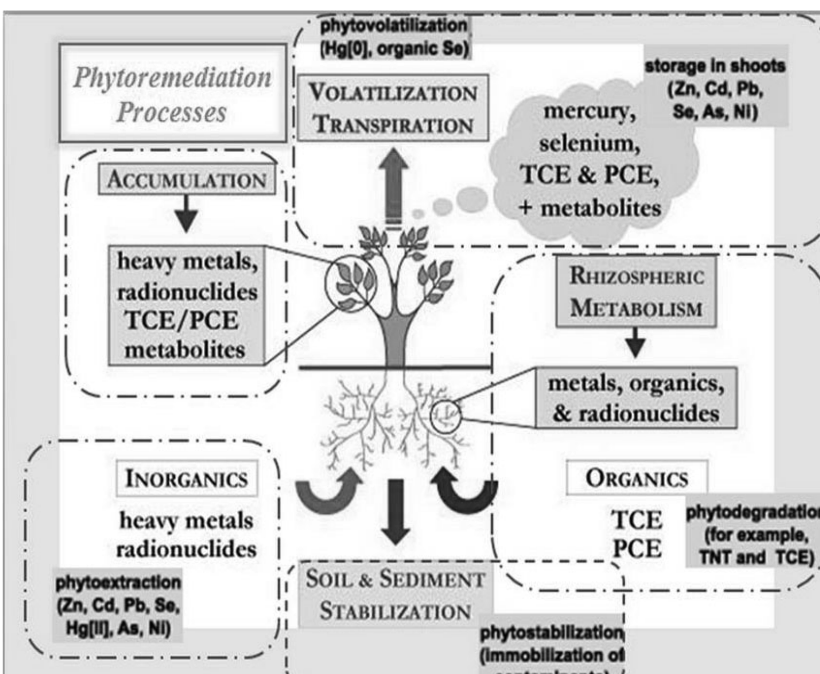

Figure 3: Various phytoremediation methods currently being used (Adapted from Godheja et al., 2016)

Case study: Impact of heavy metal pollution on agricultural land near Korba industrial area, Chhattisgarh

The Korba region in Chhattisgarh, India, is a major industrial hub known for its coal-fired power plants, aluminium smelters and mining operations. Over the years, industrial activities have emitted considerable amounts of environmental pollution near agricultural soils. The Korba region has reported high concentrations of heavy metals like Pb, Cd, As and Cr in the soil, often exceeding permissible limits set by the international agencies (Tiwari et al., 2014).

ii. **Bioremediation:** Bioremediation is an environmentally sustainable, eco-friendly approach that harnesses micro-organisms like bacteria, fungi and archaea to degrade to heavy metals in contaminated soils. Some microorganisms such as *Bacillus* and *Pseudomonas* species degrade or immobilize heavy metals, making them less toxic (Glick, 2018).

    Case study: Glick (2018) demonstrated that *pseudomonas putida* could effectively reduce lead and cadmium levels in contaminated soil by over 60% within 30 days, while promoting plant growth through siderophore and hormone production.

iii. **Chemical stabilization:** Chemical stabilization is a widely applied technique in soil remediation, wherein specific chemical ingredients are introduced to contaminated soils to reduce the solubility, toxicity, and bioavailability of pollutants. This approach has emerged from the necessity to manage soils impacted by industrial effluents, heavy metals, and hazardous wastes, where conventional removal or disposal methods are often economically and environmentally unfeasible. The fundamental principle is to transform contaminants into more stable and less mobile forms through mechanisms such as adsorption, ion exchange, precipitation, or complex formation. Materials commonly employed for stabilization include lime, cement, fly ash, phosphates, and other engineered reagents. Its major application lies in the immobilization of toxic metals such as lead, cadmium, and arsenic, thereby minimizing groundwater contamination and associated health risks. Implementation is carried out either *in situ*, by mixing agents directly into the soil, or *ex situ*, in treatment units, providing a suitable and cost-effective remediation strategy (Wu et al., 2020).

7. Conclusion

Heavy metal contamination represents a formidable challenge to soil health, with long lasting effects on microbial diversity, nutrient availability and crop productivity. The persistence and mobility of these metals are not only toxic for agricultural sustainability but also cause serious risks to food safety and animal health through bioaccumulation in the food chain. This can be solved by multidisciplinary methods such as regular monitoring, soil amendments, phyto-remediation and policy interventions. By integrating scientific understanding with sustainable practices, the adverse effects of heavy metal pollution can be mitigated through sustainable practices, thereby restoring the natural balance and functionality of the soil ecosystem.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-18

Environmental Policies: Ecotoxicology, Challenges and Problems

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AUTHORS' CONTRIBUTIONS

The chapter is a collaborative effort by both authors. Author SS was responsible for preparing the various tables included in the chapter, while Author BT took the lead in compiling and analyzing relevant literature, drafting the manuscript, and refining the final content. Both authors contributed actively to the development of the chapter and approved the final version.

ABSTRACT

Ecotoxicology plays a crucial role in understanding the impact of pollutants on ecosystems and human health. The increasing presence of contaminants such as heavy metals, persistent organic pollutants (POPs), and microplastics has raised global concerns regarding biodiversity loss and ecosystem degradation. Regulatory frameworks, environmental laws, and international treaties aim to mitigate these effects by establishing guidelines for pollutant management and risk assessment. This chapter explores the intersection of ecotoxicology and sustainable environmental practices, emphasizing key international agreements such as the Stockholm Convention, Basel Convention, and Paris Agreement. Furthermore, it highlights sustainable strategies like green chemistry, bioremediation, and renewable energy adoption to minimize environmental contamination. Despite progress in environmental policies, challenges persist due to emerging contaminants, climate change interactions and enforcement gaps in regulatory frameworks. Strengthening global cooperation and advancing research in ecotoxicology are essential to fostering a sustainable future. The policies developed by the government for addressing environmental pollution should be regularly monitored by officials responsible for coordinating and overseeing the implementation of the action plan. Local workshops/seminars should be organized to create public awareness about using polluted environment and its effect on health. This chapter examines the number of environmental policies across different regions, their impact on ecological sustainability, and the need for global cooperation in informing environmental issues. The study highlights the importance of policy integration, technological advancements, and community engagement in shaping effective environmental governance.

Keywords: Ecotoxicology, environmental policies, international treaties, sustainability, pollution control, risk assessment

1. Introduction

Environmental policies are regulations and initiatives aimed at protecting the natural environment, mitigating climate change and ensuring sustainable development. Governments, international organizations and industries develop these policies to address environmental concerns such as pollution, deforestation, biodiversity loss and climate change. However, implementing and enforcing environmental policies present several challenges i.e, lack of global cooperation, economic constraints, weak enforcement public awareness and participation, technological and scientific challenges, conflicting interests and public support and awareness of people. Environmental degradation and pollution have raised global concerns regarding their impact on human health, biodiversity and ecosystem stability. Ecotoxicology, the study of toxic effects of pollutants on biological organisms and ecosystems, plays a pivotal role in understanding these issues. As industries grow and cities expand, more harmful substances, such as pesticides, plastics and toxic metals, enter ecosystems. These pollutants can poison water, air and soil, harming living organisms and upsetting the balance of nature. Some contaminants accumulate in the food chains, making them even more dangerous over time. Understanding how these substances interact with the environment helps scientists and policymakers create strategies to reduce their impact and protect ecosystems. The regulation of pollutants through environmental laws, international treaties and regulatory frameworks ensures the protection of ecosystems and promotes sustainability. This chapter discusses the role of ecotoxicology in achieving a sustainable environment, focusing on regulatory measures, international policies and future challenges.

2. Understanding Ecotoxicology

Ecotoxicology is a multidisciplinary science that examines the impact of chemical pollutants on living organisms and their interactions within ecosystems. It integrates aspects of toxicology, ecology and environmental chemistry to assess how contaminants affect ecosystems at different levels ranging from individual organisms to entire communities and ecosystems. Key concerns include:

i. **Bioaccumulation and biomagnification**: Toxic substances accumulate in organisms over time, leading to higher concentrations in top predators through the food chain.

ii. **Effects of persistent organic pollutants (POPs) and heavy metals**: These pollutants persist in the environment for long periods, causing chronic toxicity.

iii. **Ecotoxicological risk assessments and environmental monitoring**: Assessing and predicting the risks associated with environmental contaminants help guide regulations and remediation efforts.

iv. **Endocrine-disrupting chemicals (EDCs)**: These interfere with hormone systems, affecting reproduction, growth and development in wildlife and humans.

v. **Nanotoxicology and microplastic pollution**: The increasing use of nanomaterials and plastics poses emerging challenges in ecotoxicology.

Table 1. Common pollutants and their ecotoxicological effects

Pollutant type	Examples	Ecotoxicological effects
Heavy metals	Mercury, lead, cadmium	Bioaccumulation, neurotoxicity, organ damage
Pesticides	DDT, atrazine	Endocrine disruption, reproductive failure
Industrial chemicals	PCBs, dioxins	Carcinogenicity, immune suppression
Pharmaceuticals	Antibiotics, hormones	Antibiotic resistance, hormonal disruptions
Microplastics	Plastic fragments	Ingestion hazards, chemical leaching

3. Environmental Laws and Regulations

Several national and international regulations have been implemented to minimize environmental pollution. Some significant frameworks include:

i. **The Clean Water Act (CWA, USA)**: Regulates pollutants discharged into water bodies to ensure water quality.

ii. **The Clean Air Act (CAA, USA)**: Controls air pollution from industrial and vehicular sources to protect air quality.

iii. **The European Union REACH Regulation**: Ensures the safe use of chemicals by requiring industries to register and assess their environmental and health risks.

iv. **The Environmental Protection Act (India)**: Enforces sustainable environmental management through pollution control measures.

v. **The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA, USA)**: Regulates the use of pesticides to prevent environmental contamination.

These laws serve as frameworks for controlling pollution, enforcing penalties for non-compliance, and setting permissible pollutant levels.

4. International Treaties and Agreements

To address transboundary pollution, countries have adopted international agreements. Key treaties include:

i. **Stockholm Convention on Persistent Organic Pollutants (2001)**: Aims to eliminate or reduce harmful POPs such as Dichloro Diphenyl Trichloroethane (DDT) and Polychlorinated Biphenyls (PCBs).

ii. **Basel Convention (1989)**: Regulates the transboundary movement and disposal of hazardous waste to prevent environmental and health risks.

iii. **Kyoto Protocol (1997) and Paris Agreement (2015)**: Focus on climate change mitigation by setting targets for reducing greenhouse gas emissions.

iv. **Convention on Biological Diversity (1992)**: Promotes sustainable biodiversity conservation and addresses the risks posed by ecotoxicological threats.

v. **Minamata Convention on Mercury (2013)**: Regulates mercury emissions to reduce its impact on human health and the environment.

These agreements are essential for global cooperation in addressing pollution and promoting environmental sustainability.

Table 2: Key International Environmental Agreements

Treaty/Convention	Year	Focus Area
Stockholm Convention	2001	Persistent Organic Pollutants
Basel Convention	1989	Hazardous Waste Management
Kyoto Protocol	1997	Climate Change Mitigation
Paris Agreement	2015	Greenhouse Gas Reduction
Minamata Convention	2013	Mercury Pollution Control
Marpol Convention	1973	Marine Pollution from Ships
Ramsar Convention	1971	Wetlands of Economic Importance
Convention on Biological Diversity	1992	Biodiversity Conservation

Montreal Protocol	1987	Ozone Depleting Substances

5. Regulatory Frameworks for Ecotoxicology

Regulatory frameworks provide guidelines for environmental risk assessments and pollutant control. Essential frameworks include:

- **i.** Organization for Economic Co-operation and Development (OECD) Guidelines for the Testing of Chemicals: Provide standardized methods for evaluating chemical toxicity.
- **ii.** World Health Organization (WHO) Guidelines: Address environmental health risks and provide guidance on safe chemical exposure levels.
- **iii.** International Maritime Organization (IMO) Regulations: Control marine pollution from ships, including ballast water management to prevent invasive species.
- **iv.** United Nations Sustainable Development Goals (SDGs): Integrate ecotoxicology concerns into broader environmental and sustainability objectives.

6. Sustainable Environmental Practices

To mitigate ecotoxicological impacts, sustainable practices include:

- **i.** **Green chemistry**: Developing environmentally friendly chemicals and industrial processes to reduce pollution.
- **ii.** **Bioremediation**: Using microorganisms, plants or fungi to degrade environmental contaminants, such as oil spills and heavy metals.

iii. **Eco-friendly waste management**: Implementing circular economy principles to minimize waste generation and enhance recycling.

iv. **Renewable energy adoption**: Reducing reliance on fossil fuels to decrease air and water pollution.

v. **Integrated Pest Management (IPM)**: Reducing pesticide use by employing biological control methods and sustainable agricultural practices.

vi. **Eco-labelling and consumer awareness**: Promoting environmental friendly products to encourage sustainable consumption patterns.

Table 3. Sustainable environmental practices and their benefits

Practice	Benefit
Green chemistry	Reduces hazardous waste production
Bioremediation	Removes contaminants naturally
Eco-friendly waste management	Reduces landfill waste
Renewable energy	Decreases carbon footprint
Integrated pest management	Reduces chemical pesticide reliance
Eco-labelling and awareness	Encourages responsible consumption

7. Challenges in Ecotoxicology and Environmental Regulation

Despite significant progress, several challenges persist in managing ecotoxicological risks:

i. **Emerging contaminants**: Many synthetic chemicals, including pharmaceuticals, personal care products and nanomaterials, are not yet fully regulated.

ii. **Climate change interactions**: Climate change can alter pollutant distribution and toxicity, complicating risk assessments.

iii. **Data gaps and uncertainty**: Limited ecotoxicological data on new chemicals hampers risk assessment efforts.

iv. **Global policy enforcement**: Variability in regulatory frameworks among nations leads to loopholes and inconsistencies.

v. **Industrial and economic pressures**: Balancing economic growth with environmental protection remains a challenge.

Table 4. Comparative analysis of environmental laws in India and other countries

Country	Law/Act/Regulation	Year	Impact/Challenges
India	Environmental Protection Act	1986	Implementation gaps, pollution control efforts
India	National Green Tribunal Act	2010	Effective but limited jurisdiction
USA	Clean Air Act	1970	Significant air quality improvements
USA	Resource	1976	Effective waste

	Conservation and Recovery Act		management system
European Union	REACH Regulation	2006	Strong chemical safety regulations
China	Environmental Protection Law	2014	Improving, but enforcement remains a challenge
Brazil	Forest Code	2012	Deforestation control with moderate success
Canada	Canadian Environmental Protection Act	1999	Comprehensive pollution control measures
Australia	Environment Protection and Biodiversity Conservation Act	1999	Effective biodiversity protection but industrial challenges
Germany	Federal Nature Conservation Act	2002	Strong regulatory framework, effective enforcement
Japan	Basic Environment Law	1993	Effective pollution control measures
South Africa	National Environmental Management Act	1998	Progress in environmental justice, but enforcement gaps exist

8. Enforcement Gaps in Environmental Regulations

Despite the existence of robust environmental laws and international treaties, enforcement remains a major challenge due to several factors:

i. **Weak institutional frameworks:** Many countries lack strong regulatory institutions to monitor and enforce environmental laws effectively (United Nations Environment Programme [UNEP], 2019).

ii. **Limited resources and funding:** Environmental agencies in developing nations often struggle with inadequate funding and lack of technical expertise to implement policies effectively (United Nations Development Programme [UNDP], 2022).

iii. **Loopholes and inconsistencies in policies:** Differences in environmental laws across countries create loopholes that industries exploit to bypass stricter regulations (OECD, 2022).

iv. **Corruption and lack of political will:** Corruption and political interference in environmental governance weaken enforcement mechanisms and hinder sustainability efforts (UNEP, 2021).

v. **Slow legal processes:** Judicial delays in environmental cases reduce the effectiveness of legal enforcement, as polluters often escape timely penalties (UNDP, 2022).

9. Future Recommendations for Strengthening Environmental Governance

To bridge enforcement gaps and enhance environmental sustainability, the following recommendations should be implemented:

i. **Strengthening regulatory agencies:** Governments must allocate more resources to environmental agencies and enhance their autonomy for effective law enforcement (United States Environmental Protection Agency [EPA], 2023).

ii. **Harmonizing global environmental laws:** Standardizing environmental policies across nations can close legal loopholes and create a more effective global governance system (OECD, 2022).

iii. **Incentivizing sustainable practices:** Industries should be encouraged through tax benefits and subsidies to adopt green technologies, circular economy models, and renewable energy (Stockholm Convention, 2021).

iv. **Public awareness and citizen participation:** Empowering communities through education and awareness campaigns can increase public involvement in environmental protection efforts (World Health Organization, 2022).

v. **Utilizing advanced technologies:** Integrating AI, remote sensing, and blockchain technology in environmental monitoring can enhance transparency and real-time enforcement (Basel Convention Secretariat, 2022).

vi. **Enhancing international cooperation:** Strengthening collaboration between nations through information sharing and joint environmental programs will improve the enforcement of treaties (Kyoto Protocol, 1997).

vii. **Stricter penalties for violators:** Enforcing harsher penalties, including heavy fines and business restrictions for polluting industries, can serve as a deterrent against environmental violations (Paris Agreement, 2015).

Many environmental policies suffer from inconsistencies across regions and countries. While some nations adopt stringent regulations, others have lax enforcement, leading to an imbalance in global environmental efforts. Lack of Enforcement and Compliance: Even when policies exist, enforcement remains a significant hurdle. Many developing nations lack the resources, technology, or institutional capacity to monitor and enforce environmental laws effectively. Economic Constraints:

Environmental protection often requires substantial financial investment, which can be a challenge for developing economies. Governments sometimes prioritize economic growth over environmental sustainability, leading to inadequate policy support. Political and Industrial Resistance: Policy implementation is frequently met with resistance from industries and political entities that prioritize short-term economic gains over long-term sustainability. Lobbying by powerful industries can weaken or delay environmental regulations. Lack of Public Awareness and Engagement: Public participation plays a critical role in environmental conservation. However, in many cases, citizens are either unaware of policies or lack the necessary platforms to contribute effectively. Climate Change and Global Coordination: Climate change is a global issue requiring coordinated efforts among nations. However, geopolitical differences, conflicting interests, and varied levels of commitment make global cooperation challenging. Technological and Infrastructural Limitations: Many regions, especially in developing countries, lack the necessary infrastructure to support sustainable practices. This limits their ability to transition to cleaner energy sources and adopt environmentally friendly technologies.

10. Conclusion

Ecotoxicology provides critical insights into the impacts of pollutants on ecosystems and human health. Regulatory frameworks, environmental laws, and international treaties play vital roles in mitigating these effects and promoting sustainability. Strengthening global cooperation, enforcing stricter regulations, and advancing research in ecotoxicology are essential steps toward achieving a sustainable environment.

Developed countries like the USA and Germany have strict environmental policies that have significantly improved air and water quality, waste management and biodiversity conservation. The USA's Clean Air Act and the EU's REACH regulation have been successful due to strong enforcement and regular updates based on scientific research.

In contrast, India and other developing nations have strong environmental laws but struggle with enforcement. India's National Green Tribunal (NGT) has helped resolve environmental disputes, but challenges such as bureaucratic delays and lack of resources limit its impact. Similarly, countries like China and Brazil have improved their environmental policies but still face pollution and deforestation problems.

The effectiveness of environmental laws depends on strong institutions, public participation and global cooperation. Countries with well-funded environmental agencies and strict penalties for polluters tend to be more successful. Improving law enforcement, increasing transparency and promoting sustainable practices worldwide are crucial for long-term environmental protection. International treaties and agreements play a key role in addressing cross-border environmental issues and ensuring a united global approach to sustainability. Besides these challenges, environmental policies remain an essential tool for addressing ecological concerns. Strengthening enforcement mechanisms, increasing international cooperation and integrating sustainable development with economic growth are critical for overcoming these hurdles. Governments should allocate more resources to environmental protection, promote research and innovation, and enhance public engagement through education and awareness campaigns. Additionally, industries must adopt greener practices and policymakers should create incentives for sustainable development.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-19

Bioremediation of Heavy Metal Contaminated Sites by Microbial Extracellular Polymeric Substances

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AUTHOR'S CONTRIBUTIONS

This chapter was jointly prepared by three authors. Author AA conceptualized the study and provided critical revisions to the initial draft. Author SC conducted the literature review, prepared the content, and finalized the manuscript. Both authors contributed significantly to the development of the content and PK approved the final version of the chapter.

ABSTRACT

Heavy metal (HM) contamination in the air poses a significant risk to ecosystems. Standard practices for HM removal, such as physical and chemical treatments, frequently faces challenges associated with effectiveness, cost, and sustainability. As a result, there is growing interest in exploring innovative and eco-friendly technologies, such as bioremediation. Bioremediation is an advanced approach that utilizes the extraordinary abilities of microorganisms to degrade and transform environmental pollutants. With its exceptional physiochemical properties and capacity to form symbiotic interactions with heavy metals, microbial exopolysaccharides (EPS) emerge as a revolutionary solution. This research aims to uncover the intricate mechanisms through which microbial extracellular polymers alleviate the effects of heavy metal pollution. Initially, the challenging process by which EPS captures and immobilizes heavy metals will be filtered. EPS has the outstanding capability to create metal complexes that include chelators and ion-binding sites, helping the efficient removal and immobilization of heavy metals thereby mitigating their bioavailability and toxicity. EPS can serve as a protective shield for microorganisms against heavy metal stress, aiding their survival and growth. Besides, EPS production can be powered or enhanced in response to heavy metal predisposition. This innovative solution has the potential to revolutionize the bioremediation process, improve efficiency, lower costs, and enhance overall performance.

Keywords: Bioremediation, heavy metals, microbial EPS, eco-friendly, environmental sustainability

1. Introduction

The contamination of soil and water ecosystems with heavy metals such as cadmium, lead, mercury, and chromium poses a significant threat to environmental and public health due to their toxicity, persistence and bioaccumulative nature (Fu and Wang, 2011). Industrial activities, mining, improper waste disposal, and agricultural runoff have intensified the spread of these pollutants, leading to widespread ecological damage and reduced agricultural productivity (Ali, Khan and Sajad, 2013). These metals can disrupt microbial diversity, impair nutrient cycling, and enter food chains, affecting both terrestrial and aquatic organisms (Tchounwou et al., 2012; Jaishankar et al., 2014). Long-term exposure is associated with genotoxic, neurotoxic, and carcinogenic effects, making their remediation an urgent priority (Nagajyoti et al., 2010).Conventional remediation methods like chemical precipitation, ion exchange and electrochemical treatment, though effective, often incur high costs, produce secondary pollutants, and are limited in their adaptability to diverse environmental conditions (Gadd, 2009). Moreover, these techniques may not be suitable for large-scale or low-concentration contamination, and often require post-treatment management (Gavrilescu, 2004; Wang and Chen, 2009).

Bioremediation has emerged as an eco-friendly and cost-effective alternative, utilizing biological systems to detoxify and restore polluted environments. Among various microbial mechanisms involved in heavy metal detoxification, the production of Extracellular Polymeric Substances (EPS) by bacteria, fungi, and algae plays a pivotal role (Wingender et al., 1999). Bioremediation strategies using microbial EPS are gaining attention for their adaptability and minimal environmental disruption (Glick, 2010; Singh and Kalamdhad, 2011).

These high-molecular-weight biopolymers composed mainly of polysaccharides, proteins, lipids, and nucleic acids that are secreted into the surrounding environment, where they function as bio-sorbents by binding metal ions through various functional groups such as hydroxyl, carboxyl, phosphate and amino groups (Flemming and Wingender, 2010). EPS also enhances sorption kinetics, stability and selectivity in metal binding, making them highly effective in diverse environments (Sheng et al., 2010; Kumar et al., 2015). The EPS matrix not only protects microbial communities from toxic metal stress but also enhances their survival and activity in contaminated habitats (Pal and Paul, 2008). Moreover, EPS facilitates biofilm formation, which further contributes to the immobilization, transformation, and sequestration of heavy metals (Liu et al., 2017). Biofilms form structured microbial communities that create microenvironments favourable for metal retention and reduce bioavailability (Harrison et al., 2007; Costa et al., 2018).

Recent studies have highlighted the potential of genetically modified or naturally resilient microbial strains producing EPS in the bioremediation of multi-metal contaminated sites (Gupta and Diwan, 2017). The integration of synthetic biology and omics technologies has further enhanced the efficiency and stability of EPS-producing strains in heavy metal detoxification (Valls and de Lorenzo, 2002; Singh et al., 2020).

This chapter explores the multifaceted role of microbial EPS in heavy metal bioremediation, examining the biochemical mechanisms of metal binding, environmental factors influencing EPS production, and the practical applications and challenges associated with EPS-based bioremediation technologies. Understanding these interactions can pave the way for the development of efficient, sustainable strategies for restoring heavy metal-impacted environments. Advancing this field requires interdisciplinary research focused on scaling up EPS-based systems while ensuring ecological safety and regulatory compliance (Flemming et al., 2016).

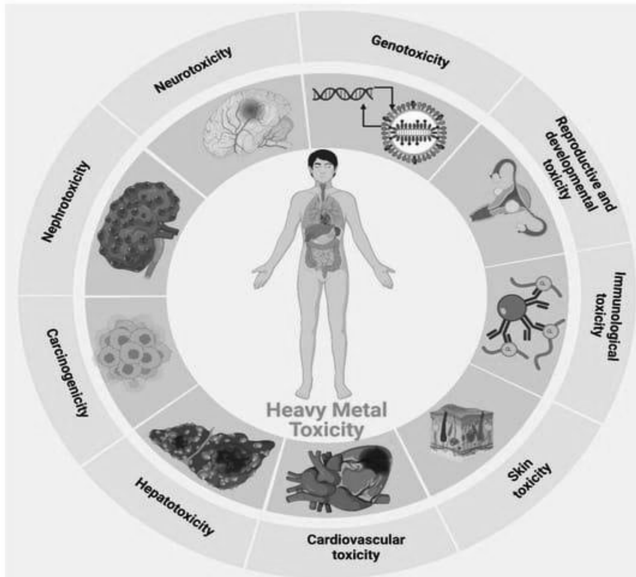

Figure 1: Effects of heavy metal pollution (Singh et al., 2023)

2. Heavy Metals

Lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) are heavy metals that are non-biodegradable and represent a significant class of persistent environmental pollutants with long-term toxic effects on both ecosystems and human health. Unlike organic contaminants, these metals persist in the environment and tend to bioaccumulate in living organisms (Ali et al., 2019). Anthropogenic activities such as industrial processes, mining and agricultural runoff are the primary sources of heavy metal contamination in soils and aquatic systems (Fu and Wang, 2011). These metals can interfere with essential biochemical processes, damage cellular structures, and accumulate across trophic levels, leading to biomagnification (Tchounwou et al., 2012; Jaishankar et al., 2014). The persistent nature and mobility of heavy metals pose challenges in maintaining soil fertility, crop productivity, and water quality (Nagajyoti et al., 2010). Effective remediation techniques are essential to address this issue, and bioremediation is an environmentally sustainable alternative to conventional chemical treatments has shown remarkable potential. Microbial communities capable of metal tolerance and transformation play a crucial role in these strategies, offering cost-effective and eco-friendly solutions (Glick, 2010; Singh and Kalamdhad, 2011).

3. Bioremediation

The bioremediation refers to biological method that uses microorganisms to remove or neutralize heavy metals from polluted environments. Detoxification of pollutants occurs via numerous mechanisms such as biosorption, bioaccumulation, enzymatic transformation, and metal precipitation (Gadd, 2009). Cyclodextrins have high solubility in water, recyclable nature, additionally, alfa-cyclodextrins (aCD) are known to enhance petroleum bioavailability in soil, thus enhancing biodegradation while maintaining the less clean-up cost (Amani and Khosravi, 2023).

4. Microbial Extracellular Polymeric Substances

Extracellular polysaccharides (EPS) are high molecular-weight natural biopolymers produced by bacteria, with a vast range of innovative applications. These exopolysaccharides are diverse macromolecules found in microorganisms that play a crucial role in biofilm formation and microbial survival. EPS serves as a profitable and eco-friendly alternative to traditional methods for removing heavy metal contaminants. EPS contains organic and inorganic components which gives it acidic properties, allowing it to withstand heavy metal stress. EPS shows a variety of functions such as promoting cell adhesion, maintaining lasting biofilm structures, and water retention capacity. The removal of metals varies, with capsular polysaccharides and mucoid polysaccharides released by bacteria showing higher elimination rates (Wei et al., 2016). The functional groups in EPS differ, leading to varying levels of metal affinity (Table 1). Many studies have revealed an exponential increase in metal adsorption in the presence of EPS. For example, it was observed when EPS was removed, the adsorption of Cu (II) by *Bacillus subtilis* and *Pseudomonas putida* decreased by 37.8% and 25.4%, respectively. Acidobacterial EPS is a profitable and justifiable resource for industries because of its origin and reduced toxicity. It is abundantly found in the biosphere and have protective properties that allow it to stand for long periods. Both unicellular and multicellular organisms, including phytoplankton, eubacteria, and archaebacteria, are essential for exopolysaccharide production. The differential characteristics of microbial EPS makes it more inviting than EPS from other sources, and to support urbanization, it is necessary to enhance quality, increase production rates, and lower manufacturing costs. Dextran, which is a polar compound originated from bacteria and produced by different bacterial species was the first commercialized exopolysaccharide (Zhang et al., 2012). A wide range of applications in different fields of science are shown by EPS such as in cosmetics, food, and medicine. Therefore, identifying potential EPS-producing candidates and developing cost-effective extraction methods are crucial for commercialization. Compared to other sources, the production and extraction of microbial EPS are relatively easy (Jaishankar et al., 2014). Many studies have revealed that the key cause behind the capability of exopolysaccharides to remove the heavy metal contamination is the presence of negatively charged functional groups such as carboxyl (COOH), hydroxyl (-OH), and amino (-NH2) groups. EPS can show various structural modifications, such as altering the polymeric length and introducing different links. The composition of EPS majorly depends on factors such as the category and quantity of carbon source available in the surrounding medium, and abiotic stressors (Zhang et al., 2014). A number of commercially available exopolysaccharides with the required ionicity have been reported such as, alginate (*Pseudomonas aeruginosa*, *Azotobacter vinelandii*), gellan (*Sphingomonas paucimobilis*), hyaluronan (*Pseudomonas aeruginosa*, *Pasteurella multocida*, Streptococci attenuated strains), xanthan (*Xanthomonas campestris*), and galactosyl (*Pseudomonas oleovorans*).

Table 1. Showing various bacterial strains their EPS, functional group and metal specificity

Strain	Functional group	Metal specificity	Surface EPS
Bacillus subtilis	COO-	Cu (II)	EpsA-O
Pseudomonas putida	$-PO_3$, COO-	Cu (II)	Alginate
Xanthomonas campestris	OH-, COO-	Cu (II)	Xanthan
Bacillus cereus	COO-, OH-, $-NH_2$	Cr (IV)	Bacillus cereus EPS
Pseudomonas aeruginosa	COO-	La (III)	Hyaluronan

5. Biosynthesis of EPS

The process of EPS biosynthesis mainly depends upon the place where it is being generated, either intracellularly or extracellularly. While there is still much to learn about the mechanism of exopolysaccharide biosynthesis, the existing literature provides valuable insights into the process (Jang et al., 2007). The biosynthesis of homopolysaccharides mainly occurs outside the cell, where enzymes transfer activated monosaccharides to the growing polysaccharide chain and as a result of this process, the polysaccharide chain is arranged in a particular pattern with a specific range. Some of the homopolysaccharides such as Dextran and Levan require certain specific enzymes like dextran sucrase and levansucrase and substrates such as sucrose. Studies show that some gram-positive cocci are also known to produce exopolysaccharides (Zhang et al., 2014).

Carbohydrate synthesis is a complex process which requires the assemblage of carbohydrates, nucleic acid precursor molecules inside the cell, which are then transferred to the cell exterior. The first step involves the entry of a sugar substrate into the bacterial cell after which it is metabolized. Some precursor molecules that are not part of the biosynthesis pathways are utilized as raw materials for exopolysaccharide synthesis (Jaishankar et al., 2014). The constituents inside the cell require carbohydrates, which act as substrates, and the energy source in the form of NDP/NMP from sugars that are incorporated by the self-organizing process (Kondakindi et al., 2024). The primary activated residue is a phosphorylated sugar, such as sugar-1 phosphate, sugar-2 phosphate, or sugar-6 phosphate. Intermediates formed during the metabolic pathway, such as Fructose-6P or Glucose-1P, are utilized as the precursor molecules for the synthesis of EPS, including UDPGlcNAc, UDP-GalNAc, and dTDP-rhamnose (Gupta and Diwan, 2017). The phosphoglucomutase enzyme catalyzes the modification of sugar-6 phosphate to sugar-1 phosphate, which acts as a major donor for NDP/NMP sugar production. UDP-glucose PP and dTDP-glucose PP enzymes change sugar1phosphate to UDP-glucose and dTDP-glucose. In some cases, UDP-*N*acetylglucosamine 4-epimerase activates the conversion of UDP-GlcNAc to UDP-GalNAc. In a study, it was identified that in *Lactobacillus rhamnosus* a few genes that are participate in the synthesis of the dTDP-L-rhamnose NDP sugar moiety. These sugar molecules are then transferred to an Isopentenyl pyrophosphate (IPP) lipo carrier undeca prenyl phosphate (C55-P) present in the membrane of cytosol with help of an enzyme named glycosyltransferase. Studies have suggested that L. *rhamnosus*, has few glycosyltransferase genes that are involved in the assemblage of six carbon saccharide units comprising the rhamnose compound

(Jang et al., 2007). The transportation of lipids allows the assemblage of substrate molecules which are monomers and thus controls peripheral transportation. While some gram-positive bacteria also use the lipid intermediate pathway for exopolysaccharide assemblage, it has a more critical part in gram-negative exopolysaccharide assemblage and transportation due to the diverse structure of cell walls in gram-negative bacteria. In gram-positive bacteria, the assembled repeating moieties are transported to the cell surface where elongation continues. However, gram-negative bacterial species uses another pathway such as Wzx-Wzy dependent or an ABC transporter pathway for the assembly and transport of EPS (Jaishankar et al., 2014).

6. EPS Vs Heavy Metals Interaction

Microbes excrete extracellular polymeric substances (EPS) as protection against harmful environmental conditions. The functional groups (-OH, -COOH, $-NH_2$) present in these compounds are responsible for binding and immobilizing heavy metals (More et al., 2014). EPS plays a crucial role in metal detoxification through several mechanisms:

6.1 Biosorption

Biosorption is a passive method that involves binding of metal ions to EPS by electrostatic attraction, ion exchange, and complexation (Volesky, 2007). Microbial biofilms enriched with EPS have been successfully applied for heavy metal removal from wastewater because of their higher metal adsorption capacity (Gupta and Diwan, 2017). Mechanisms of adsorption are depicted in figure 2.

6.2 Biofilm formation

Microbial biofilms, which consist of EPS and microbial cells, create a protective environment that shields microorganisms from metal toxicity. These biofilms act as a barrier, limiting metal penetration while facilitating metal sequestration within the EPS matrix (Flemming and Wingender, 2010). Additionally, biofilm formation enhances microbial resistance to metal stress and improves the overall efficiency of bioremediation processes (Singh et al., 2016).

6.3 Metal precipitation and redox transformation

Some microbes utilize EPS to modify the oxidation states of heavy metals, reducing their toxicity and facilitating their removal. For example, microbial activity can convert Cr^{2+} into the less toxic Cr^{3+}, thereby decreasing chromium contamination risks (López-Maldonado et al., 2014). Similarly, EPS can promote the precipitation of soluble metal ions into insoluble forms, preventing further environmental damage (Jiang et al., 2018).

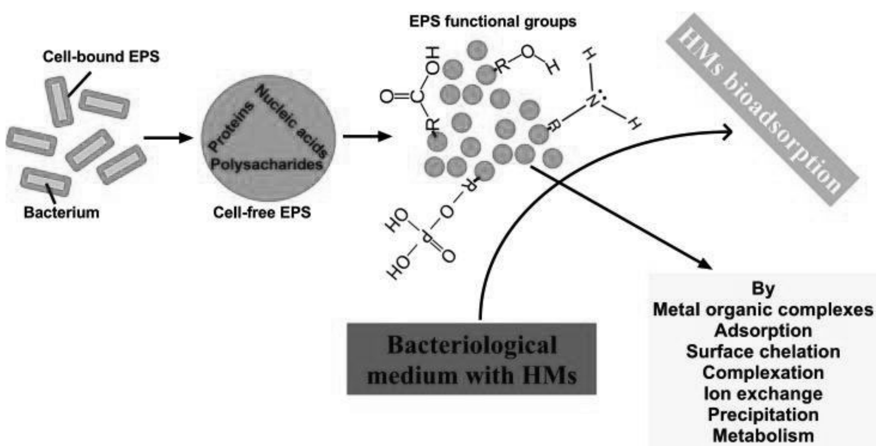

Figure 2: Mechanism of extracellular polymeric substance-based bioremediation (Kondakindi et al., 2024).

7. Applications of Exopolysaccharides

7.1 Mining

Azotobacter b3d9 is a potent producer of EPSs capable of fixing nitrogen without forming symbiotic relationships. Besides this, Azotobacter can also withstand and remove mercury contamination by producing EPSs. Another classic example of heavy metal removal is by the cyanobacterium *Anabaena doliolum*

Ind1, which was capable of eliminating cadmium at neutral pH (7) and 25 °C, with a high removal percentage of 92% within 7 days of the confluence (Dangi et al., 2018). EPS-producing microbes such as *Bacillus subtilis* and *Pseudomonas putida* have also demonstrated high tolerance to metal stress, playing key roles in biosorption of lead and chromium in mining waste (Wang and Chen, 2009). The application of such strains in bioleaching and biorecovery is gaining momentum due to their environmental compatibility and metal selectivity (Gavrilescu, 2004).

7.2 Agriculture

Achyranthus aspera strains are capable of generating biofilm which can be utilized for the decontamination of Ni (II) contaminated soil. Another example is the *Pseudomonas Psd* strain which can form EPS responsible for the removal of zinc by the process of biosorption. Knocking out this gene resulted in decreased zinc adsorption (Naghipour et al., 2016). EPS-producing plant-growth-promoting rhizobacteria (PGPR) also enhance soil structure, metal immobilization, and nutrient cycling under heavy metal stress (Costa et al., 2018). Furthermore, microbial consortia producing EPS have been successfully used in phytoremediation setups to improve metal tolerance in crops (Singh et al., 2020).

7.3 Industry

Rhizobium radiobacter VBCK1062, a species extracted from the rhizosphere of *Vigna radiata*, shows resistance to arsenate by taking up arsenate through EPS, with evidence showing that it can uptake 0.068 mg of arsenic per gram of component. Studies reveal that the strain has a MIC of 10 mM relating to other HMs (Naghipour et al., 2016b). Industrially relevant EPS-producing microbes have been tested in wastewater treatment facilities for their efficiency in removing multi-metal contaminants from effluents (Valls and de Lorenzo, 2002). The biotechnological production of EPS is also being optimized for scalable applications using engineered microbial platforms in heavy-metal-intensive industries (Kumar et al., 2015).

8. Conclusion

The polysaccharide components of microbial extracellular polymeric substances (EPS) are vital for the bioremediation of environments polluted by heavy metals. These biological macromolecules secreted by microbial communities provide both structural and functional support for heavy metal sequestration through processes such as biosorption, biofilm formation, and redox transformation. Functional groups like amino ($-NH_2$), carboxyl (-COOH), and hydroxyl (-OH) play a crucial role in binding and immobilizing metals. Due to their cost-effectiveness, eco-friendliness and versatility, EPS-mediated bioremediation presents a sustainable alternative to conventional methods and finds applications in wastewater treatment, soil remediation, and industrial waste management. Additionally, the ability of microbial biofilms to form protective matrices enhances microbial resistance to metal toxicity, thereby supporting long-term effectiveness.

The increasing research interest in this field is clearly reflected in the growing number of publications from 2014 to 2023. This trend emphasizes the rising global attention toward EPS-based bioremediation. Looking ahead, advancements in microbial engineering and synthetic biology offer tremendous potential to improve EPS production and metal-binding efficiency. The integration of these strategies with nanotechnology and bioelectrochemical systems may further elevate the effectiveness and precision of heavy metal removal from contaminated environments (Ak et al., 2024).

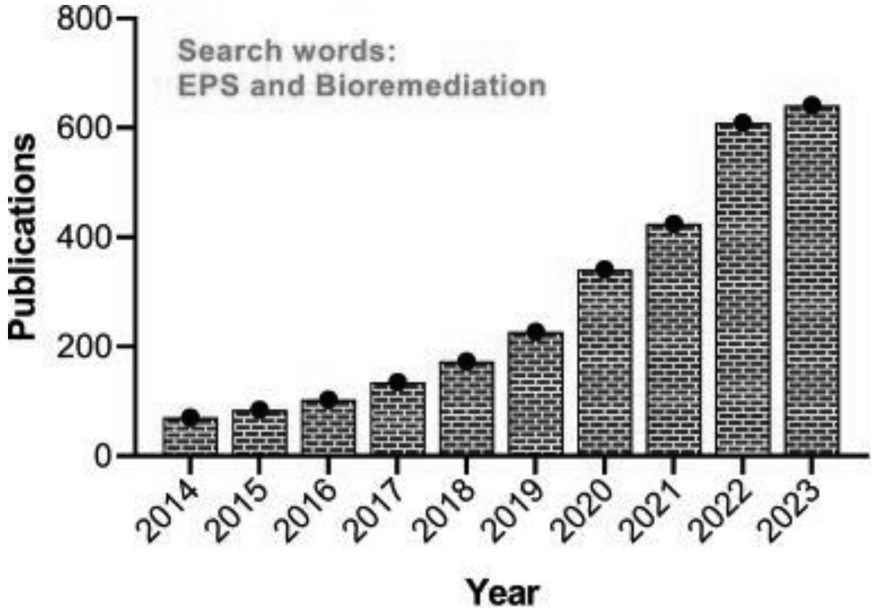

Figure 3: Number of publications on EPS-based bioremediation from 2014 to 2023

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-20

CRISPR Cas System and Its Role For Monitoring and Controlling the Environmental Pollution and Toxicants

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ABSTRACT

A biological system that consists of all living and non-living organisms (plants and animals) in an area where living organism interacts with each other and with their surroundings, makes an ecosystem. The ecosystem is controlled by the flow of energy and the substances. In a balanced ecosystem, both biotic and abiotic components interacts each other cooperatively to maintain the ecological stability. Sustained energy flow, efficient nutrient cycling, properly maintained bio-diversity, self- regulation, homeostasis, minimal pollution and lack of environmental stress makes an ecosystem balanced. On the other hand, presence of toxic substances, habitat destruction, deforestation and also introduction of the invasive species makes the ecosystem imbalanced. All these factors lead to change in the ecological balance. Ecotoxicology deals with the effect of toxic substances on the ecosystem to understand how the pollutants (such as heavy metals, pesticides, pharmaceuticals, microplastics etc.) affect the environment.

Sustained environmental practices and conservation methods are the key strategies to prevent ecological imbalance. It requires the involvement of the scientific, technological and community driven programs for controlling these toxicants that includes biological, chemical, physical approaches along with the involvement of the strict regulatory and policy measures. Traditional methods for controlling the pollutants and toxicants often need expensive and time consuming procedures. One novel approach is CRISPR Cas system, which is a revolutionary gene-editing technology used to precisely cut and modify DNA. This system was originally recognized as an adaptive immune mechanism in bacteria. CRISPR-Cas gives new methods for accurately detecting, tracking and reducing the environmental pollution. This chapter focuses on the recent advancements, challenges, and future prospects of CRISPR-Cas based technologies in addressing environmental contamination.

Keywords: Homeostasis, ecotoxicology, CRISPR-Cas, gene-editing, heavy metals.

1. Introduction

Pollution is the presence of unwanted harmful substances or contaminants in the environment which adversely affect the living organisms and ecosystem. Pollution has posed a serious threat to mankind since their existence. In fact, pollution is one of the challenges since the time of our ancestors. Increasing human populations have accelerated this process and have opened the door for various types of air, water and noise pollution. Not only the human activities but also the natural sources are responsible for the environmental pollution which includes the volcanic eruptions, wild fires, dust storms, sea salt aerosols and the release of poisonous gases like the SO_2 and radon gas (Ukaogo et al., 2020). Pollution leads to disrupt the ecological balance, depletes natural resources and poses significant threat for the human health along with the biodiversity and climate stability. Industrialization, urbanization and agricultural expansion have accelerated the emission of hazardous substances into the environment which are continuously disrupting the natural cycles and causing long-term damage (Shetty et al., 2023). Any toxic substance occurring artificially or naturally in the environment that changes the quality of air, water or soil and make it unsuitable for humans and other living organisms are considered as toxicants. These toxicants enter the environment through different ways which includes industrial discharge, agricultural practices, mining, waste water treatment, combustion, land-fillings etc. Toxicants have wide range of health problems which includes various types of chronic diseases, neurological and genetic damage (Sokan-Adega et al., 2023). When we see the effect of the pollutants on the ecosystem, throughout history numerous events have occurred resulted in serious impacts on both humans and the environment. It includes Bhopal gas tragedy, Chernobyl disaster, Seveso disaster, London smog, Fukushima nuclear disaster, Hungarian red slug spill etc. Controlling pollution isn't just necessary; it's our responsibility to manage it in order to sustain future generations on the planet. Every breath, every drop of water, and every bite of food depends on a clean environment. Ignoring pollution risks are devastating our health, ecosystems, and global stability. Environmental pollution and toxicants are being controlled through various physical, chemical, biological and advanced biotechnological approaches. These include filtration and adsorption, chemical precipitation, electrocoagulation, microbial degradation, bioremediation and phytoremediation. Additionally, nanoparticles and biosensors are increasingly being utilized for effective pollution control (Patel and Bhatt, 2022; Gavrilescu et al., 2015).The old methods to control the pollution provide remarkable benefits, but their limitations have created urgent need for the introduction of innovative methods such as CRISPR Cas system. This revolutionary technology has the potential for monitoring the environment and remediation by precisely creating genetic modification, waste management and efficient degradation of pollutants. With this technique, researchers can make target specific, precise changes in the genome. This method has been proven effective for managing toxins in a variety of biological system. When plants are exposed to heavy metals, certain genes attributed to detoxifying these metals get activated. These specific genes have been edited for enhancing their phytoremediation property. Microorganisms such as *Pseudomonas* and *E.coli* have also been engineered for the degradation of pollutants such as pesticides, hydrocarbons, dyes, and they also sequester heavy metals such as arsenic, lead, and cadmium by altering the detoxification pathways. Some microbes such as bacteria and BGA's release toxins in their environment such as microcyctin and cyanotoxins, these toxins make the water contaminated (Chaterjee and More, 2023). Application of CRISPR editing technique has successfully demonstrated considerable reduction in these biological toxicants. Together, these applications of CRISPR show the adaptability of this tool for monitoring, reducing and managing toxic substances in different fields.

2. CRISPR Cas System

CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) is a type of adaptive immune system found in about 40% of bacteria and 90% of archae. CRISPR makes them immune for the invading phages, viruses and other type of foreign genetic material (Barrangou et al., 2007; Brouns et al., 2007). It is endogenous machinery that makes use of an RNA molecule which recognizes the target site by complementary binding to it and guides the Cas9 nuclease (Wiedenheft et al., 2011). These organisms use CRISPR-associated (Cas) protein, including Cas9, which recognizes and destroy viral DNA upon reinfection. The CRISPR system works by acquisition of short sequence of viral DNA within CRISPR arrays in the bacterial genome. This stored sequences acts as the genetic memory that allows the organism to produce RNA molecules which guides Cas proteins to target site and degrade foreign DNA at the specific location.

2.1 Key components of CRISPR-Cas9

a. **Guide RNA (gRNA):** gRNA is a sequence of nucleotide which guides the Cas9 nuclease to the correct target site.It has two components, one is the CRISPR RNA (crRNA) whose sequence is complementary to the target DNA responsible for binding to the specific target site and the second one is the trans-activating CRISPR RNA (tracrRNA), it binds to the crRNA that helps in recruiting and stabilizing Cas9 protein. In most cases, these two RNA molecules are fused to form a single synthetic guide RNA (sgRNA). The gRNA ensures the specificity and determines at what location the DNA sequence will be targeted by the Cas9 nuclease (Schneider, 2020).

b. **Cas9 nuclease:** Cas9 is an enzyme responsible for cutting the DNA at the site specified by the gRNA. It has two key domains. One is the RuvC Domain that cleaves one strand of the target DNA and another one is HNH Domain that cleaves the complementary DNA strand (Jinek et al., 2012). The double-strand break (DSB) created by Cas9 nuclease triggers the cell’s natural repair system which leads to either gene disruption or precise modifications via homologous recombination.

c. **Protospacer adjacent motif (PAM):** PAM is a short sequence of DNA which is necessary for Cas9 nuclease to recognize and bind at the target. PAM is located adjacent to the target DNA sequence. Most commonly used Cas9 of *Streptococcus pyogenes* recognizes the “NGG” sequence (where "N" is any nucleotide, and "G" is guanine). Cas9 cannot effectively bind or cut the DNA in absence of the PAM even if the gRNA perfectly matches the target sequence. So, presence of PAM and complementary binding of gRNA to the target DNA provides specificity of binding and prevents Cas9 from cutting DNA at other sites throughout the genome (Gleditzsch et al., 2019).

2.2 Mechanism of CRISPR-Cas9 gene editing

The CRISPR-Cas9 system follows a stepwise process to achieve precise gene editing. It includes the target gene selection in which genome sequence is identified for which gRNA is designed that have complementary sequence to the target region. Presence of PAM is crucial for effective binding of the Cas9. The gRNA-Cas9 complex scans the genomic sequence for matching and once the correct matching site is found, the gRNA binds to DNA and Cas9 induces the double strand break. After the break is introduced, the cell activates one of the two repair mechanism. One is the Non-Homologous End Joining **(NHEJ)** which often results in small insertions or deletions (indels) leading to gene modification. Another one is Homology-Directed Repair **(HDR)**, in which repair template is provided which is used by the cell to introduce precise modification (**Figure 1**) (Liu et al., 2019; Oh, 2024).

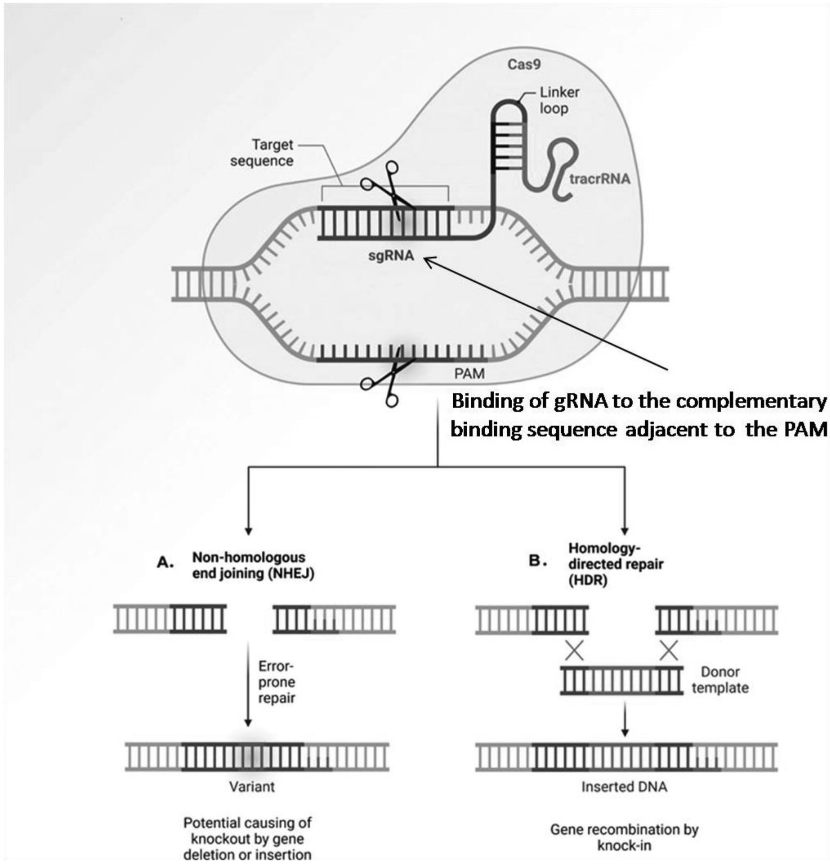

Figure 1: CRIPSR Cas mechanism showing gene editing via HDR and NHEJ (Image modified from Oh, 2024).

3. CRISPR Interference

CRISPR interference (CRISPRi) is a gene repression system derived from the CRISPR-Cas9 gene-editing mechanism. Unlike traditional CRISPR genome editing, which introduces permanent changes by cutting DNA, CRISPRi blocks the expression of the gene without altering the genomic sequence. It is achieved by using a modified, catalytically inactive form of Cas9 (**dCas9**) that binds to DNA but does not cleave it, thereby preventing transcription (Larson et al., 2013).

3.1 Components of CRISPRi

CRISPRi relies on two key components (Kampmann, 2018; Ghavami and Pandi, 2020);

a. **Catalytically dead Cas9 (dCas9):** dCas9 is the mutant form of Cas9 where two critical nuclease domains (RuvC and HNH) are inactivated. As a result of this mutation dCas9 retains the ability to bind to a specific DNA sequences but lacks the ability to cleave. It physically blocks RNA polymerase from transcribing the target gene.

b. **Guide RNA (sgRNA):** A short RNA sequence that directs dCas9 to a specific DNA sequence in the genome. The sgRNA consists of a 20-nucleotide sequence complementary to the target DNA. The presence of a **PAM** (Protospacer Adjacent Motif) sequence (e.g., NGG for Streptococcus pyogenes Cas9) is required for dCas9 binding.

3.2 Mechanism of CRISPRi (Kampmann, 2018; Ghavami and Pandi, 2020; Kashtwari et al., 2022)

a. **Design and introduction of sgRNA**: A custom-designed single-guide RNA (sgRNA), which is complementary to the target gene, is delivered into the cell.

b. **Target recognition by dCas9-sgRNA complex**: The dCas9 protein forms a complex with the sgRNA and searches the genome for a matching DNA sequence. This binding occurs only if a nearby PAM sequence (such as NGG for SpCas9) is present.

c. **Inhibition of transcription**: Once bound, dCas9 acts as a physical barrier to RNA polymerase, blocking the initiation or elongation of transcription. When fused with a transcriptional repressor domain like Krüppel-associated box (KRAB), the gene-silencing effect is further strengthened. Figure 2 given below shows the mechanism of CRISPRi involving dCAS9-sgRNA complex.

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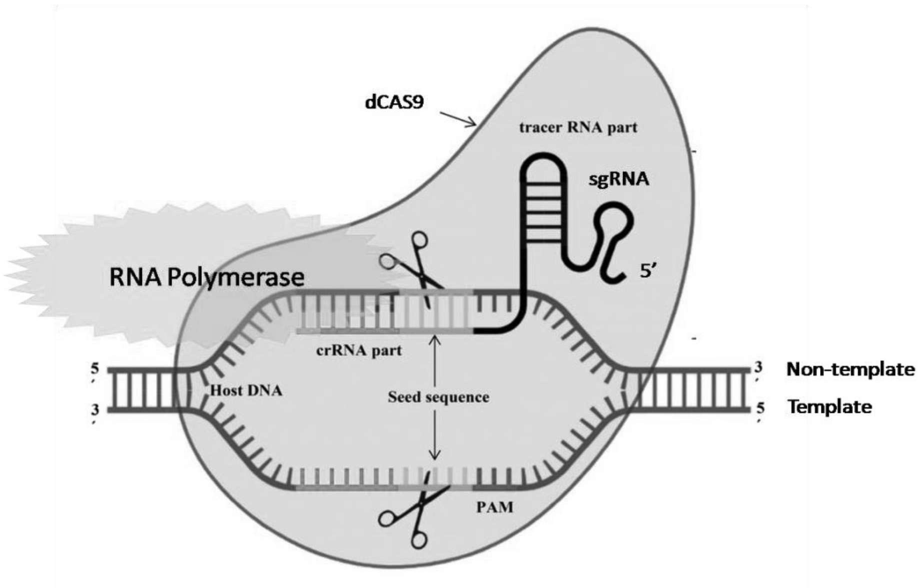

Figure 2: Schematic representation of CRISPR interference showing dCas9-sgRNA complex binding to the gene of interest and blocking RNA polymerase activity, leading to transcriptional repression (Image modified from Kashtwari et al., 2022).

4. Types of CRISPR/Cas Systems

CRISPR-Cas systems are categorized into two distinct classes based on differences in interference complexes (Markarova et al., 2020).

a. **Class 1 System**: Involve multi-subunit effector complexes with multiple Cas proteins (e.g., Cas3, Cas5–Cas8, Cas10, Cas11).

b. **Class 2 System:** Contain single-subunit effectors (e.g., Cas9, Cas12, and Cas13).

Both classes are further divided into three types each:

4.1 Class 1: Type I, Type III, Type IV

Type I CRISPR-Cas system is the most widespread and functions in a PAM-dependent manner for targeting and degrading the invading DNA. It utilizes a Cascade complex which composed of multiple Cas proteins, including Cas5, Cas7, Cas8, and Cas11, which first recognize the PAM sequence on target DNA (Markarova et al., 2015). This recognition promotes crRNA pairing which leads to the recruitment of Cas3, an endonuclease that initiates DNA degradation. Type III CRISPR-Cas systems employ similar Cascade complex but it differs in that it can target both DNA and RNA and its function is independent of PAM sequence. It is categorized into four subtypes (III-A to III-D), in which, Type III-A targeting mRNA, Type III-B targeting DNA, while the exact targets of Type III-C and III-D remain unclear (Markarova et al., 2015).

4.2 Class 2: Type II (Cas9), Type V (Cas12), Type VI (Cas13)

A member of class 2 CRISPR system (Type II, Type V and Type VI) relies on a single Cas protein instead of a multi-subunit complex. It has Cas9, crRNA, and tracrRNA that forms a RNP complex which targets the DNA in a PAM-dependent manner. The tracrRNA (trans-activating crRNA) and the crRNA binds together to form the tracrRNA-crRNA duplex. This interaction makes the RNaseIII active which processes the pre-crRNA into mature crRNA. The mature crRNA then guides Cas9 to the target DNA, where it induces cleavage. Type II systems are further include; II-A, II-B, and II-C, each with unique variations in their molecular mechanisms (Markarova et al., 2015 and 2020).

5. Role of CRISPR Cas in Controlling The Pollution

CRISPR technology is a very robust gene editing tool that has revolutionized various fields including ecological science. Its potential of accurately altering the DNA has been harnessed for managing toxic substances improving phytoremediation in plants, modifying bacteria for bioremediation and boosting human cells to become resist for pollutants. It has been made possible using the CRISPR technology to develop plants which can eliminate the heavy metals, microorganisms that can enhance the breakdown of industrial contaminants, and human cells that can withstand environmental toxins. Additionally, CRISPR has been employed for silencing the genes which are involved in toxin production by some microbes. These advanced properties make the CRISPR Cas as a hopeful tool for mitigating the environmental pollution and safeguarding the ecosystem from the harmful substances. The CRSIPR Cas system has extended much further and is no longer limited up to the medical or genetic works. A new application of this technology is emerging in the realm of environmental science for the regulation of pollution and the hazardous substances. Various microbes have been edited to assist in the cleanup of the oil leaks, decomposition of the plastic waste and neutralizing the heavy metals. CRISPR has been proven to be the ground breaking technology for enhancing the microbial strains for the purpose of ecological restoration. Many studies have shown its efficacy in altering the bacterial and fungal cells for metal detoxification, decomposing organic pollutants and forming synthetic microbial communities for addressing the future pollution challenges (Gavrilescu et al., 2015; Patil and Bhatt, 2022).

5.1 Enhancing heavy metal tolerance in crop plants: Stress created by the presence of the heavy metals directly affects the productivity of the plants (Jha and Bohra, 2016). Plants naturally activate some specific genes that help them to make tolerant against the harmful impact of heavy metal toxicity (Noor et al., 2022). The 5-oxoprolinase (OXP1) gene plays a critical role in γ-glutamyl cycle which is very important for glutathione metabolism. When this gene was mutated using the CRISPR technology in Arabidopsis thaliana, it enhances the cadmium metal tolerance in the plant probably by enhancing the antioxidant capacity or metabolic shift (Baeg et al., 2021).

5.2 Engineered biofuels: Agricultural and industrial sector produces a huge amount of waste which is a major cause of the environmental pollution (Koul et al., 2022). Using the CRISPR

Cas system, the HvCOMT1 (caffeic acid O-methyltransferase 1) gene was mutated in barley which reduces the lignin content by 14% in the mutant as the lignification of the cell wall lowers the bio-refinery efficiency. Beside this, it also enhances the fermentable glucose recovery rate by 34% (Lee et al., 2021).

5.3 CRIPSR Cas as a monitoring tool for toxicants: Presence of heavy metal contamination in the environment affects almost all living organism. These metals cause some severe disease such as Minamata, Plumbism, Itai itai, Black foot disease etc (Haidar et al., 2023). CRISPR-Cas technology, in addition to its uses in gene editing, is being increasingly investigated as a highly sensitive tool for monitoring environmental contaminants. Its programmable capability allows for the accurate detection of specific nucleic acid sequences or biomarkers associated with toxic exposure. This facilitates swift, cost-efficient, and field-ready biosensing of pollutants, including heavy metals, pesticides, and microbial toxins. Therefore, CRISPR-based systems offer considerable potential for real-time assessment of environmental health hazards. In *Bombyx* embryonic cell lines (BmE), the effect of some salts such as NaF and CdCl2 has been monitored using the CRISPR and identified genes that were resistant or sensitive to these pollutants respectively. Cadmium and fluoride induces the cell death by activating the MAPK signaling pathway, DNA damage and repair mechanism (Liu et al., 2021). **Table 1** below summarizes studies in which CRISPR has been used to engineer plants and bacteria to overcome environmental pollution.

Table 1. The table summarizes the studies in which CRISPR has been used for gene editing to control or detoxify environmental toxicants.

S.No	Application	Organism/model	Target Outcome
1.	Bioremediation of heavy metals	*Escherichia coli*	Engineered for enhancing mercury resistance and detoxification
2.	Degradation of aromatic hydrocarbons	*Pseudomonas putida*	CRISPR used to knock-in pathways for PAH degradation
3.	Micro plastic degradation	*Bacillus subtilis*	Upregulating plastic-degrading enzyme genes
4.	Enhanced degradation of textile dyes	*Shewanella oneidensis*	CRISPR modified genes regulating electron transfer for dye reduction
5.	Control of antibiotic resistance pollution	*Acinetobacter baumannii*	CRISPR used to delete resistance genes in polluted wastewater strains
6.	Toxin degradation from pesticide exposure	*Arabidopsis thaliana*	Gene edited for expressing detoxifying enzymes against organophosphates

5.4 Engineered *Acidithiobacillus ferridurans* for reducing the production of sulphuric acid released as byproduct during bio-mining: With the help of CRISPR Cas9 system, genes such as HdrA and TusA have been knockdown or repressed which were involved in sulphur oxidation. These modification reduced the production of sulphuric acid and heavy metals to make bio mining cleaner and more sustainable (Chen et al., 2023).

5.5 CRISPR based biosensors their advantages and limitations: CRISPR (Cas9, Cas12, Cas13, Cas14) systems allows rapid detection and identification of infectious disease, tumor DNA and cancer related viruses. Sensitivity of some CRISPR based biosensors have reached femtomolar to attomolar concentrations, outperforming conventional PCR or ELISA in sensitivity. Cas12 and Cas13, known for their collateral cleavage activity, are particularly utilized for generating amplified signals in biosensors (Li et al., 2023). CRISPR systems have been adapted to detect heavy metal-responsive genes, antibiotic resistance genes, and microbial contamination in water and soil. Coupled with isothermal amplification based technologies (IATs), including recombinase polymerase amplification (RPA), loop mediated isothermal amplification (LAMP), and rolling circle amplification (RCA), CRISPR biosensors can detect low concentrations of contaminants without the need for intricate laboratory facilities. Integration with portable devices (paper-based sensors, microfluidics, smartphone-readouts) makes them field-deployable (Li et al., 2023; Haider et al., 2023; Wu et al., 2021).

In case of health monitoring CRISPR-based diagnostics such as Specific High sensitivity Enzymatic Reporter unlocking (SHERLOCK), DNA Endonuclease Targeted CRISPR Trans Unlocking (DETECTR) and FnCas9 Editor Linked Uniform Detection Assay (FELUDA) have already proved effective for the detection of infectious diseases like COVID-19, HIV, HPV, SARS, Hepatitis, Dengue etc. In addition, CRISPR based sensors can identify biomarkers of oxidative stress, inflammatory responses, or mutagenic activity in biological samples. High sensitivity of these techniques can detect early exposure biomarkers before clinical symptoms appear which is crucial for preventive healthcare (Li et al., 2023; Kellner et al., 2019).

Despite significant opportunities and advantages, CRISPR-Cas systems encounter several challenges-many of these emerging concepts are still primarily at the prototype or proof-of-concept phase in environmental toxicology. The process of sample preparation, particularly the removal of inhibitors from soil, water, and biological fluids, still remains a bottleneck. Another concern is the stability of CRISPR reagents under field conditions. For complex toxic substances, such as heavy metals that lack a nucleic acid signature, indirect detection methods will be necessary, including the use of reporter genes, responsive microbes and aptamer-CRISPR hybrids.

6. Conclusion

Unlike traditional methods, CRISPR offers a ground breaking approach for controlling the pollution and toxicants. This technology offers precise and efficient genetic modifications across various organisms. Traditional methods generally suffer from limitations like incomplete detoxification, secondary pollution and long processing time. CRISPR has been successfully applied for enhancing phytoremediation in plants and engineering microbes for pollutants degradation. In future, coupling of CRISPR with AI and machine learning could enhance the discovery of novel genes involved in detoxification. Nevertheless, it is crucial to thoughtfully assess biosafety, unforeseen ecological impact, ethical concerns and public acceptance to ensure that CRISPR related remediations are safe and acceptable for the real world.

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Chapter-21

A Brief Introduction to Green Chemistry and Its Applications

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AUTHOR'S CONTRIBUTION

The present chapter was initially thought and prepared by VS. Both the author's co-ordinately designed the study. CB later contributed by suggesting and writing the applications of green chemistry. However, the chapter's conclusion, formatting and final drafting was done by VS.

ABSTRACT

The development of such chemical processes and products that minimize the utilization and fabrication of perilous and hazardous compounds are alluded to "green chemistry." There are several primary ways to accomplish the environmental protection objectives of green chemistry. Green catalysts are among some of them (such as biocatalyst, phase transfer catalyst) alternative green solvents (such as ILs i.e. ionic liquids, supercritical H_2O, supercritical CO_2, different reaction conditions (microwave activation) can also lead to novel photocatalytic phenomena. Also, avoiding the use of toxic substances is fundamental to green

chemistry's mission to safeguard the Earth's natural resources. One of the leading objectives of green chemistry is to diminish pollution and toxic waste. Modifications in consumption and production patterns are being pursued in an attempt to accomplish this. Moreover, it was discovered that developing various eco-friendly technologies is crucial for both human health and the environment to prevent further harm to well-being and the ecological system. This includes reducing the emission of harmful or toxic substances into the air, which can damage lung health. Furthermore, in order to produce safe chemical substances it is the best time to upgrade some chemical production techniques. Producing cleaner and economic products in industrial manufacturing is possible when natural enzymes are used instead of toxic chemicals. In 1998, Anastas and Warner published the twelve principles of green chemistry to diminish the unfriendly impact of pollution on human health and the biosphere.

Keywords: Green catalyst, green chemistry, sustainable chemistry, green solvent.

1. Introduction

Sustainable chemistry, called green chemistry, is a discipline of study inside the chemical sciences that focuses on designing such products and processes that diminish or eliminate the use and generation of perilous or toxic substance. The main goal of green chemistry is to reduce the negative impact of chemical processes on human health and the environment. Green chemistry efficiently uses the raw substance or renewables, eliminates waste and avoid the hazardous and precarious reagents and solvents in the production of chemical products. This discipline emerged as a response to the increasing awareness of the nature and health risks connected with traditional chemical techniques. There are 12 principles of green chemistry given by Paul Anastas and John Warner, which act as guidelines for prompting more sustainable chemical techniques. Reducing chemical use, avoiding waste, and maximizing energy efficiency are all tenets of this strategy. The aim is to promote the development of products and processes that are economical, eco-friendly, and socially responsible. The idea of "green chemistry" pertains to the practice of developing, producing, and using chemical substances in a way that minimizes or does away with the production of potentially harmful byproducts (Ivanković, 2017).

2. Origin of Green Chemistry

Green chemistry or sustainable chemistry, originated in the early 1990s as a response to growing concerns about environmental pollution and the need for safer chemical practices. The U.S. Environmental Protection Agency (EPA) was a big part of its growth, particularly through the launch of the Pollution Prevention Act of 1990, which emphasized reducing pollution at its source rather than managing waste after it is created. The concept of Green Chemistry was popularized by Dr. Paul Anastas and Dr. John Warner, who co-authored the book Green Chemistry: Theory and Practice in 1998. Twelve Principles of Green chemistry were presented by them, which provide a framework for designing products and processes that minimize environmental impact, improve safety and enhance efficiency (Anastas et al., 1998).

3. Principles of Green Chemistry

a) **Prevention:** The initial rule of environmentally friendly chemistry, or sustainable chemistry, emphasizes on the importance of waste prevention, prioritizing the avoidance of waste generation over the treatment or cleanup of waste, which presents a more advantageous scenario for both humanity and the ecosystem. It follows the principle "prevention is better than cure."

b) **Atom economy or atom efficiency:** The principle of Atom Economy or Atom efficiency is connected to the previous principle of green chemistry i.e. waste prevention, since it requires maximum utilization or inclusion of all raw substance in the end product to reduce the amount of waste (Trost, 1991; Sheldon, 2007). Chemical synthesis, then, needs to be structured in a way that makes the most efficient use of the raw materials needed to make it, or at least that makes full use of all the ingredients required to make it. In 1990, Trost introduced the concept of % atom economy and quantified by Sheldon as given below;

% Atom economy is defined as-

c) **Use of less perilous and toxic chemicals**: When possible, we should develop synthetic methods to use and produce materials that are either minimally hazardous or non-toxic to human health and the environment.

d) **Designing safer chemicals**: The approach of Designing Safer Chemicals emphasizes the fabrication of chemical products that minimize toxicity while preserving their efficacy. The key aim of this principle is manufacturing safest chemicals that are non-carcinogenic, non-mutagenic, non-neurotoxic and at the same time achieve equilibrium between maximum performance and chemical product function, minimizing toxicity and risk to the utmost extent. The use of toxic and harmful chemicals should be eliminated and replaced with eco-friendly ones as much as possible however, their effectiveness should be considered.

$$\text{Risk} = (\text{function})\ \text{hazard} \times \text{exposure}$$

e) **Safer solvents and auxiliaries:** The use of auxiliary chemicals, including solvents and separation agents, should be minimized as much as possible, and when required, only safe alternatives should be employed. Many conventional organic solvents, such as CCl_4, $CHCl_3$, and benzene, are toxic, flammable, volatile, and corrosive. Due to their volatility and solubility, these solvents contribute significantly to environmental pollution. Water, supercritical fluids (SCFs), polyethylene glycol, and, more recently, ionic liquids are considered examples of green solvents. The criteria for green solvents include low vapour pressure, high boiling point, non-toxicity, non-volatility, non-flammability, good dissolving ability, and recyclability. In addition to using eco-friendly solvents, chemical processes should also allow for easy separation and purification of products (Tomar and Jain, 2023).

f) **Design for energy efficiency:** The energy demands of chemical processes must be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure. Energy requirement for a chemical process can be reduced by considering following measures, using fewer numbers of reaction steps, using mordant temperature and pressure, employing catalysts and bio-catalysts and using microwave and sonification as energy source.

g) **Renewable raw materials or feedstocks:** According to this principle a raw substance or feed stocks should be renewable rather than depleting as far as technically and economically possible. The regular use of non-renewable feedstocks such as fossil fuels can deplete the conventional resource. Biological product can be used as renewable starting materials such as CO_2 and methane gas. Example of some chemicals derived from natural resources are adipic acid from corn starch, biodiesel from rapeseed oil, biofuel from algae, biopolymer such as PHV (polyhydroxyalkanoate), PHB (poly-B-hydroxybutyrate) by using microorganism, levulinic acid from biomass (Pfaltzgraff and Clark, 2014).

h) **Reduce derivatives:** Unnecessary derivatization such as blocking group, protection or deprotection temporary modification of chemical or physical processes should be avoided. The best way to avoid unnecessary derivatization is by using enzymes such as Penicillin acylase (Penacylase) in the synthesis of semi-synthetic penicillin. This synthesis occurs at room temperature (Arroyo et al., 2003).

i) **Use of catalytic reagents:** The use of selective catalytic reagents is better than stoichiometric reagents. Due to unreacted starting material in stoichiometric reaction a lot of waste byproducts are generated which cannot be reused. A catalyst is defined as material which usually increases the rate of reaction without itself being change in the process. A catalyst reduces the activation energy of the process. Such catalytic reactions have high atom efficiency and generate less waste.

j) **Design product for degradation:** This principle states that chemical products such as plastics, pesticides etc. should be designed in such a way that at the end of their function they don't persist in environment and break down into useful products. Detergents were used to be based on sodium salt of alkyl benzene sulphonic acid and the alkyl groups are branched. These were not degraded naturally, causing foaming in water. Now branched alkyl groups are replaced with linear alkyl groups which can be easily biodegraded.

k) **Real-Time analysis for pollution prevention:** Analytical methodologies need to be developed or modified to allow real time processing, monitoring and control prior to the formation of hazardous materials. In order to monitor the chemical process, it needs to have effective analytical techniques that are helpful in monitoring the hazardous substances. Non-biodegradable products remain in the environment for a longer time. These chemicals when taken up by plant and animals bioaccumulate in their bodies and become very harmful.

l) **Inherently safer chemistry for accident prevention:** Selected substance for the chemical process should not be hazardous such as explosive or inflammable.

4. Goals of Green Chemistry

The main objectives or purposes of Green chemistry are;

a) **Protection of environment:** Designing new chemical processes which are non-toxic to human and environment. Developing such products which are biodegradable, non-bioaccumulative in nature and non- hazardous to ecosystem.

b) **Minimization of byproducts:** Green chemistry focuses on maximum percentage atom economy and don't release byproducts or waste.

c) **Production of non-toxic product:** Designing such chemical processes which can minimize formation of toxic products.

d) **Removal of volatile organic solvents:** Replace the organic solvents by green solvent such as water, supercritical CO_2, ionic liquids, fluorous solvents, and solvent free reaction.

e) **Use of renewable substance:** For the synthesis of a product green chemistry use renewable materials in place of non-renewable ones.

f) **Utilization of minimum energy:** Green chemistry uses catalysts or biocatalysts to minimize activation energy so that consumption of energy can be minimized and chemical reaction takes place at ambient temperature and pressure.

g) **Eco-friendly and biodegradable products:** Starting substance and product should not be inflammable or explosive and the product should be biodegradable at the end of their function.

5. Applications of Green Chemistry in Life

a) **Waste water treatment:** Photocatalytic materials are generally semiconductors which are used in water purification through degradation of organic pollutants. Many semiconductors like TiO_2, ZnO and ZnS acts as photocatalysts (Goutam et al., 2017). Heavy metals are non-biodegradable, toxic, and carcinogenic. For the removal of heavy metal from water bodies adsorption technology is commonly used. Adsorption method uses various low-cost adsorbent materials such as bio-adsorbent, clays, zeolites (mordenite, clinoptilolite) etc. Bio-adsorbents are obtained from agricultural waste and have capability of complex formation with heavy metals (Cd, Zn, Pb) (Mo et al., 2018).

b) **Biodegradable polymer:** The petroleum-based polymers and plastic can cause environmental pollution because of its toxic and non-biodegradable nature. Biopolymers have been considered as alternative to petroleum-based polymers. After its function, biodegradable polymer breaks down into natural gas, water and biomass by bacterial decomposition process. Biopolymer is an environmentally benign polymer. Polylactic acid (PLA) is a widely used biopolymer which is obtaining from corn, sugar beet, milk (Taib et al., 2022).

c) **Designing of eco-friendly marine antifoulant:** Fouling results due to growth of marine organism on the hull of ships and boats. This results in the reduction of speed and increased consumption of energy. For this reason, antifoulant agents are needed to prevent the growth of organism (like plants, algae, diatoms) on the hull of ships and boats. Antifoulant agents are mixed with the paint used as protecting layer on hull of ships and boats. Most frequently used antifoulant agents is tributyl tin oxide (TBTO). But due to its toxic nature, persistence for long time, and bio-accumulation in food chains, TBTO is a threat to marine ecosystems. The SEA-NINE (DCOI) is an isothiazolene which is environmentally benign antifoulant and can be used as an alternative to TBTO (Willingham and Jacobson, 1996).

d) **Dry cleaning:** Many volatile organic solvents like PERC, CFCs are used in industries for different purposes such as cleaning in microelectronics, and dry cleaning of cloths. The VOCs cause pollution in ecosystem. PERC cause ground water pollution and act as carcinogen to human health. To avoid risks micelle technology is used in the cleaning industry. In this technology, super-critical carbon dioxide is used as solvent with co-polymer surfactant (fluorocarbon based) in place of PERC. Moreover, hydrogen peroxide is also being used now a day for bleaching of clothes. H_2O_2 provides better results and require less quantity of water (Tiwari et al., 2022).

e) **Pulp bleaching in paper industry:** At present day chlorine is replaced by hydrogen peroxide (H_2O_2). Conventionally bleaching was done with chlorine. Nowadays, H_2O_2 can be used for bleaching paper in the presence of catalyst. Green chemistry is applied for bleaching paper. Earlier chlorine gas was used but now hydrogen peroxide is used which give better results and no environmental hazards.

f) **In agriculture:** The use of pesticides in agriculture is harmful not only to the environment but also to those organisms that are beneficial to us, like microorganisms, insects, etc. To overcome this problem, there are several alternatives to chemical pesticides, such as harpin technology. Harpin technology is based on harpin proteins, which are non-toxic, naturally occurring proteins. The source of harpin protein is genetically engineered *Escherichia coli*. These proteins enhance the quality and quantity of crops and activate the crops' natural defence systems and make them more resistant to diseases (Akbudak et al., 2006).

6. Disadvantages (Iravani, et al., 2017)

Eco-friendly living is a positive idea, but there are some possible limitations of green processes and technology such as:

- High carrying out costs, complex and lack of knowledge.
- Alternative chemical raw material is unknown.
- Alternative process technology is unknown.
- Most ionic liquids are water-feasible and can easily reach the ecosphere through that pathway.
- Uncertainty about performance.

7. Conclusion

The key dream of each industry is to gain profit from available raw component and basic capital within sustainable manufacturing activities. Sustainable industrial operation must meet immediate necessities without jeopardizing the needs of the next generations, which means chemical processes must employ raw materials, water, and energy in such a way that does not affect the environment and is economically feasible. A sustainable balance between natural resource utilization, economic development, and environmental protection can be achieved through green chemistry, which focuses on developing chemical processes and products that minimize toxicity to humans and the ecosystem. Implementing the principles of green chemistry which promote chemical safety, requires strong legal backing through regulations, that govern essential procedures and activities necessary for its effective adoption. The rule of green chemistry is based on twelve principles that focus on reducing or eliminating hazardous or toxic substances from the synthesis, production and application of chemical products and thus the use of substances that are hazardous or toxic to human health and the environment is diminished or eliminated.

At the time of designing a green chemistry process, it is not possible to follow all 12 principles of the process at the same time, but in some synthesis stages, it aims to apply as many principles as practical. There are several main ways that green chemistry achieves its objectives of protecting the environment while generating wealth. Several of them: biocatalysis, catalysis, use of different renewable raw materials (biomass) or feedstocks, differentreaction solvents (H_2O, ILs, SCFs, CO_2), different reaction conditions (microwave activation) as well as new photocatalytic reactions. Catalysis is the key part of green chemistry, with advanced catalytic reactions and types of advanced catalysts offering several opportunities with regard to process utilization, selectivity, energy consumption reduction, and the use of different reaction solvents. The massive potential of microorganisms and enzymes in the transformation of synthetic substances with selectivity gives biocatalysts a leading position in the "green" program. Photocatalytic reactions that represent the latest methods of disinfecting contaminated air and water also contribute to green chemistry, creating conditions for advancing the mission of green chemistry.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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Chapter-22

Conservation and Biodiversity Protection: A Multifaceted Approach

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AUTHOR'S CONTRIBUTIONS

This work was conveyed with the joint efforts of both the authors. VK guided the study, edited the rough draft of manuscript and helped in searching of relevant portion of literature. Author PV first wrote preliminary manuscript and compiled the reference list. Finally, both authors reviewed and submitted the final chapter.

ABSTRACT

The biodiversity of life on Earth is a subject of significant concern, as human activities are posing a considerable threat to it. This abstract explores three significant methodologies for its protection, namely sustainable agriculture, habitat-restoration and pollution control. The cultivation of crops must be executed in a manner that ensures the judicious utilization of resources, and rehabilitation of areas that have been degraded to a state that is conductive to the resurgence of life without causing harm to the environment. This approach is designated as sustainable agriculture. The concept encompasses agro-ecology, organic farming and permaculture practices, all of which have been demonstrated to assist in the mitigation of the adverse environmental impacts of conventional agricultural practices. The process of restoring degraded ecosystems, termed "habitat restoration," involves a variety of measures. These include replanting of forests, enhancement of wetland biodiversity, and creation of corridors that facilitate the movement of wildlife between distinct habitats. It is imperative to acknowledge the significance of pollution control as a pivotal strategy for safeguarding flora and fauna, as well as human life. The management of diverse forms of pollution, including water, soil and air contamination, assumes paramount importance. The objectives are to minimize the use of plastic, ensure proper disposal of waste and impede the capacity of factories to pollute the air. It is evident that each of these strategies has its own merits; however, the optional approach to address the complex challenges posed by biodiversity loss is the integration of these strategies. The combination of these elements has the potential to engender a favorable future in which both human beings and the natural world can flourish.

Keywords: Biodiversity, sustainable agriculture, habitat restoration, pollution control.

1. Introduction

The ecological complex formed by living organisms like animals, plants and microorganisms with its surrounding environment and the ecological processes including ecosystem diversity, species diversity and genetic diversity is referred to as biodiversity (Adom et al., 2019). It is the common wealth of all mankind. For the goal of conservation and sustainable use of biodiversity, the Convention on Biological Diversity (CBD) has been signed by about 150 countries in June, 1992. 15th conference of the parties of CBD held in Kunming, Yunnan Province in 2020. It was aimed to determine the new global biodiversity conservation targets for the next decade (Baillie and Zhang, 2018). Biodiversity (Biological diversity) was defined at the first Earth Summit in Rio de Janeiro as the variety among living organisms including terrestrial, marine and aquatic ecosystems and the ecological complexes which includes diversity within species, between species and ecosystem (Hambler, 2004).

The two fundamental concepts, i.e. Conservation and Biodiversity protection are deeply entangled and necessary for the well-being of our planet. Biodiversity encompasses the variety of life on earth from the genetic variation to the vast array of ecosystems such as forests, oceans and wetlands. It is the foundation of the complicated web of life that sustains and provides essential resources like clean air, fresh water, food and medicine. However, these invaluable natural resources are facing unprecedented threats due to various human activities like habitat destruction, climate change, pollution and overexploitation of resources (Jepson, 2013). Therefore, conservation is the method of protection and management of biodiversity as well as natural resources for the benefit of both current and future generations. Thus, a combination of scientific research, policy making and community engagement is a multifaceted discipline to address the root causes of biodiversity loss. The negative impact of human activities, restoration of degraded ecosystems and to ensure the long-term survival of countless species can be curtailed by implementing conservation strategies. Sustainable agricultural practices are aimed to minimize environmental impact to ensure food security. Their focus is on preserving soil health, reducing the use of pesticides and fertilizers and to integrate the biodiversity with farming systems.

2. Factors leading to Biodiversity loss

The planets biodiversity is greatly affected by human beings in different ways either intentional or unintentional. The main threat to biodiversity is anthropogenic, because humans have intervened to reshape the natural habitats in order to harvest natural resources or to make way for farmland. Loss of biodiversity appears to have an impact on ecosystems. The web of life is like an image which encloses the intricate interconnections between living organisms and their environments. This delicate tapestry is highly susceptible to the impacts of pollution. Environmental pollution created due to human activities has become a cause of major global concern as the anthropogenic activities affect the biodiversity. Air, water and soil pollution can harm various species by degrading their habitats, physically harming them, or making them susceptible to diseases. When pollutants like pesticides and heavy metals pass through the food chains, contaminate many levels of the ecosystem. One of the most important universal challenge, both developed and developing countries are facing is environmental pollution. Understanding the different aspects of in which pollution affects biodiversity is crucial for planning effective conservation strategies and sustainable environmental ethics is the need of today (Verma, 2017).

Increased economic movements, continuous population growth and climate change all responsible for spoilage of natural resources are threatening the biodiversity as well as ecosystem. Even a small change in pattern of climate has severe impact on the biodiversity, altering the habitats of the species and poses a threat for their survival making them vulnerable to extinction (Prakash, 2021). The various factors are responsible for the loss of biodiversity such as pollution, habitat loss, hunting, introduction of invasive species, overexploitation of preferred species, climate change and natural disasters (Verma, 2021). Eutrophication causes the depletion in the oxygen level which is deleterious for biodiversity. Alike fertilizers, pesticides may also accumulate in water bodies (ponds and lakes) and living beings (Bhateria and Jain, 2016). Micro plastics in the environment also impact the survival rate of larvae, diminished food consumption and gradually weight loss in aquatic animals (Wright et al., 2013). The agricultural pollutants such as nitrogen from fertilizers alter the pH and the nutrient level of the soil. The enhanced presence of nutrients in the soil causes the vigorous growth of grass species, leading to stifle in the growth of wild flowers, essential for bees and other pollinating insects (Savci, 2012). This greatly impacts the biodiversity.

The habitat destruction is the huge destruction of the natural habitat of the species due to which it becomes incapable of upholding the natural ecosystems and the species. It ultimately results in species extinction, i.e. biodiversity loss. Preparing the fields for agricultural use by cutting of forests, filling the wetlands and moving fields for creating residential and commercial sites, harvest of the fossil fuels etc. are all responsible for habitat destruction (Martins et al., 2018). Hunting is the root cause of extinction of large number of animals holding positions in the food web. Due to this, various species in the region are adversely affected as they face food scarcity or complete food availability compared with the normal situation (Symes et al., 2018). Besides all these, overexploitation, climate change, invasive species and natural disasters are other causes for biodiversity decline.

3. Impact of Biodiversity loss

The loss of biodiversity has been demonstrated to have a detrimental effect on the health, stability and function of ecosystems. This has the effect of reducing the capacity of ecosystems to address contemporary issues such as climate change, disease and invasive species. It is evident that a multitude of industries, including but not limited to agriculture, forestry, fisheries and pharmaceuticals, are inherently dependent on biodiversity. The collapse of fish stocks due to overfishing, habitat degradation, declining productivity, deforestation and the loss of new medicines as well as increasing pollution levels from extinct species, all represent potential economic losses. It is evident that the ongoing loss of biodiversity poses a significant threat to human well-being and the planet's capacity to support life in the long term (Van Ruijven and Berendse, 2010).

4. Need to Protect Biodiversity

It is imperative to safeguard biodiversity to ensure environmental health and assist in safeguarding the planet from diseases and climate change. This necessitates the preservation of diverse flora and fauna, which are integral to maintaining a healthy environment. To achieve these objectives, it is essential to provide essential services that facilitate the realization of these goals (Alcamo, 2003). Biodiversity is of paramount importance for both the natural environment and human welfare. It plays a crucial role in the purification of water, the elimination of pollution, and the revitalization of soil fertility (Randolph, 2004). The significance of genes is evident in their role in facilitating the development of novel materials, pharmaceuticals and enhanced crop varieties. This is achieved by providing a vast array of distinctive compounds and genetic characteristics. The loss of biodiversity is a matter of grave concern, as it has the potential to engender a plethora of significant problems that could jeopardize the continued existence of the planet (Gagné et al., 2020; Rawat and Agrawal, 2015).

5. Methods to Protect Biodiversity loss

i. **Sustainable agriculture:** It is defined as a type of farming that is environmentally sustainable, economically viable and socially responsible (Harwood, 1990). The primary objective of sustainable agriculture is to ensure the present generations' access to sufficient food and fibres, while safeguarding the future of subsequent generations. The concept of sustainability is predicted on the twin imperatives of environmental stewardship and economic prosperity. This notion entails the preservation of the natural world (comprising flora, fauna, soil, air and water) in a manner that is mutually beneficial to humanity, commercial enterprises and the environment (Poincelot et al., 2024). In the absence of external inputs, sustainable agriculture practices have been shown to promote local soil fertility, emphasize the use of renewable resources and encourage a balanced cycle and energy use on farm (National Research Council, 2010). It is instrumental in the maintenance and enhancement of environment al quality through the minimization of non-renewable resource usage. This approach is pivotal in the promotion and presentation of biodiversity (Altieri, 2018). The present and future role of emerging technologies such as artificial intelligence, drones, precision farming and biotechnology is to enhance efficiency and productivity. It is evident that the aforementioned parties will be tasked with the resolution of issues pertaining to food security of the environments (Lal, 2004).

ii. **Habitat restoration:** Habitat restoration is an area of conservation science that focuses on the rehabilitation of ecosystems that have been degraded by natural causes or human activities. The primary objective of habitat restoration is to facilitate the recovery of ecosystems to a more natural and stable state. This process is expected to enhance biodiversity, particularly by supporting the recovery of threatened species (Cao et al., 2009). Additionally, it is anticipated to improve water and air quality, thereby contributing to the mitigation of climate change through carbon sequestration (Dobson et al., 1997; Wu et al., 2019). Wetlands are among the most productive ecosystems on the planet, yet they are currently under threat. The Ramsar convention on wetlands, established in 1971, constitutes a significant international instrument for the prudent protection and utilization of wetlands. The fundamental objective of the convention is restoration of habitats. It is evident that concerted efforts are being made to rectify areas that have been damaged (Bridgewater and Kim, 2021).

iii. **Pollution control:** There is growing awareness among the general public on the importance of health and environmental issues. Recent research has demonstrated a clear correlation between exposure to air pollution and the development of health complications, including chronic respiratory diseases, cardio-vascular diseases and an elevated risk of certain types of cancer and developmental disorders (Manisalidis et al., 2020). The present moment is a particularly exciting one in terms of the global efforts to combat this issue. The issue of air pollution is addressed through the combination of conventional and contemporary approaches. In traditional form, electrostatic precipitations and catalytic converters are utilized, while bio-filters are employed in a manner consistent with modern practices (Asif et al., 2022). The utilization of Compressed Natural Gas (CNG) and electric vehicles, in conjunction with the implementation of recent policies such as India's Battery Waste Management Rules, 2022, and the prohibition of single use plastic, signifies a concrete endeavor to address environmental remediation, there is a growing emphasis on the utilization of bioremediation and phyto-remediation techniques for the treatment of contaminated soil and water. These techniques involve the application of microorganisms or plants to facilitate the restoration of the affected environment (Saha et al., 2022; Lai et al., 2022). In addition, it plays a pivotal role in mitigating the impact of climate change by regulating the emission of greenhouse gases. Recent advancements in pollution control, encompassing both everyday consumer choices and industrial processes suggest the potential for a more sustainable and healthier future for all (Awewomom et al., 2024).

6. Conclusion

In order to ensure the planet's health and human well-being, sustainable agriculture, habitat restoration, and pollution control are considered to be pivotal in the context of biodiversity conservation. It is imperative to acknowledge and address the pressing multifaceted issues that are crucial for the preservation of biodiversity and conservation of our planet's diverse and invaluable natural heritage. Sustainable agriculture should be adapted to ensure the availability of adequate amounts of food to everone without causing harm to the environment, water sources, and wildlife. In order to facilitate the connection of various components of landscape, it is imperative to undertake measures aimed at restoration of the habitat. This approach will contribute to the establishment of secure refuges for species that are facing threats, thereby assisting in the recovery of their populations. It is needed to implement effective measures for the control of pollution, with a view to mitigating the deleterious effects of contaminants on land and maintaining the integrity of ecosystems. It should be mandatory that all parties concerned commit to the implementation of these strategies, if the objectives are to demonstrate human progress and environmental stewardship can be harmonized for the future of our planet.

COMPETING INTERESTS

Authors declare that they have no competing interests.

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