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# Advances and Challenges in Hazardous Waste Management

*Edited by Hosam M. Saleh,  
Amal I. Hassan and Refaat F. Aglan*





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# Preface

Hazardous waste management has become an increasingly pressing issue in recent decades, as industrialization and economic development worldwide have led to growing volumes of dangerous byproducts and emissions. This book provides a timely overview of the current challenges, developments, and opportunities within hazardous waste management, focusing on reducing ecological damage and promoting more sustainable practices.

The chapters in this volume examine hazardous waste from various perspectives, covering crucial topics such as industrial air pollution, biological waste, fertilizer production from steel slag, e-waste recycling, and winery waste valorization. Readers will gain critical insights into the scale of the hazardous waste problem in key regions like Africa and Pakistan, as well as innovative waste management solutions being implemented globally. Expert analysis weighs the progress made toward critical sustainable development goals while also outlining the policy, technology, and research advancements that are still required.

With its blend of big-picture analysis and targeted case studies, this book is a valuable resource for policymakers, researchers, industry leaders, and anyone interested in the multifaceted issue of hazardous waste management. The contributions from diverse international experts provide a comprehensive framework for understanding current best practices, implementation challenges, and promising directions for future dangerous waste management.

The editors wish to thank all the chapter authors for their valuable contributions as well as the staff at IntechOpen, especially Publishing Process Manager Ms. Zrinka Tomicic for her continuous assistance in finalizing this work.

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Section 1

# Hazardous Waste Management

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# Introductory Chapter: Foundations and Challenges in Hazardous Waste Management

*Hosam M. Saleh, Amal I. Hassan and Refaat F. Aglan*

## 1. Introduction

Hazardous waste can arise from diverse origins, including industrial manufacturing procedures, laboratories, hospitals, and even residences (e.g., specific cleansers, pesticides, or electronics) (**Table 1**). Proper management of these wastes necessitates specific procedures for managing, treating, and disposing of them in order to minimize their detrimental impact on human health and the environment [1]. The specific delineation and oversight of perilous waste can differ among nations and regions, conforming to both domestic legislation and global accords. Ingesting or absorbing the excrement can be detrimental or lethal. The potential long-term health hazards of this substance include chronic toxicity, carcinogenicity, teratogenicity (producing developmental abnormalities), or other systemic consequences [2].

Hazardous waste items frequently include noxious compounds that, when released into the environment, can present substantial health hazards to humans [3]. Exposure to these compounds can result in a range of detrimental health consequences, such as cancer, reproductive abnormalities, respiratory diseases, and neurological impairments [3]. Hence, it is imperative to implement effective management strategies to avert or alleviate these health risks.

The efficient handling of hazardous waste is crucial for environmental preservation. Inadequate management of such trash can lead to significant ecological harm. Toxic waste has the potential to pollute ecosystems, cause harm to wildlife, and disturb natural habitats. Therefore, it is crucial to adopt waste management solutions that reduce the ecological consequences of hazardous waste, thereby safeguarding the fragile equilibrium of ecosystems [4].

Moreover, ensuring the prevention of soil and water contamination is an essential component of effectively managing hazardous waste. Hazardous waste possesses the capability to infiltrate the ground and pollute soil and groundwater reserves [5]. Remediating polluted soil and water can be prohibitively expensive and arduous. Therefore, it is crucial to ensure the appropriate confinement, management, and elimination of dangerous waste in order to avert such forms of pollution and their resultant ecological and financial repercussions [6].

Air quality maintenance is intricately connected to the management of hazardous waste. If certain categories of dangerous waste are not properly managed, they can release noxious fumes and fine particles into the atmosphere [7]. Implementing efficient waste management strategies aids in minimizing the emission of these

<b>Origin</b>	<b>Examples of hazardous waste</b>
Industrial	<ul style="list-style-type: none"> <li>• Chemical solvents and byproducts</li> <li>• Heavy metals (e.g., lead, mercury)</li> <li>• Toxic chemicals and compounds</li> <li>• Radioactive materials</li> </ul>
Laboratories	<ul style="list-style-type: none"> <li>• Laboratory chemicals</li> <li>• Contaminated glassware and equipment</li> <li>• Biohazardous materials (e.g., pathogens)</li> <li>• Old or expired chemicals and reagents</li> </ul>
Hospitals	<ul style="list-style-type: none"> <li>• Pharmaceuticals and expired medications</li> <li>• Infectious waste (e.g., used needles, cultures)</li> <li>• Chemical disinfectants</li> <li>• Radioactive medical waste</li> </ul>
Residences	<ul style="list-style-type: none"> <li>• Household cleaning products (e.g., bleach)</li> <li>• Pesticides and herbicides</li> <li>• Electronic waste (e-waste)</li> <li>• Batteries and fluorescent light bulbs</li> </ul>

**Table 1.**  
*Understanding hazardous wastes: Origins and examples.*

contaminants into the air, thereby enhancing air quality and mitigating potential health hazards [8].

Moreover, the management of hazardous waste is crucial for ensuring adherence to legal regulations and minimizing responsibility. Numerous nations have strict legislation and regulations that control the management, transportation, processing, and elimination of dangerous waste. Adhering to these requirements is not only a legal obligation but also essential for mitigating the possibility of litigation, fines, and the possible harm to an organization’s reputation and financial stability [9].

## **2. Waste management technologies and regulatory framework**

Hazardous waste management also brings about substantial economic advantages. Effective management procedures can result in the retrieval of valuable materials through recycling and reuse, hence diminishing the overall expense of trash disposal [10]. In addition, efficient administration prevents the significant costs related to medical interventions for persons impacted by exposure to dangerous waste and the expensive remediation of polluted locations.

Furthermore, the management of hazardous waste entails a global obligation, in addition to these pragmatic factors. The transboundary movement of hazardous waste is a worldwide environmental issue. Adopting responsible practices for processing and disposing of waste is crucial in order to avoid the spread of contamination across borders and safeguard the ecosystem worldwide [11].

The successful handling of dangerous waste ultimately corresponds to the ideas of sustainable development. Sustainable development guarantees the satisfaction of present requirements while safeguarding the capacity of future generations to fulfill their

own demands, thereby fostering a balanced cohabitation of human endeavors and environmental conservation [12]. To summarize, effectively handling hazardous waste is of utmost significance, as it involves crucial aspects of public health, environmental welfare, adherence to laws, economic advantages, and worldwide accountability. Global agreements, such as the Basel Convention, have a critical function in regulating and managing the cross-border transportation and disposal of dangerous waste [13]. They provide a vital foundation for international collaboration and environmental safeguarding. The Basel Convention, ratified in 1989 and operational since 1992, serves as a fundamental pillar in the worldwide regulation of dangerous waste. The main goals of this initiative are many, including reducing the production of dangerous trash, controlling the transit of waste across borders, and encouraging the adoption of environmentally responsible waste management methods [14]. The primary objective of the Basel Convention is to promote the reduction of hazardous waste generation directly at its origin. It achieves this by promoting the use of more environmentally friendly production practices and tactics to reduce waste [15]. The Convention aims to address the problem at its source in order to reduce the amount of hazardous waste that needs to be managed and disposed of, thereby minimizing the hazards to human health and the environment. The Basel Convention establishes a comprehensive framework to govern the responsible handling of hazardous waste across borders in order to control transboundary migrations [16]. This is especially important in preventing the transfer of dangerous trash from highly developed countries to less developed countries, a practice that can have harmful effects on the environment and public health of the latter. The provisions of the Convention are designed to protect the interests of nations that receive aid and encourage fair global accountability.

Another crucial element of the Basel Convention is the advocacy for the implementation of ecologically sustainable management practices in every member nation. This encompasses the creation of strong and reliable systems for the management, containment, and elimination of dangerous waste [17]. The Convention promotes the adoption of optimal methods and the utilization of cutting-edge technologies to decrease the environmental hazards linked to the management of dangerous waste [17]. The Basel Convention includes a Prior Informed Consent Process, which is crucial in guaranteeing that countries receiving dangerous waste are adequately informed about its characteristics and potential hazards. This approach enables recipient countries to make well-informed decisions and gives them the chance to either accept or reject imports of hazardous waste. By engaging in this action, the Convention maintains and supports values of openness and responsibility in the global exchange of waste materials.

Moreover, the Convention deals with issues related to accountability and compensation that arise from occurrences involving hazardous waste. It highlights the significance of implementing systems for financial accountability among those who produce garbage, which acts as a disincentive against reckless waste disposal methods [18].

The Basel Convention aids developing nations in achieving these goals by facilitating technical assistance and capacity-building activities. The Convention facilitates the improvement of less developed nations' skills, promoting fair and efficient management of hazardous waste worldwide [19].

In addition to the Basel Convention, several other international agreements and initiatives play a role in governing and overseeing hazardous waste. These include the Rotterdam Convention, the Stockholm Convention, the Minamata Convention, and various multilateral environmental agreements that intersect with the management of hazardous waste [20, 21].

The principles dictating hazardous waste management encompass a complete structure that directs the responsible management, processing, and elimination of hazardous waste. These concepts are crucial for reducing the environmental and health hazards linked to hazardous waste [22].

The notion of waste reduction is a fundamental aspect of competent hazardous waste management. To effectively manage hazardous waste, it is best to reduce its production at the point of origin. This notion is in line with the concept of “source reduction,” which prioritizes minimizing waste generation [23]. By advocating for cleaner manufacturing techniques, making adjustments to processes, and implementing waste reduction initiatives, industries and organizations can substantially reduce the amount of hazardous waste they produce. This reduction not only decreases the expenses associated with disposal but also mitigates the possible hazards to human health and the environment [23]. Another core idea involves the reuse of materials obtained from hazardous waste. This principle promotes the practice of recycling and reusing hazardous materials whenever feasible. The act of recycling hazardous waste not only helps to save resources but also diminishes the need for new materials, which can have a detrimental impact on the environment due to the energy-intensive extraction and processing processes involved. Recycling initiatives involve extracting useful components from waste streams, which helps to achieve both environmental sustainability and economic efficiency [24].

Implementing suitable treatment methods is a crucial aspect of the management of dangerous waste. The harmful waste frequently necessitates specialist treatment to reduce its harmful nature or to immobilize pollutants. The treatment methods employed for different waste streams may encompass physical, chemical, or biological processes. Treatment procedures such as burning, chemical stabilization, and bioremediation are employed to handle various categories of hazardous waste. The choice of the best appropriate treatment approach is contingent upon the specific attributes of the waste, environmental factors, and regulatory obligations.

Appropriate means of disposal are a fundamental principle in the management of hazardous waste. When hazardous waste is unable to be reduced, recycled, or treated to eliminate its harmful qualities, it is necessary to safely dispose of it [25]. Disposal procedures must comply with rigorous environmental regulations to avoid soil, water, and air contamination. Typical means of trash disposal include the use of secure landfills that are specifically built to store hazardous waste, deep-well injection for particular types of waste, and some forms of land application. The most suitable form of disposal is contingent upon the specific attributes of the trash and the regulations set forth by the local governing body.

The concepts of hazardous waste management include a comprehensive approach aimed at minimizing the environmental and health hazards associated with hazardous waste [26]. Industries, regulatory organizations, and communities can collaborate to ensure the responsible management of hazardous waste by giving priority to waste reduction, reutilization of materials, employing suitable treatment techniques, and implementing adequate disposal methods. These principles not only protect human health and the environment but also encourage sustainability by minimizing waste production and preserving valuable resources. Adhering to these principles is crucial for attaining environmentally responsible and sustainable methods in the treatment of hazardous waste. The focus of responsible hazardous waste management is on implementing strategies to reduce trash generation at its source, with the goal of minimizing waste production [27]. These measures are crucial for minimizing environmental effects, lowering disposal expenses, and fostering sustainability. This section focuses on essential tactics for minimizing waste [27].

Implementing cleaner production procedures is a key approach to reduce waste. Industries and organizations have the capability to adopt procedures that automatically produce a reduced amount of waste or utilize fewer items that are potentially harmful. This strategy prioritizes the optimization of manufacturing techniques to limit the formation of waste while ensuring that product quality and efficiency are not compromised. For example, implementing alterations to production procedures to minimize the usage of toxic chemicals or creating goods with fewer hazardous components can greatly diminish the amount of hazardous waste generated [28].

The importance of product design is crucial to reducing waste. Eco-design, also known as designing things with an emphasis on sustainability, seeks to minimize the environmental impact of products from their creation to their disposal [29]. Manufacturers can minimize the production of hazardous waste at the end of a product's life cycle by carefully addressing variables such as material selection, ease of disassembly, and recyclability throughout the design phase. This approach is especially efficient in sectors characterized by items with a limited duration of usefulness, such as the electronics industry [29].

Implementing trash segregation and separation techniques is an effective approach to minimizing the presence of dangerous waste. Through the practice of segregating hazardous and non-hazardous waste from its origin, companies can guarantee that dangerous substances are handled and disposed of separately, thereby diminishing the total amount of hazardous waste produced. Appropriate categorization and containment of dangerous substances streamline this procedure and reduce the likelihood of unintentional blending [30].

Effective inventory management and procurement methods are crucial to minimizing waste. Implementing effective inventory management practices minimizes the probability of hazardous products reaching their expiration date or becoming obsolete, therefore reducing the risk of their turning into hazardous waste [31]. In addition, firms can implement procurement rules that give priority to the acquisition of non-hazardous or less hazardous alternatives, thereby diminishing the overall influx of hazardous materials into the workplace. Waste audits and monitoring systems are highly beneficial instruments for reducing waste. Conducting routine waste audits enables firms to detect recurring waste-generating trends, precisely identify areas for improvement, and establish specific reduction objectives [32]. Through the process of monitoring and tracking trash generation over a period of time, companies can evaluate the efficiency of their waste reduction methods and implement any required modifications.

Contemporary treatment technologies have completely transformed the manner in which hazardous waste is handled. The purpose of these modern techniques is to mitigate the detrimental effects of hazardous waste or to immobilize pollutants, thereby minimizing their adverse influence on the environment and public health. Hazardous waste incineration is the deliberate combustion of waste materials at elevated temperatures. This technique decomposes perilous substances and diminishes the quantity of waste [33]. Advanced incineration methods, such as high-temperature incineration and waste-to-energy incineration, reduce emissions and harness energy from the process. Chemical stabilization procedures entail the addition of substances to hazardous waste in order to bind or chemically modify pollutants, thereby reducing their leachability and toxicity [34]. This approach is highly efficient in the treatment of specific categories of dangerous waste, such as soils contaminated with heavy metals. Bioremediation utilizes microorganisms to degrade toxic chemicals in polluted soil or water. It is highly beneficial for remedying organic pollutants. Bioremediation is an

ecologically sustainable and economically efficient approach that harnesses natural processes. Thermal desorption is a technique that uses heat to vaporize and segregate dangerous pollutants from soil or solids. Subsequently, the impurities are trapped and subjected to individual treatment. This technique is beneficial for eliminating volatile organic compounds from polluted substances [35].

### **3. Risk assessment and safety procedures**

Safe disposal techniques are crucial for the ultimate confinement and administration of hazardous waste that cannot be diminished, processed, or reused. Secure landfills are purpose-built structures designed to effectively confine and manage hazardous garbage in a safe manner. These products incorporate numerous layers and liners to effectively prevent the seepage of liquids into the adjacent soil and groundwater. To adhere to environmental rules, hazardous garbage is carefully deposited in specific compartments within the landfill and closely supervised. Deep-well injection is the process of injecting hazardous waste into specially built underground wells at significant depths. The garbage is effectively segregated from groundwater and the surface environment due to the presence of impermeable rock formations. This approach is appropriate for specific categories of dangerous waste. Land application is a method of disposing of non-hazardous liquid hazardous waste, such as treated wastewater, by spreading it onto the land. Vigilant supervision and strict compliance with regulatory protocols are necessary to avert any potential environmental pollution with this approach. Encapsulation is the process of enclosing hazardous waste in materials that effectively immobilize pollutants, thereby preventing their release. This technique is frequently employed for materials that contain asbestos and waste that is radioactive.

The significance of contemporary treatment technologies and secure disposal procedures cannot be exaggerated. These strategies guarantee that dangerous waste is handled in a way that reduces hazards to human health and the environment. Contemporary treatment technologies effectively neutralize or stabilize dangerous substances, reducing their level of harm. Implementing proper disposal techniques serves as a conclusive safeguard against the infiltration of dangerous waste into the soil, the contamination of groundwater, or the pollution of the air [36]. To ensure the efficacy of these measures in protecting our environment and well-being, it is crucial to adhere to environmental standards and conduct thorough monitoring.

The implementation of sustainable management techniques is crucial in the realm of hazardous waste management, as it provides a comprehensive and accountable strategy for tackling the difficulties presented by hazardous waste [9]. These practices provide the highest importance to safeguarding the environment, ensuring long-term sustainability, and promoting the well-being of both present and future generations.

The main rationale for implementing sustainable management techniques is their pivotal role in protecting the environment. Sustainable methods aim to mitigate the environmental consequences of hazardous waste management, thereby diminishing pollution and the exhaustion of natural resources. Through the prioritization of sustainability, we may effectively minimize the negative impact on ecosystems, avert soil and water pollution, and decrease air pollution caused by incorrect waste management [37].

Furthermore, sustainable management techniques are in accordance with the principles of environmental preservation. Their objective is to save natural habitats, conserve biodiversity, and secure the sustainability of crucial ecosystems. Improper

management of hazardous waste can pose a significant peril to wildlife and cause disruption to delicate ecosystems. Implementing sustainable practices helps to reduce these hazards, thereby making a positive contribution towards the well-being of our world [38].

Resource efficiency is another vital component of sustainable management. Sustainable approaches promote the retrieval and reutilization of valuable materials from hazardous waste streams. This not only diminishes the need for new resources but also preserves energy and diminishes greenhouse gas emissions linked to the mining and processing of resources. Sustainable waste management is in line with the principles of the circular economy, wherein garbage is transformed into a valuable asset rather than being seen as a burden [39].

Moreover, the implementation of sustainable management methods is crucial to advancing public health and safety. Through the reduction of the emission of perilous compounds into the surroundings, these methods diminish the chances of human contact with detrimental chemicals and impurities. Sustainable waste management places a high priority on safeguarding the health and well-being of vulnerable communities situated in close proximity to hazardous waste facilities, thereby ensuring that their safety is not compromised [40].

Economic factors are essential components of sustainable management strategies. Although it may necessitate initial financial commitments, implementing sustainable waste management practices can result in significant long-term cost reductions [41]. Recycling and resource-efficient technologies can help reduce waste management costs by recovering valuable resources. Furthermore, there are economic benefits to be gained from reducing the environmental and health expenses linked to inappropriate garbage disposal.

Sustainable management practices are future-oriented and take into account the requirements of future generations. Their main focus is on prioritizing the responsible management of trash and implementing long-term strategies to prevent hazardous waste from becoming a burden for future generations. By adopting sustainable behaviors in the present, we alleviate the responsibility of future generations to rectify the repercussions of previous mismanagement [42].

The management of hazardous waste will encounter changing and complex issues and trends in the future, influenced by factors such as technical progress, shifting waste compositions, regulatory changes, and environmental considerations [43]. Tackling these obstacles is crucial to guaranteeing efficient and enduring handling of hazardous waste. With the introduction of novel chemicals and materials, the composition of hazardous waste streams may change to incorporate emerging pollutants. These compounds may possess health and environmental consequences that are either unknown or not well comprehended. In order to ensure appropriate treatment and containment of developing pollutants, future management of hazardous waste must be able to adjust to the evolving composition of trash. The widespread use of electronic devices has resulted in a significant increase in the amount of electronic garbage (e-waste). The management of electronic trash presents distinct difficulties as a result of the inclusion of perilous substances like lead, mercury, and flame retardants within electronic parts. Future endeavors will entail the development of effective and sustainable techniques for the recycling and disposal of electronic trash [44]. The adoption of a circular economy, characterized by the minimization of waste and the recycling and reutilization of resources, will have a substantial effect on the management of hazardous waste. The increasing prominence of sustainable practices that promote resource recovery and waste reduction will lead to a restructuring of

waste management techniques. The presence of climate change presents potential dangers to the infrastructure used for managing hazardous waste, such as landfills and treatment facilities. It is essential to prioritize the preparation for climate change effects, including the escalation of severe weather events, the rise in sea levels, and the alteration of precipitation patterns, in order to safeguard the effectiveness of hazardous waste containment systems [44].

The future of hazardous waste management will be greatly influenced by advancements in waste treatment technology, robotics, automation, and artificial intelligence. These technologies have the potential to improve the effectiveness and security of waste management and processing procedures [45]. The landscape of hazardous waste management will be influenced by changing legislation and policies at the local, national, and international levels. Possible future avenues may encompass more stringent regulations for waste management, heightened levels of openness, and broader mandates for waste tracking and reporting. The future trajectory will be influenced by the augmentation of public consciousness about hazardous waste matters and the significance of conscientious waste administration [46]. The trend of increasing community involvement in waste management decision-making and the need for more environmentally friendly methods will persist. International collaboration and agreements will be crucial due to the worldwide scope of hazardous waste challenges. Cooperative endeavors to tackle the cross-border transportation and disposal of dangerous waste will continue to be crucial for safeguarding the environment on a worldwide scale [47]. Continued attention and remediation efforts will be necessary for legacy hazardous waste sites, such as abandoned industrial buildings and toxic landfills. Upcoming difficulties include discovering inventive and economical methods to tackle these locations. Progress in monitoring technologies will enable more precise monitoring of the effects of hazardous waste on human health and the environment. Implementing real-time monitoring and data analysis will facilitate expedited responses to possible contamination occurrences.

Overall, the trajectory of hazardous waste management will be influenced by the convergence of technological progress, regulatory modifications, environmental factors, and public consciousness [48]. The field's primary directions include adapting to developing toxins, embracing the circular economy, and addressing the issues posed by climate change. Effective management of hazardous waste necessitates cooperation among governments, industry, communities, and researchers to guarantee its sustainability and proper handling, thereby protecting human health and the environment.

#### **4. Future challenges and opportunities**

As we contemplate the future, the management of hazardous waste encounters ever-changing difficulties. The persistent growth in industrial activities, particularly in fast-emerging nations, results in a corresponding escalation in the production of hazardous waste. The current trend presents a substantial obstacle for the existing waste management infrastructure, which frequently faces difficulties keeping up with the quantity and intricacy of garbage generated. In addition, the rise of newer hazardous substances, especially from the technology and pharmaceutical sectors, presents significant complexities in the management and elimination of waste.

The effects of climate change also have a substantial impact on the management of hazardous waste. Severe weather phenomena, such as floods and hurricanes, can

cause the accidental discharge of dangerous substances into the environment, making existing environmental and health dangers worse [49]. Moreover, it is increasingly important to take into account the carbon footprint of methods used for treating and disposing of hazardous waste, ensuring that they are in line with international efforts to address climate change.

Amidst these difficulties, there exist significant prospects for innovation and progress. The advancement of technology in trash treatment, including the utilization of modern chemical and biological treatment techniques, shows potential for improving efficiency and reducing the environmental impact of waste management [50]. Bioremediation techniques, which employ microorganisms to render harmless or eliminate dangerous pollutants, are increasingly being recognized as a sustainable substitute for conventional approaches [50].

The incorporation of digital technologies such as artificial intelligence and the Internet of Things (IoT) in waste management has the potential to fundamentally transform the processes of monitoring, treating, and disposing of hazardous waste. These technologies provide improved monitoring and reporting capabilities, resulting in more knowledgeable decision-making and higher compliance with regulatory standards [51].

These new challenges and opportunities are anticipated to prompt changes in policy and regulatory frameworks. More stringent restrictions for the production and disposal of dangerous waste, in accordance with global standards, are expected to be enforced in order to protect human health and the environment [52]. Moreover, the implementation of policies that advocate for circular economy concepts, which consider garbage as a valuable resource rather than a problem, has the potential to completely transform the field of waste management.

Global collaboration and the standardization of legislation are crucial for efficiently controlling the cross-border transportation of dangerous waste. Collective endeavors are required to avert the unlawful disposal of perilous waste, especially in nations with less rigorous environmental legislation [53].

An area for improvement is the implementation of risk-based management systems that entail evaluating potential hazards linked to certain waste categories and disposal techniques. Researchers contend that by integrating toxicological and epidemiological data, it is possible to develop customized management strategies that address the specific risks associated with a particular waste stream to both human and environmental well-being [54]. Canada has adopted a risk-matrix approach to categorize dangerous waste based on its type and levels of exposure. This method is used to develop specific laws for the treatment and disposal of such garbage. In addition, the United States Environmental Protection Agency (US EPA) has created risk assessment tools such as SW-846 [55]. These tools offer methodology for evaluating the risks associated with site pollution resulting from landfills or spills. The assessment takes into account elements such as transport mechanisms, chemical fate data, and probable routes of exposure [55]. As emerging complex waste streams proliferate in the future that do not fit neatly into traditional categories, developing robust risk-based classification schemes and contingency protocols will be essential for responsible, sustainable management [56]. Standardizing these more adaptable hazardous waste assessment methods globally can help drive innovation in life-cycle handling while avoiding reliance on primitive disposal options. Overall, a transition towards flexible and information-driven hazardous waste management systems will present major advantages moving forward.


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Section 2

**Innovative Issues in Waste  
Treatment and Resource  
Recovery**

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## Chapter 2

# Development of a Novel Steel Slag-Based Sulfur-Enriched Multi-Nutrient Fertilizer and Its Performance in Agriculture

*Bhupinder Singh, Shrenivas Ashrit, Manoj Shrivastava, Kalidindi Usha, Pratik Swarup Dash, Prem Ganesh and Subrat Kumar Baral*

### Abstract

Linz-Donawitz (LD) slag, a by-product of steel manufacturing process, is rich in iron oxide, calcium oxide, silica, various macro, and micronutrients as well as varying degrees of heavy metals residues. The steel slag, thus, presents an opportunity for their utilization in agriculture beyond the conventional routes of consumption in cement, transport, construction industries. In this chapter, we explore a sustainable waste management technology for utilizing LD slag in the development of sulfur enriched nutrient supplement “Dhurvi Gold (DG)” and determine its effect on physico-chemical characteristics of the soil and its impact in the growth, quality, and economic yield on selected crops under natural field conditions. Heavy metal accumulation among the plant parts following the supplementation with DG was also studied. The results indicate the farming and economic benefits of utilizing DG in agriculture, which thus, presents itself as an opportunity both for the steel industry and the agriculture sector desirable for the development of a sustainable strategy for management of steel (LD)-slag. However, it is important to determine the long-term effects of the steel slag-based fertilizers on physico-chemical and biological characteristics of soil including accumulation of heavy metals in soil-plant continuum, if any.

**Keywords:** steel industry, Linz-Donawitz slag, sulfur fertilizer, crop nutrition, heavy metal uptake, Dhurvi Gold

### 1. Introduction

India is the second-largest producer of steel after China, and it is likely to continue its global dominance in steel production in years to come. However, the strides being made, the steel industry needs to be based on green processes in terms of carbon emissions and waste management. Huge quantities of steel slag get generated during

the production of steel from the iron ore, the major raw material, which is processed *via* the BF/BOF or LD routes [1–3]. It is estimated that the steel industry produces about 125 kg of steel slag per ton of steel produced during the Linz-Donawitz (LD) process [4]. While the BF-slag is utilized in cement production, management of the LD slag is a concern, several possible routes are being explored for sustainable management of LD slag [5].

The LD steel slag is rich in calcium-bearing silicates and free lime along with metallic iron. A typical chemical composition of the reject portion can be represented as 47–52% CaO, 2–13% free lime, 12–19% Fe, 1.5–2% P, 1.5–2% Al<sub>2</sub>O<sub>3</sub>, and 11–18% SiO<sub>2</sub>. This slag is processed in a waste recycling plant (WRP) so as to separate the magnetic iron portion and the non-magnetic portion by water quenching and solidification and by using a series of magnetic separators. This is followed by crushing the slag to –300, –80, and –6 mm size fractions and subjecting it to roll magnetic separators so as to recover the metallic iron. At this point, iron is in the form of FeO and Fe<sub>2</sub>O<sub>3</sub> as metallic iron is recovered in WRP [6–8].

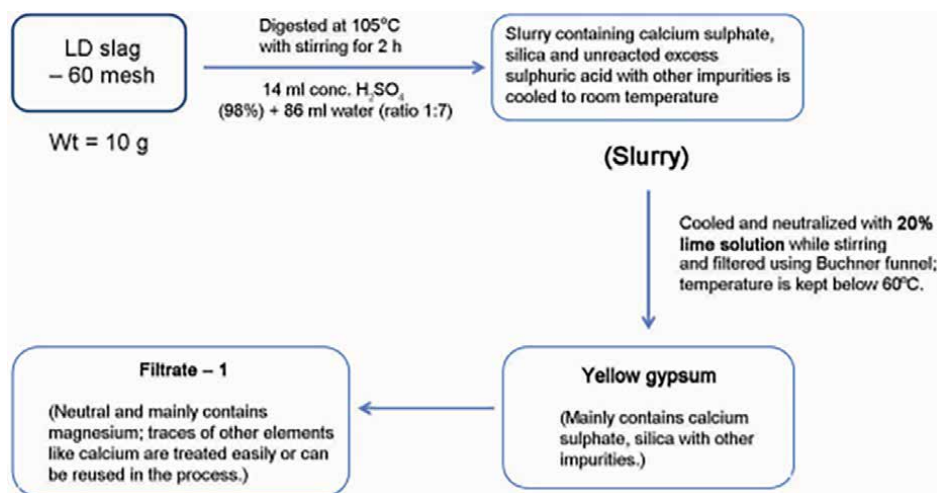
The LD slag is used as an aggregate in the construction of roads [9–11]. Other applications include the use of LD slag as a starting material for production of cement clinker and as a fertilizer in the agricultural sector [12, 13]. Significant positive effect of steel slag-based silicate fertilizer application on shoot silica content and growth of paddy on acidic soil has been reported [14]. In line with the enormous stockpile of LD slag being generated by the steel industries, other applications need to be identified, which can be helpful in the synthesis of value-added products of industrial importance [15]. Use of LD slag either in un-amended form as a soil conditioner or in an amended or modified form as a soil fertilizer could open up new avenues and opportunities for both the steel and the agriculture sector with positive environmental significance [16]. The following sections provide details of the development of a LD slag-based sulfur-enriched multi-nutrient fertilizer and soil conditioner and an evaluation of its effect on agricultural soils and selected crop productivity and its potential enrichment of the soils with undesirable heavy metal accumulation along the soil-plant continuum.

## **2. Materials and methods**

### **2.1 Production of LD slag-based synthetic gypsum “Dhurvi Gold”**

Dhurvi Gold (calcium sulphate) was produced from –60 mesh size LD slag fines obtained from Tata Steel Limited, Jamshedpur, India. The production of synthetic gypsum using LD slag was carried out by acid digestion of LD fines with concentrated sulfuric acid followed by pyrolysis steps at temperatures ranging between 105 and 900°C [17]. The digestion process helps in leaching of all major impurities and other minor elements present into the solution and precipitation of calcium as calcium sulphate [18] while also precipitating the silica. The slurry so formed was neutralized to pH 7.0 using 20% lime solution and filtered through Whatman no. 41 membranes. The solid residue so collected on filter paper, “the Dhurvi Gold,” was washed with double-distilled water and allowed to dry at temperature below 60°C for 24 h. A general scheme of DG production is given in **Figure 1**. Further, the nutrient content of DG was determined using ICP-OES following standard procedure [19].

The LD slag-based nutrient fertilizer, DG, described in this study, was characterized by ICP and various other characterization techniques [20] such as X-ray



**Figure 1.**  
Flow chart of lab-scale production of Dhurvi Gold [17].

diffraction (XRD), thermogravimetric analyzer, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS).

## 2.2 Crop response to DG application at the farm level

Field treatments were identified and undertaken to evaluate the effect of DG on crop growth, yield, and nutritional quality and on soil attributes across two separate experiments, wherein experiment 1 studied the contribution of varying doses of DG as the source of mineral nutrients to plant and soil health under full and half the dose of the recommended fertilizer (NPK), while the second experiment involved assessment of crop response to LD slag (LDS) and the effect of nutrient-solubilizing bacteria and fungi (PSB and PSF, respectively) and NPK availability (recommended dose of fertilizer (RDF) and half of the RDF on the vegetative and reproductive crop yield.

Treatment details under Experiment-I are as follows: T1: 100% NPK (Recommended dose of the crop); T2: 50% NPK + 5 t/ha FYM; T3: T1 + 30 kg/ha sulfur as DG; T4: T1 + 45 kg/ha sulfur as DG; T5: T1 + 60 kg/ha sulfur as DG; T6: T2 + 30 kg/ha sulfur as DG; T7: T2 + 45 kg/ha sulfur as DG; and T8: T2 + 60 kg/ha sulfur as DG. Meanwhile, the treatments under Experiment-II conducted with LD-slag (LDS) were: T1: RDF; T2: 50% of T1 + 5 t/ha FYM; T3: T1 + 0.5 t/ha LDS; T4: T2 + 0.5 t/ha LDS; T5: 0.5 t/ha LDS; T6: 0.5 t/ha LDS + PSF; T7: 0.5 t/ha LDS + PSB; and T8 = 0.5 t/ha LDS + PSF + PSB. All experiments were performed with a minimum of three replicates following the randomized block design (RBD). Crop response to both DG and LD slag was determined in brinjal (*Solanum melongena* L) cv Pusa hybrid-6 and okra (*Abelmoschus esculentus*) cv DOV 92. Observations in respect of plant biomass, macronutrients (P, K, S and Ca), micronutrients (Fe, Zn, Cu and Mn), heavy metals (Cd, Pb, Cr), beneficial nutrient: Na, and economic yield were recorded.

Experiments involved studies on crops' growth and yield response of Dhurvi Gold and LD slag with recommended (RDF), reduced NPK (50% RDF) nutrition, and biological amendments as stated in earlier sections in both experimental vegetable crops. A control treatment without application of any fertilizer and DG was also maintained.

### 3. Results and discussion

#### 3.1 Production and characterization of LD slag-based synthetic gypsum “Dhurvi Gold”

Dhurvi Gold produced from LD fines not only was comparable to gypsum but also may replace natural gypsum in terms of varied applications including its use in the cement industry [21] and as a starting material for production of different preformed building elements and plaster products in the medical field. Gypsum is also used as a soil conditioner on alkaline soils [22]. We believe that the LD slag-based Dhurvi Gold, a synthetic gypsum, can replace natural gypsum in the cement industry [23], thus helping us conserve the resource of natural gypsum. Also, Dhurvi Gold produced from the industrial waste can supplement gypsum requirement for various chemical industries. Researchers at the Chemical Laboratory, Tata Steel Limited, thus, developed Dhurvi Gold, which is yellow in color owing to the presence of iron. Use of LD slag as liming agent on acid soils has also been reported [24].

The synthesis of DG helped to achieve a major objective in environmental sustainability of steel production by presenting a route for the synthesis of a value-added product (synthetic gypsum) from LD slag, which is an industrial waste product of the steel industry [17, 25]. This is an important development and a step forward for generating wealth from waste. The composition of DG, a source of sulfur and other macro- and micronutrients, is given in **Table 1**. The DG has a major amount of sulfur, which is about 14–16%. For experimental purposes and for assessing the crop response to application of DG, all calculations were done taking the S content of DG as 16%.

#### 3.2 Effect of Dhurvi Gold on brinjal (*Solanum melongena*)

A distinct positive effect of DG on shoot mass of brinjal (*Solanum melongena*) plants was observed at all levels of applications (30, 45, 60 kg S/ha) under both 100% & 50% NPK when compared with respective NPK and zero fertilizer controls. Positive effect of DG on shoot mass was higher under 100% NPK than 50% NPK treatments. Fruit yield per plant was also improved under the DG application; however, the most significant increase was observed at 30 kg S/ha dose under both 100 and 50% NPK treatments. Increase in fruit yield per plant observed with DG was

Parameters		Specifications (Min)	Typical Range, %	
Ca	=	23.0%+	23 - 28	Major
S	=	14.0%+	14 - 20	
SiO <sub>2</sub>	=	3.00%+	3 - 7	Additional nutrients
Fe	=	2.00%+	2 - 7	
MgO	=	0.5 - 1.00%+	0.5 - 2.0	
P <sub>2</sub> O <sub>5</sub>	=	0.50 - 0.90+	0.50 - 1.5	
MnO	=	0.10%+	Max 0,15	
PH	=	7.5 - 8.0 (Very good for application to all soils)		

**Table 1.** Nutritional characteristics of LD slag-based synthetic gypsum, Dhurvi Gold [26].

improved when compared with respective NPK controls. A similar positive effect of DG on individual fruit mass was observed under 30 and 45 Kg S/ha DG doses with both 100 and 50% NPK treatments (T1 and T2). The increase in individual fruit mass at 60 kg S/ha treatment was not significant when compared with respective NPK control (Figure 2).

Change in essential and beneficial mineral element content and those for the toxic heavy metals as affected under an interactive influence of NPK and DG application were measured. K concentration of the shoot in general was 2–3 folds lower than that of fruit across all treatments. A significant increase in fruit K was, however, noticed with increasing concentration of 30–60 kg S/ha under 100% NPK treatment when compared with the respective control. On the other hand, an insignificant change in shoot and fruit Ca was observed under individual interactive treatment of NPK and DG, except that at the highest dose of DG application (60 kg S/ha), a higher increase in shoot and fruit Ca was evidenced under both T1 and T2 (100 and 50%) NPK when compared with respective treatment controls (Figure 3).

A DG dose-dependent increase in shoot phosphorous (P) was observed under both 100 and 50% NPK treatments up to 45 kg S/ha level, beyond which a decline was observed. A similar significant increase in fruit P was observed at all DG treatments under both 100 and 50% NPK levels, when compared with respective treatment controls. More or less a similar P concentration was observed in the shoot and fruit of brinjal (*Solanum melongena*) across the treatments. A significant increase in shoot and fruit S content was observed under the variable NPK treatments with different doses of DG (30, 45, 60 kg S/ha) when compared with respective fertilizer and absolute controls. The response in shoot S was, however, more marked under the 100% NPK than the 50% NPK treatment. Fruit S, on the other hand, showed more or less a similar incremental response under both 100 and 50% NPK complementations (Figure 4).

A higher shoot iron (Fe) content was observed under the increasing DG dose, more so with 100% NPK when compared with their respective fertilizer and absolute controls. In general, no significant increase in the fruit Fe was observed under 100% NPK with DG treatment. However, the increase in fruit Fe was significant under 50% NPK at (30 and 45 kg S/ha) DG application when compared

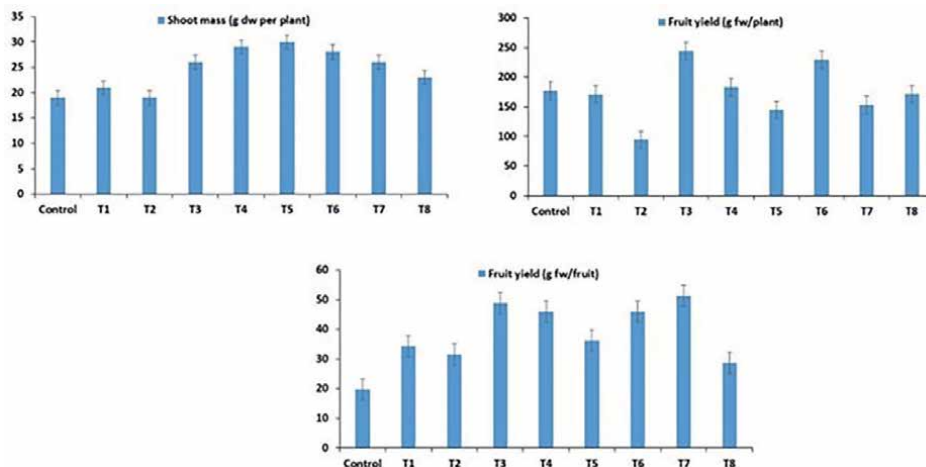
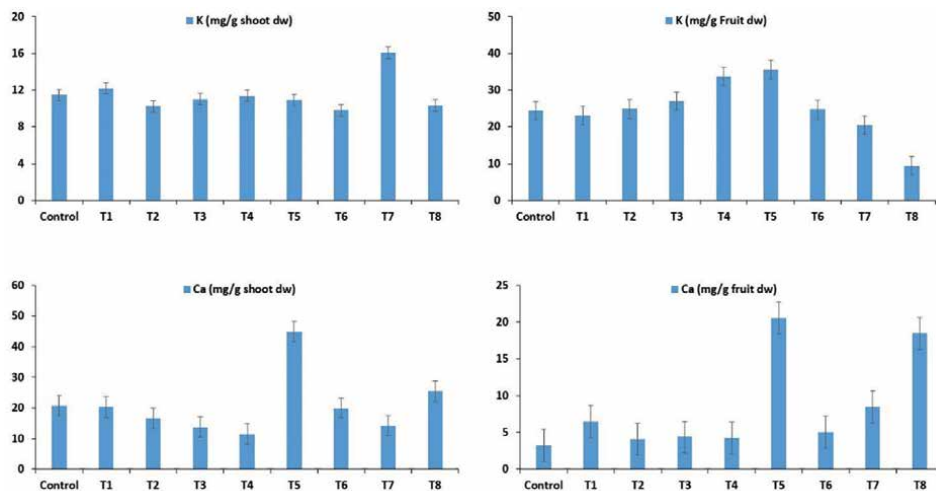
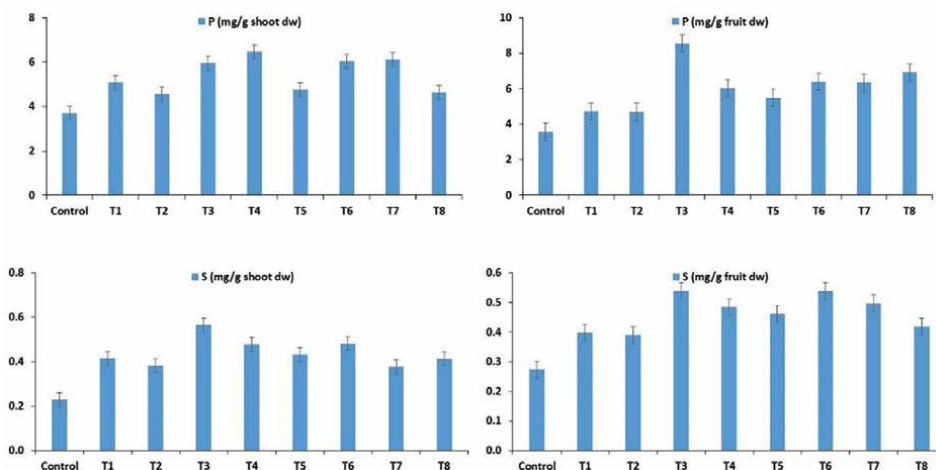


Figure 2. Effect of Dhurvi Gold on shoot mass and fruit yield attributes in brinjal (*Solanum melongena*) at harvest.



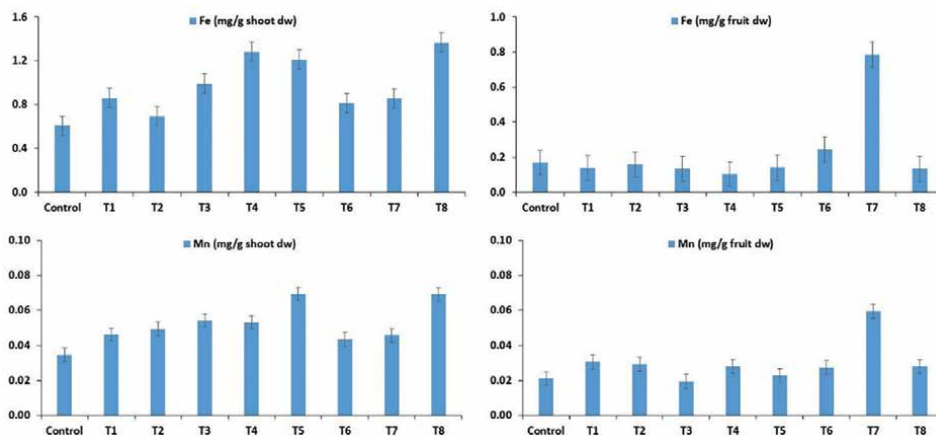
**Figure 3.** Effect of Dhurvi Gold on potassium and calcium of shoot and fruit in brinjal (*Solanum melongena*) at harvest.



**Figure 4.** Effect of Dhurvi Gold on phosphorus and sulfur content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

with respective controls (**Figure 5**). A positive effect of steel slag application as an alternate to iron fertilizer was observed in corn in terms of plant growth and soil micronutrients [13].

It was also observed that the shoot manganese (Mn) concentration was higher than the fruit Mn levels across experimental treatments. A significant increase was observed at 60 kg S/ha DG under both 100 and 50% NPK treatments when compared with other DG doses and respective fertilizer and absolute controls. No significant change in Mn level was, however, observed under the DG application treatment irrespective of NPK and DG doses except under T7 (i.e. 45Kg S/ha DG + 50% NPK), which showed a higher increase in fruit Mn when compared to other experimental treatments and controls (**Figure 5**). A significant increase in the shoot zinc (Zn)

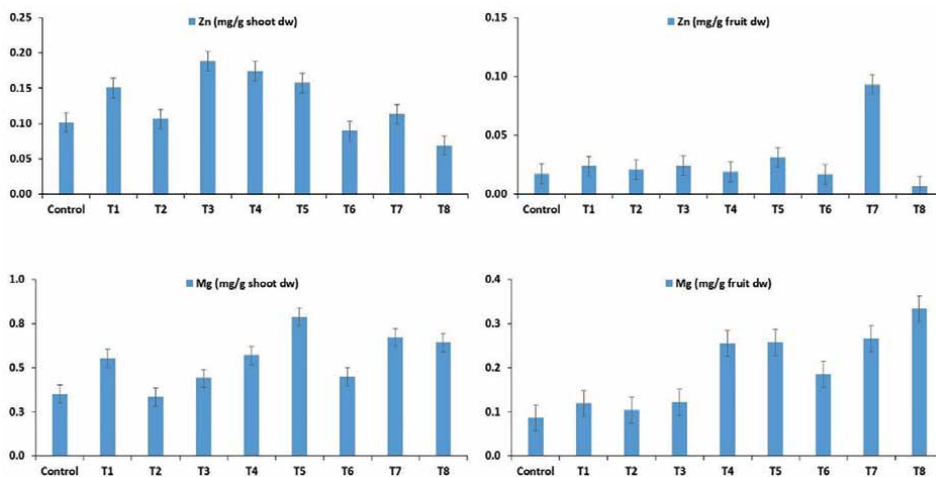


**Figure 5.**  
 Effect of Dhurvi Gold on iron and manganese content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

irrespective of DG level was observed under 100% NPK supplementation when compared with its respective control; however, under 50% NPK treatment, no significant effect of DG on shoot Zn was observed, which was similar to the pattern of variation observed for concentration of Fe and Mn. In the fruit, Zn concentration also did not vary with DG application except under T7 compared to other experimental treatments and controls (**Figure 6**).

An incremental increase in shoot and fruit magnesium (Mg) was observed under both 100 and 50% NPK supplementation treatments when compared with the respective fertilizer and absolute controls. Shoot Mg level was in general higher than the fruit Mg concentration, and the shoot-to-fruit translocation of Mg was observed to be higher under 50% NPK than 100% NPK treatment (**Figure 6**).

Certain heavy metals are unwanted inputs that may cause phytotoxicity effect; thus, it is important to understand the levels of these metals in soil and plants.



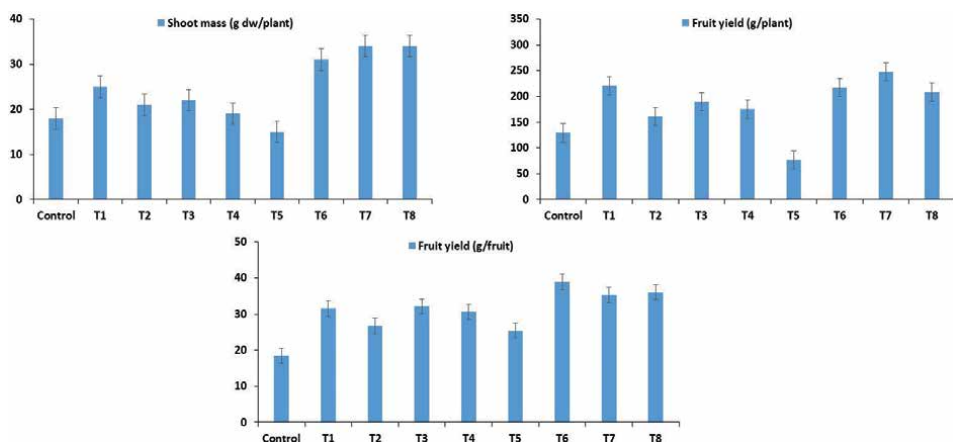
**Figure 6.**  
 Effect of Dhurvi Gold on zinc and magnesium content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

Chromium (Cr) is an element of concern in respect of utilization of steel slag [27] in agriculture. In the present experiment, the concentrations of Cr alongside cadmium (Cd) and lead (Pb) both in shoot and in fruit under different experimental treatments were below the detection limit showing that application of the fertilizer did not pose phytotoxicity that could affect human/animal health issues in respect of use of DG application in farms.

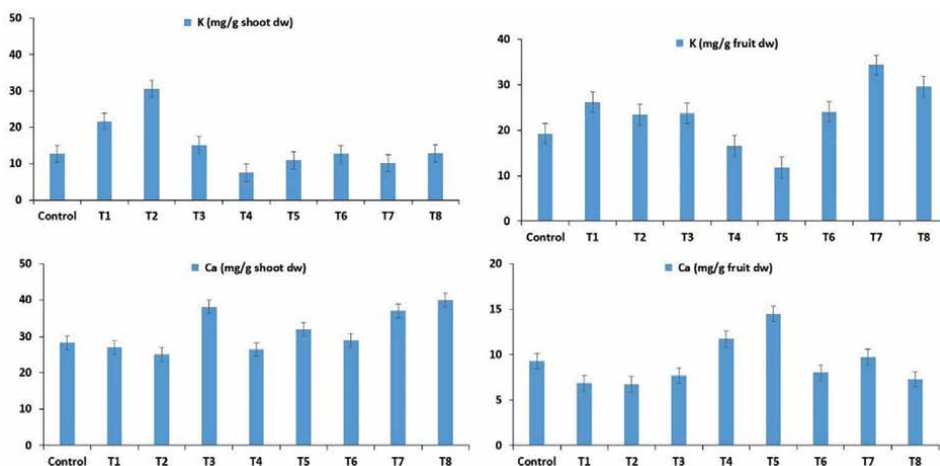
### 3.3 Effect of LD slag on brinjal (*Solanum melongena*)

Effect of LD slag on growth and nutritional characteristics of brinjal (*Solanum melongena*) crop when supplemented with 100 and 50% NPK and with different microbiological interventions such as phosphate solubilizing bacteria (PSB), phosphate solubilizing fungi (PSF), and their combination was studied, and results are presented in the following section. Plant shoot mass, in general, declined with LD slag application without any NPK supplement when compared even with the absolute control. The microbiological amendment with both PSB, PSF, and their combination caused significant increase in shoot mass when compared with all other experimental treatments; a similar significant inhibition and increase in fruit yield were observed under LD alone and microbiological intervention, respectively. A look into the individual fruit mass shows that LD slag application reduced the fruit not much more than the fruit mass. Here again, the biological amendment improved the mass accumulation in fruits (**Figure 7**).

A comparison of potassium (K) concentration between shoot and fruit of LD slag-treated brinjal (*Solanum melongena*) plants showed a much higher level of K in the fruit than the shoot. Shoot K level did not change over control under different LD slag treatments with biological amendment. However, the fruit K level was improved with biological intervention given alongside LD slag when compared with LD slag alone or fertilizer and/or absolute controls. The LD-slag-alone treatment showed significant increase in fruit K when compared with all other experimental treatments (**Figure 8**). Since DG and LD slag are also a major source of Ca (**Table 1**), the effect of different experimental treatments on plant tissue Ca was determined and discussed. Shoot Ca concentration was higher under LD slag application; max Ca level was observed



**Figure 7.** Effect of LD slag on shoot mass and fruit yield attributes in brinjal (*Solanum melongena*) at harvest.

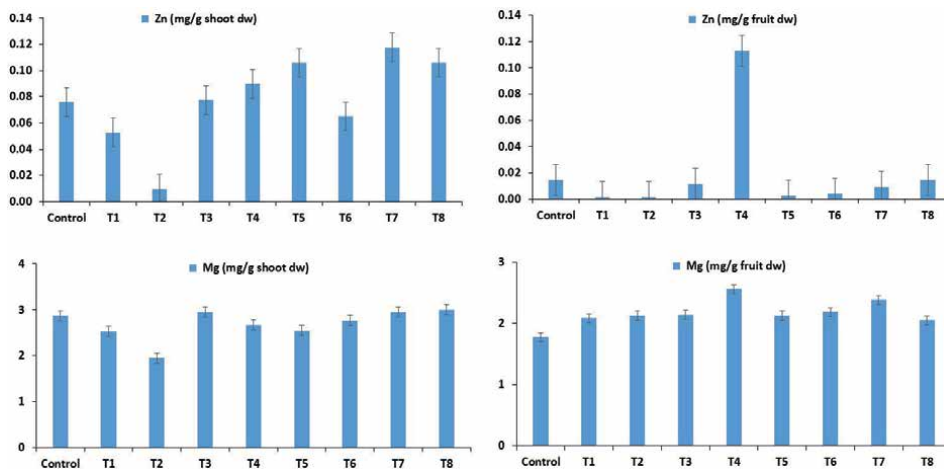


**Figure 8.** Effect of LD slag on potassium and calcium content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

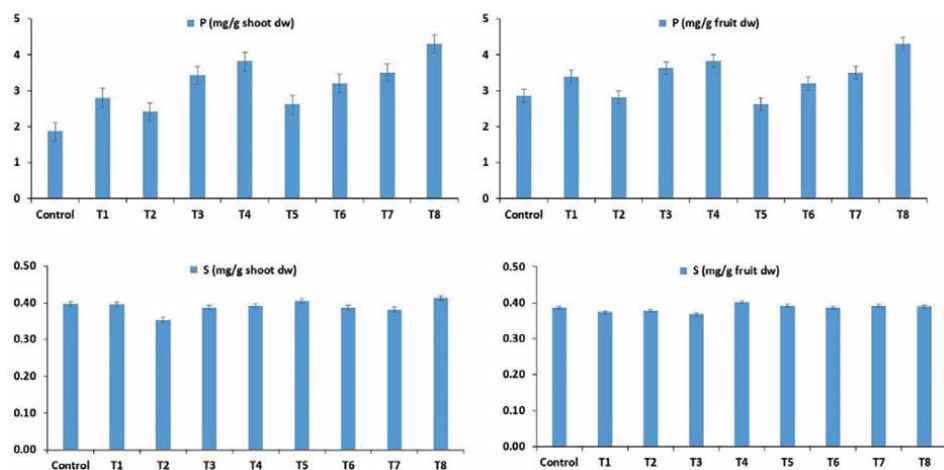
under T3 treatment that is 100% NPK and slag, while a reduced NPK supplementation alongside slag treatment inhibited the uptake and accumulation of Ca in the shoot. PSB alone and PSB in combination with PSF and alongside LD slag improved the shoot Ca level at par with the T3 treatment. Ca concentration in fruit was in general almost 3–4 times lower than that of shoot and increased with D slag application either with 100 or with 50% NPK supplementations when compared with respective controls. Max fruit Ca was observed under LD slag alone treatment (T5). Biological interventions also improved the fruit Ca level over different experimental controls; however, the effect was significant under LD slag + PSB treatment (T7) (**Figure 8**).

A significant increase in shoot P was observed with the use of phosphate-solubilizing bacteria and fungi or their combination; when applied alongside the LD slag to brinjal (*Solanum melongena*) plants, it caused a significant increase in the tissue P accumulation when compared with NPK fertilizer and absolute controls. The least tissue concentration of P was recorded for the LD-slag-alone treatment, while maximum increment in tissue P was evident under the combined intervention of PSB and PSF (**Figure 9**). Application of LD slag with variable NPK levels and biological amendment did not alter the fruit and shoot S content over the fertilizer and absolute controls. Application of LD slag alone (T5) did not inhibit the S uptake (**Figure 10**).

LD slag application with NPK supplementation in general did not improve the shoot Fe content when compared with respective fertilizer treatment and controls. A significant decline in shoot Fe accumulation was evident under the LD-slag-alone treatment (T5). Biological intervention seems to facilitate the availability, uptake, and accumulation of Fe from LD slag in the shoot. However, the Fe content in the fruit was unaffected by fertilizer (**Figure 11**). Variation in shoot and fruit Mn as affected by LD slag in conjunction with fertilizer and biological amendment is presented in **Figure 12**. Application of LD slag either with NPK amendment or with biological intervention did not alter the shoot Mn level when compared to the slag-alone treatment; however, an increase in shoot Mn was observed when LD slag was applied alongside 50% NPK (T4) in comparison with the (T2) control. No significant variation in fruit Mn concentration was, however, observed either with or without the fertilizer and biological amendment (**Figure 11**).

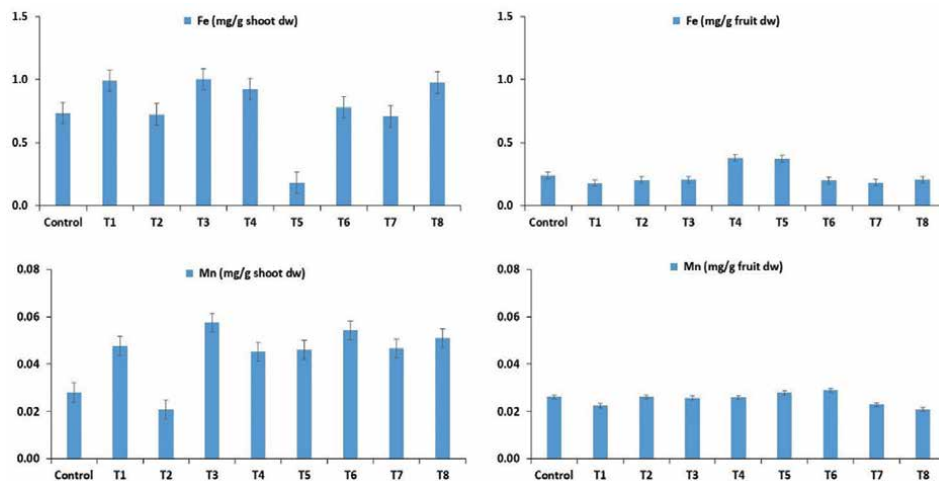


**Figure 9.** Effect of LD slag on zinc and magnesium content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

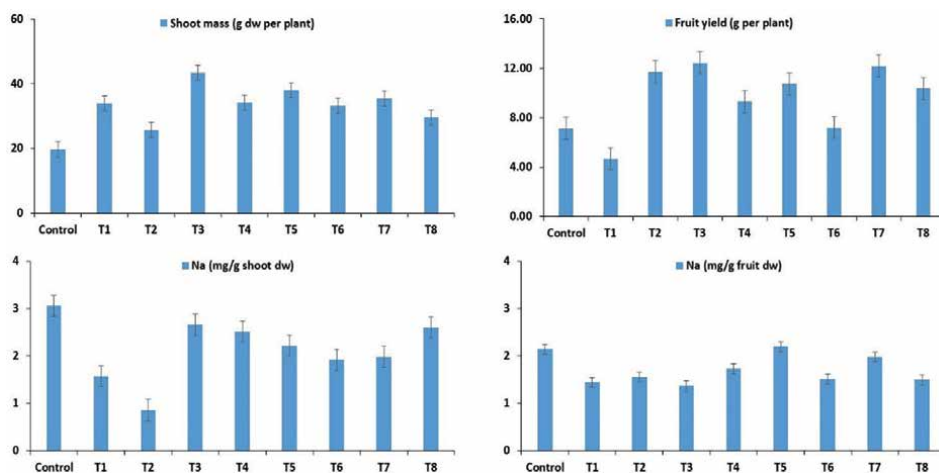


**Figure 10.** Effect of LD slag on phosphorus and sulfur content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

The significant positive effect of LD slag on shoot Zn when applied alongside 100 or 50% NPK or as biological amendment was recorded in comparison with the respective control treatments. PSB rather than PSF, when supplemented along with LD slag, improved shoot Zn concentration. An insignificant variation in fruit Zn level was observed under the various fertilizer and biological amendments of LD slag in brinjal (*Solanum melongena*) plants (**Figure 13**). Application of LD slag alongside NPK or biological amendment improved the shoot Mg concentration when compared with the respective fertilizer and absolute control treatments. The LD-slag-alone treatment reduced the uptake of Mg by brinjal (*Solanum melongena*) shoot; none of the experimental treatments/amendments caused significant intertreatment variation in the fruit Mg concentration either with or without the presence of LD slag (**Figure 9**).



**Figure 11.** Effect of LD slag on iron and manganese content of shoot and fruit in brinjal (*Solanum melongena*) at harvest.

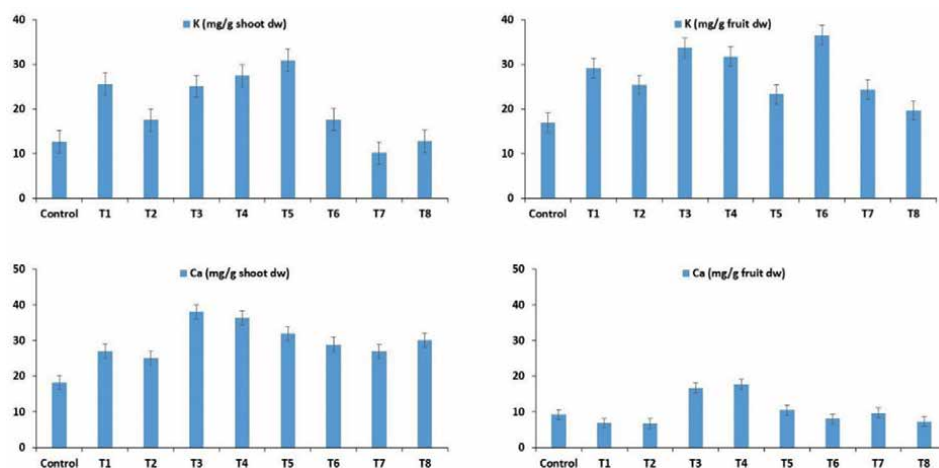


**Figure 12.** Effect of Dhurvi Gold (DG) on plant growth and fruit yield of okra (*Abelmoschus esculentus*) at harvest.

Even with the LD slag application, we did not observe any built up of heavy metals in the shoot and fruit of brinjal (*Solanum melongena*), all of which were in the undetectable range and may be attributed to the dilution or varietal affect.

### 3.4 Effect of DG on okra (*Abelmoschus esculentus*)

Effect of DG with 100% and 50% RDF (NPK) application on plant growth and development, economic production, and accumulation of essential macro- and micronutrients, beneficial elements, and heavy metals, Pb, Cd and Cr, was studied in the shoot and fruits of okra (*Abelmoschus esculentus*). Results are surmised as follows: DG application at all doses under 100% NPK yielded a better shoot growth over the respective fertilizer control (T1). Same was also true for the other fertilizer

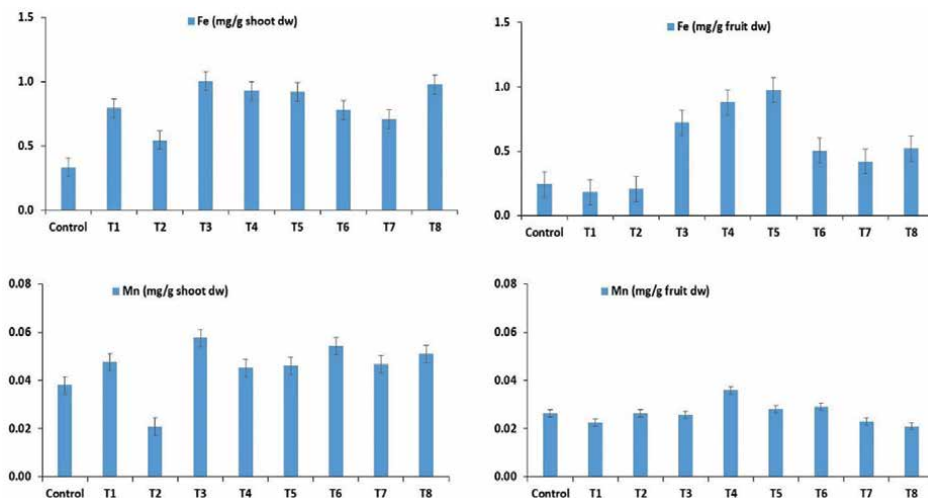


**Figure 13.** Effect of Dhurvi Gold (DG) on potassium and calcium content of shoot and fruit of okra at harvest.

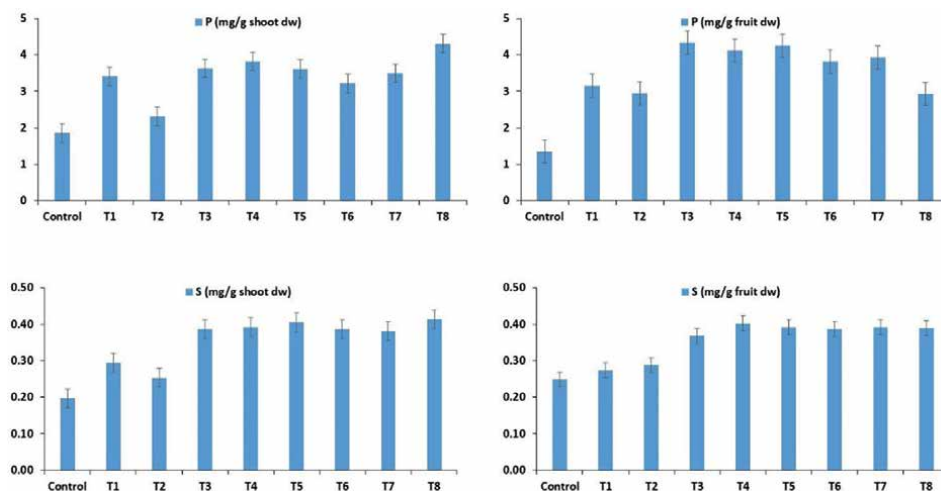
application treatment, that is, 50% NPK, which although showed an increase in shoot mass with DG when compared to the fertilizer-alone-control treatment (T2), the plant response under T1 was higher than T2 treatments both alone and in combination of DG. A similar increase in fruit yield per plant and single fruit mass was evident under RDF treatment when supplemented with different amounts of DG. The response of DG under 50% RDF treatment was not significant (Figure 12).

DG application improved the shoot K level when supplemented with the recommended dose of NPK fertilizer; however, under 50% RDF condition, an insignificant effect of DG supplementation on K concentration of the shoot was observed when compared with their respective fertilizer controls (T1 and T2). Similarly, an increase in fruit K was evident with DG under 100% RDF at 30 and 45 kg dose (T3 and T4) and at 30 kg DG dose (T6) with 50% RDF (Figure 14). Further, an increase in calcium content of shoot was observed at all doses of DG both at RDF and at 50% RDF. However, the increase in calcium content across DG treatments was higher at RDF than at 50% RDF treatment over absolute and respective NPK controls. A similar pattern of variation between the NPK treatments under variable DG doses was also evident for the fruit calcium content. T3 and T4 treatments showed maximum fruit calcium content (Figure 13).

Okra (*Abelmoschus esculentus*) with DG shoot phosphorus (P) content in general increased with increasing level of DG application; however, the P content with DG was more significant at 50% RDF when compared with its respective control (T2) in comparison with the observed increase with DG under RDF viz-a-viz its control treatment (T1). Increase in fruit P content was observed with DG irrespective of the dose and the NPK availability application to the soil. Different DG treatments, however, did not vary in terms of their fruit P content with an exception of (T8), which showed marginal decline when compared with T6, T7, and its control (T2). A significant increase in shoot S and the fruit S content was observed under the DG application irrespective of the DG dose and the NPK availability in the soil (T3-T8) when compared with the experimental control (T1 and T2). It so appears that the S application in okra (*Abelmoschus esculentus*) benefits the crop in improving its shoot and fruit S content (Figure 15).

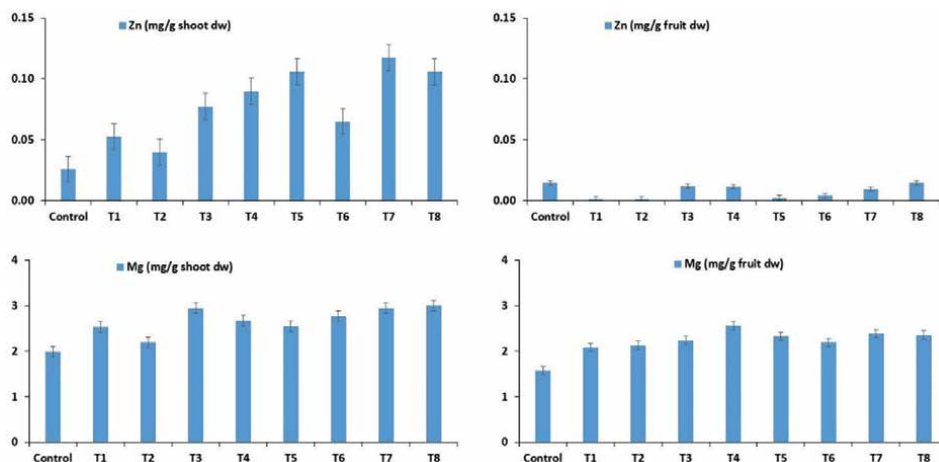


**Figure 14.** Effect of Dhurvi Gold (DG) on iron and manganese content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.



**Figure 15.** Effect of Dhurvi Gold (DG) on phosphorus and sulfur content of shoot and fruit of okra at harvest.

A look into the micronutrient content of okra (*Abelmoschus esculentus*) as affected by the application of DG and availability of NPK in the rhizosphere (**Figure 14**) shows a significant increase in shoot Fe content across DG application treatments (T3-T8), irrespective of NPK application treatments (RDF and 50% RDF) over their respective controls T1 and T2. A similar increase was also evident for the Fe content of the okra (*Abelmoschus esculentus*) fruit; however, the increase was dependent on DG application at RDF treatment. Fe content of the fruit was also higher with DG application at 50% RDF compared to its respective control (T2); however, the variation between treatments (T2-T6) was insignificant (**Figure 14**). Mn content of the shoot, on the other hand, increased at T3 but not at T4 and T5 when compared to



**Figure 16.** Effect of Dhurvi Gold (DG) on zinc and magnesium content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.

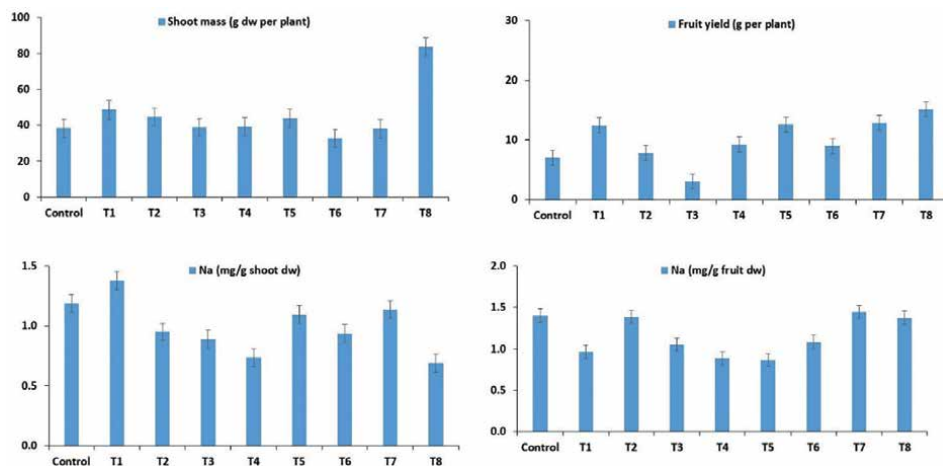
its respective control T1; however, at 50% RDF (T2), the supplementation of DG irrespective of the dose caused a more significant but similar increase in shoot Mn between T6 and T8 over its respective control (T2). Fruit Mn content, on the other hand, showed either a marginal or an insignificant increase in different doses of DG application (T3-T8) over the respective NPK controls (T1-T2) with an exception of T4, which showed a significant higher fruit Mn content (Figure 14). Observed variations in shoot and fruit Zn and Mg content as effected by DG treatment are shown in Figure 16. Shoot Zn concentration with DG doses 30, 40, and 60 kg S/ ha with 100% RDF had a slight increase when compared with its respective control (T1 and T2), whereas the shoot Zn concentration increased in T4 as compared to the controls (T1 and T2). Mg content with DG application in shoot and fruit did not show any significant change (Figure 16).

Here again, undetectable levels of heavy metal accumulation of Cr, Pb, and Cd were observed in the shoot and fruits of okra (*Abelmoschus esculentus*) at harvest under DG, irrespective of its dose of application with full or 50% NPK treatment.

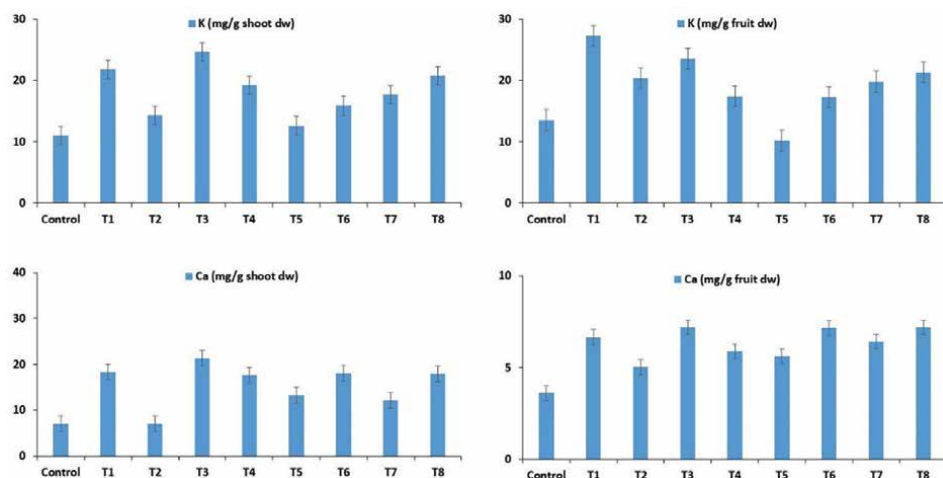
### 3.5 Effect of LD slag on okra (*Abelmoschus esculentus*)

Effect of LD slag on growth and yield attributes and accumulation of macro- and micronutrient and phytotoxic heavy metals of consequence (Pb, Cd and Cr) in the shoot and the fruit of okra (*Abelmoschus esculentus*) is presented in the subsequent sections.

Shoot mass was insignificantly affected by the application of LD slag except in case of T8 where the microbial interventions improved the vegetative growth of okra (*Abelmoschus esculentus*) (Figure 17). Fruit yield was also not affected by the application of LD slag alone but when complemented with microbial interventions (PSB and PSF), the fruit yield was improved over the T1, T2, and absolute controls. LD slag application alone without any biological amendment showed a reduced content of potassium in the shoot and the fruit when compared with all other experimental treatments (Figure 18). An increase in shoot and fruit K was observed at 100% NPK treatments either with or without LD slag. Biological amendment improved the shoot



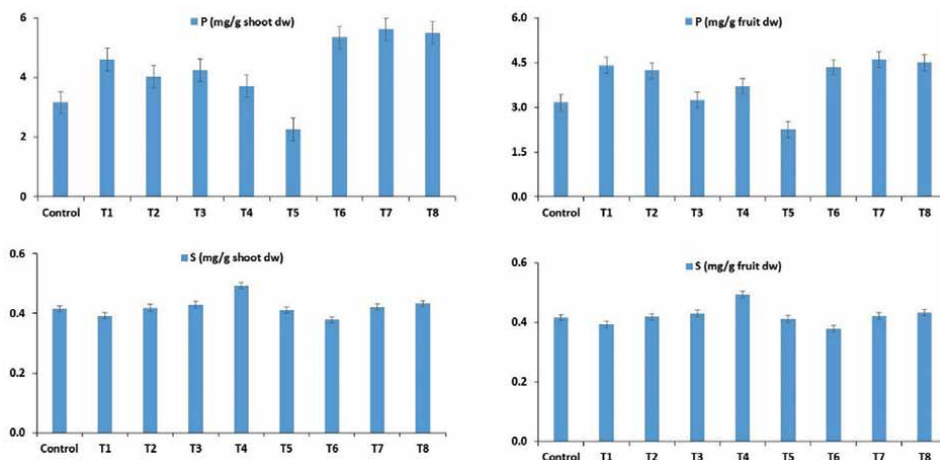
**Figure 17.**  
 Effect of LD slag on shoot mass and fruit yield of okra (*Abelmoschus esculentus*) at harvest.



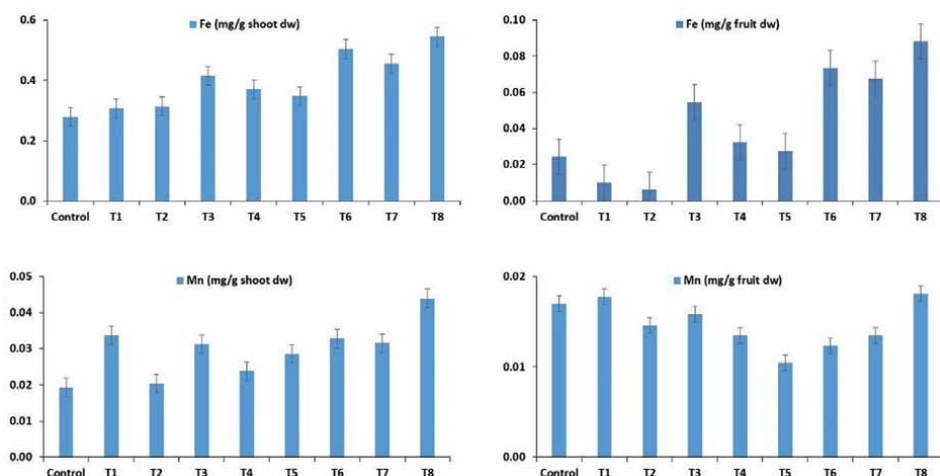
**Figure 18.**  
 Effect of LD slag on potassium and calcium content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.

and fruit K level when compared with the LD-slag-alone treatment (T5). A significant increase in shoot and fruit Ca was evident with LD slag application whether given with 100% or 50% NPK or with different biological amendments (PSB or PSF or their combination).

An increase in shoot and fruit P content was observed with PSB and PSF treatments or their combination, when co-applied with LD slag compared to the LD-slag-alone treatment (T5). A similar increase in fruit and shoot P was also evident under 100% or 50% NPK when compared to the absolute control (**Figure 19**). No significant variation in shoot and fruit S was observed across treatments of LD slag with 100/50% NPK or with the investigated biological amendments. A significant increase in shoot and fruit Fe content was observed with LD slag treatment when made alone (T5) or in complementation with 100% or 50% NPK (T3 to T4) or any of



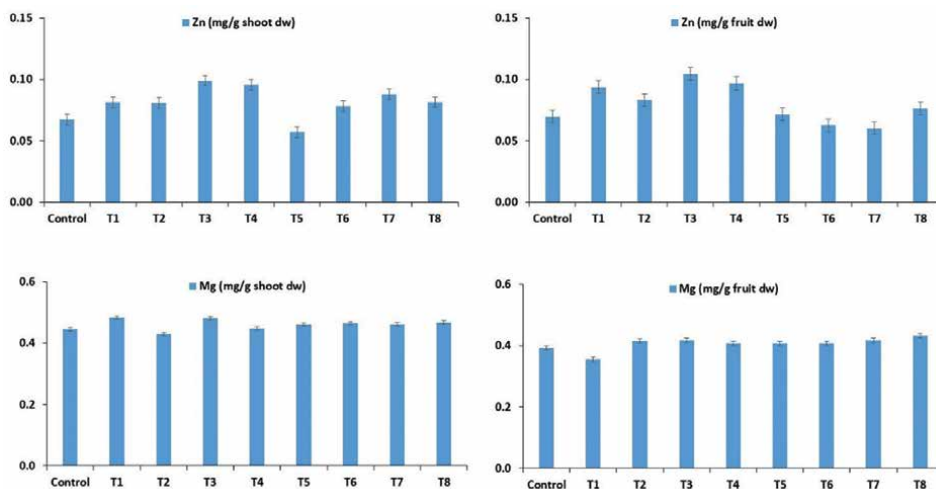
**Figure 19.** Effect of LD slag on phosphorus and sulfur content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.



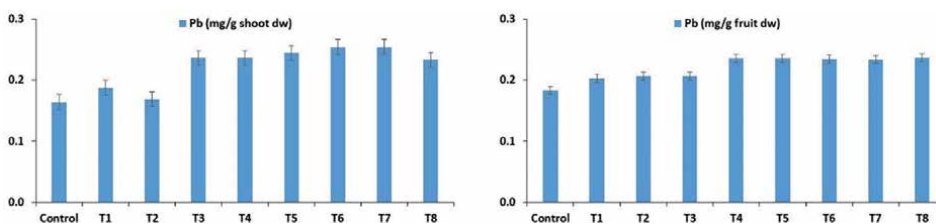
**Figure 20.** Effect of LD slag on iron and manganese content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.

the biological amendments (T6 to T8) when compared to the respective NPK controls (T1 and T2) and absolute control. An increase in shoot Mn was observed with 100% NPK and reduced at 50% NPK level when supplied either with or without LD slag. The LD-slag-alone treatment showed Mn level similar to 100% NPK treatments, and an increase in Mn content was observed with the biological treatments with the PSB + PSF combination treatment (**Figure 20**). More or less a similar pattern of response in terms of shoot Mn accumulation was observed in the fruits. However, shoot-to-fruit translocation of Mn was somewhat restricted or inhibited under LD slag alone (T5) (**Figure 20**).

A significant increase in shoot zinc but a decline in fruit Zn was observed when LD slag was applied. The highest content of shoot Zn was observed when slag was applied along with NPK, both at 100% and at 50% RDF levels (**Figure 21**). Biological amendments (T6 to T8) in comparison to LD slag alone increased the shoot Zn but reduced



**Figure 21.** Effect of LD slag on zinc and magnesium content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest.



**Figure 22.** Effect of LD slag on lead content of shoot and fruit of okra (*Abelmoschus esculentus*) at harvest (cadmium and chromium levels of shoot and fruit were below the detectable limit).

its translocation and accumulation in the fruits when compared with the fertilizer and absolute controls. No significant change in shoot or fruit Mg was evident under different fertilizer or biological treatments with or without LD slag application (**Figure 21**). An increase in shoot and fruit Pb level was observed with co-slag application (Treatments T3 to T8) when made with fertilizer or biological amendments compared to treatment and absolute controls. Undetectable levels of Cd and Cr were observed in response to LD slag application in okra (*Abelmoschus esculentus*) (**Figure 22**).

The above results on crop response to DG and LD slag across different crops indicate a genetic variation besides reasserting and underlining the observation that DG application is beneficial for improving the vegetative and the economic yield and their nutritional attributes. LD slag as such is not advocated for direct application; however, biological amendments can be useful in improving the advantages of the slag for plant growth and development. A positive effect of steel slag application on soil health, environmental stability and sustainability, and food security has also been suggested by Das et al. [28]. Das et al. [29] also showed a significant impact of steel slag amendment on soil biological activity and related enzymes. Further, an immobilization of heavy metal in presence of slag-based fertilizer has also been reported by Yang et al. [30]. In the present study, as such Pb but not Cd and Cr was detected in the shoot and the seed across the experimental crops. That too, the Pb content was lower

and within the prescribed permissible limits of phytotoxicity. Further, this study also elucidated the effect of application of such waste to wheat-products on heavy metal accumulation and leaching, which were found to differ insignificantly between 0 and 15 and 15–30 cm soil depth.

#### **4. Conclusions**

In conclusion, the value-added transformed slag, Dhurvi Gold, developed and for which the crop response was determined in the present study, is likely to open up new vistas for sustainable utilization of steel slag, which at the moment is a major challenge for the steel industry. Development of slag-based products in Dhurvi Gold background will not only help in remediation of degraded soils but also boost the economy of both the steel and the agriculture sectors in the years to come. However, the emphasis as is always should be laid on conducting a detailed phytotoxicity and risk assessment, across short- and long-term application studies, before making any recommendation for its use under the farm condition. The study also shows that the technological advancement in terms of the development of slag-based novel/customized nutrient supplements and fertilizers is now not a dream but a reality, which will also open up other avenues for the steel-agro-allied industry.

#### **Acknowledgements**

We acknowledge the pioneering contribution of late Dr. Shrinivas Ashrit who dedicated his life to add value to the LD slag waste and to develop Dhurvi Gold. We hope to nurture his dream of ensuing success of Dhurvi Gold in agriculture as a mineral nutrient supplement and soil conditioner. We also acknowledge the funding support provided by Tata Steel Limited and the laboratory facilities and infrastructure support provided by ICAR-IARI.

#### **Conflict of interest**

There is no conflict of interest relevant to the work under consideration.

#### **Abbreviations**

BF slag	blast furnace slag
BOF slag	blast oxygen furnace slag
EAF slag	electric arc furnace slag
LD slag	Linz-Donawitz slag
DG	Dhurvi Gold

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## Chapter 3

# The Conundrum: Transforming African E-Waste Landfills to Urban Mines

*Vusumuzi Maphosa and Pfano Mashau*

### Abstract

The amount of discarded electrical and electronic equipment (EEE), popularly known as e-waste, is rising alarmingly and drawing immediate attention from stakeholders. Governments in emerging economies support importing second-hand EEE to bridge the digital divide and allow communities to access the information super-highway. E-waste contains toxic elements deleterious to the environment and human health. Simultaneously, e-waste contains rare earth minerals that generate USD65 billion in revenue annually through recycling. Urban mining is reclaiming minerals from anthropogenic materials, reducing the extraction of virgin minerals facing depletion and with some sourced from unstable regions and conflict zones. The unidirectional flow of e-waste into Africa from the developed world is viewed as the re-colonisation and the carbonisation divide. Due to a lack of appropriate infrastructure and policies and low knowledge levels in developing countries, the management of e-waste is left to the informal sector, which uses rudimentary tools to extract rare earth metals. This chapter highlights the contentious definition of e-waste, its movement from the Global North, and its epidemiological and environmental impact. It advocates for setting policies and infrastructure to turn landfills and dumpsites into urban mines. This chapter also recommends that developing countries monitor the state of EEE imports and transform informal to formal recycling supported by coordinated collection and storage centres.

**Keywords:** Africa, knowledge economy, E-waste, E-waste management, sustainability, urban mining

### 1. Introduction

The world population has been steadily growing, developing countries have been experiencing urban population growth, and Africa has the fastest urban growth rate, estimated at around 3.5% [1]. Africa's urbanisation has not been matched by corresponding economic growth, service provision and job creation. The lack of job opportunities and the economic crisis in most African countries has resulted in the booming of the informal sector [2]. The rise of the knowledge economy has triggered our dependence on electrical and electronic equipment (EEE). Moreover, EEE is crucial to the country's social and economic development. It is inconceivable for modern

businesses and society to run effectively without EEE [3]. Cities depend on technological devices for efficiently and effectively managing their operations [3], thus fuelling the adoption of EEE. Humanity’s pursuit of a comfortable life has resulted in rapid changes in EEE design and functionality, shorter product lifespan, exacerbating obsolescence and raising the burden of electronic waste (e-waste).

E-waste refers to various EEE, from computer-related and telecommunications equipment, household appliances, solar, lighting and hospital equipment, that are discarded without any intention of reuse. The computer’s useful life declined from 5 years in 1990 to 2 years in the mid-2000s and will continue decreasing [4], thus fuelling e-waste. The life expectancy of small EEE such as cell phones, tablets, and laptops has been declining [5]. However, even working and meeting the functional requirements, EEE will be replaced due to obsession with the latest technology. The manufacturers also favour making new EEE products, and little effort is put into repairing old ones, referred to as design for obsolescence. Limited repair options, changes in consumer behaviour and frequent changes in technology resulting in shorter life cycles exacerbate the e-waste burden [6]. E-waste’s uncontrolled growth threatens the natural habitat and epidemiology.

E-waste generation is proportional to economic development worldwide. Based on the current consumption levels, e-waste output will reach 74.7Mt annually by 2030 from 53.6Mt in 2019 [7]. Only 17.8% of this colossal output was accounted for as recycled [6]. About 45Mt of e-waste is unaccounted for and was destined for dumpsites and landfills where it was improperly disposed of, causing public health and environmental catastrophes. Africa only produces 5.4% of the global output, but the transboundary movement of e-waste into Africa is alarming. The West illegally exports 80% of its generated e-waste to China, India and Africa [8]. Developing countries have witnessed a high demand for technological devices to participate in the knowledge economy [9], primarily met by importing second-hand EEE, which becomes e-waste quickly. E-waste management challenges are more significant in Africa, where only 0.9% of e-waste is accounted for and recycled, while 99% is unaccounted for, as shown in **Table 1** [6]. E-waste management schemes such as extended producer responsibility and licencing dealers for sorting and disassembling waste do not exist in Africa, thus making e-waste management an insurmountable task. Developing countries are adversely affected by the toxic threat from e-waste as they pursue radical technological development while lacking infrastructure, policies and knowledge to deal with the emergent e-waste crisis [10]. Less than a fifth of African states have policies for sustainable e-waste management compared to a 71% global average [6].

Region	E-waste generated in Mt	E-waste recycled in Mt	Percentage of e-waste recycled
Americas	13.1Mt	1.2Mt	9.4%
Europe	12Mt	5.1Mt	42.5%
Asia	24.9Mt	2.9Mt	11.7%
Oceania	0.7Mt	0.06Mt	8.8%
Africa	2.9Mt	0.3Mt	0.9%
Total	53.6Mt	9.56Mt	

**Table 1.**  
*E-waste generation and recycling by region [6].*

Some of the earth's rare metals, such as iridium, palladium, barium, terbium, europium, and gold, are used to manufacture EEE [11]. Similarly, EEE contains some of the most toxic elements, such as polybrominated biphenyls, cadmium, nickel, chlorofluorocarbons, lead and mercury. Precious metals, including palladium, iron, cobalt, gold, copper, niobium, titanium and aluminium, have over 50% re-usability rate [12]. The rare metals needed to manufacture the Olympics' 5000 medals (gold, silver and bronze) were recycled from about 79,000 tons of electronic devices donated by residents and 6.21 million used phones [7]. As shown in **Table 1**, over 80% of global e-waste is processed informally, releasing environmental pollutants [13]; concerted effort is required to address this problem. The biggest challenge with managing e-waste in the Global South is the lack of regulation, leaving e-waste management in the hands of the informal players, who determine handling and disposal methods [14]. The informal sector is characterised by marginalised communities and migrant workers who scavenge on e-waste to sustain a living. Illegal and informal workers recycle e-waste using rudimentary tools to disassemble gadgets and often burn components to extract valuable materials [5]. Burning and incineration release hazardous pollutants, causing environmental risks and health hazards. Toxic elements found at dumpsites leach into the soils, polluting water bodies and contaminating vegetation. In the Global South, e-waste is managed by informal workers concerned with feeding their families at the expense of epidemiological effects and environmental degradation. E-waste workers suffer from various cancers, dermal diseases and respiratory infections, while children, the elderly and pregnant women who live near dumpsites are the most affected [15].

E-waste represents a significant global challenge, but the challenges faced by the Global South, such as lack of awareness and knowledge and lack of infrastructure and policies, pose a more significant threat that requires immediate attention. However, little research, policy implementation and infrastructural investments for sustainable recycling are coming from the Global South. E-waste is the leading segment of solid waste and is generating serious management challenges due to the toxic elements contained [10]. E-waste contains rare earth metals, which must be harnessed to achieve global resource efficiency, but this requires proper recycling. The Global South must approach e-waste as a resource, not garbage; this will spur investment and development of the sector and integrate formal and informal recycling. The Global South's strength is its vibrant informal sector which can supplement the Global North by collecting and segregating e-waste, where complex components can be exported for further recycling. The informal sector's role in e-waste management is critical; apart from earning a livelihood, discarded equipment destined for landfills is repurposed through repairing and some usable parts are used to build new products. Recycling e-waste saves the environment and energy, reducing carbon emissions and demands for virgin materials.

## **2. Unidirectional flow of e-waste**

From the 53.7Mt of e-waste produced globally, Africa generates 2.9Mt but is home to some of the most notorious e-waste dumpsites, such as the Olusosun and the Agbogbloshe. The illegal movement of e-waste from the West into Africa is described as the re-colonisation of Africa and the decarbonisation divide [16]. History shows that the Global North has always exploited Africa through the slave trade and continues to plunder its natural resources. About 43Mt (80%) of global e-waste is illegally dumped into Africa and other emerging economies [17]. Developing countries are wood winked as e-waste is illegally dumped with the promise to bridge

the technological digital divide [10, 18]. The second-hand EEE exported into Africa would have reached its useful lifespan and immediately becomes non-functional and is discarded as waste into dumpsites and landfills. Most of the used EEE illegally dumped into developing countries is unusable, unrepairable, and detrimental to environmental sustainability and human health. It fuels informal recycling by poor communities who scavenge to recover precious materials [19].

Although Canada is legally bound by the Basel Convention, prohibiting the export of toxic waste, about 80% of its generated e-waste is shipped to emerging economies [20]. Some leading e-waste exporters into Africa are the United States (USA) and European countries, which distribute waste across the entire continent through Ghanaian and Nigerian ports [21]. Although the European Union is a global leader in environmental sustainability and governance and has strict laws in managing e-waste, it exports most of its used EEE to the Global South [22]. Worryingly, a fifth of the African countries enacted e-waste management policies, while less than 10% have appropriate infrastructure for recycling e-waste [21].

Most e-waste policies are mode around the Extended Producer Responsibility (EPR), which appropriates the disposal burden to the manufacturer. These policies favour formal e-waste management, where consumers return products to manufacturers for a fee. Manufacturers, therefore, design products knowing the need to repair, disassemble and recycle [23]. This approach does not work for Africa as there are no manufacturers, and most of the EEE is illegally exported second-hand with no warranties. Thus, the African e-waste policy should restrict illegal imports, apportion e-waste management responsibilities to the importer, and integrate with the informal sector. African policies must reflect the current and existing realities. E-waste presents negative and positive outcomes to recipient countries; those capable will extract the rich materials in e-waste can spur economic development. At the same time, those with infrastructural limitations will expose citizens and the environment to the hazardous effects of e-waste.

It costs \$72,000 to adequately recycle a ton of e-waste compared to \$500 per ton to ship e-waste to developing countries [24, 25]. Iqbal et al. [26] aver that developed countries avoid e-waste recycling expenses and disposal responsibilities by illegally exporting their generated e-waste to the Global South, with no infrastructure, policies or knowledge to manage e-waste. In the digital space, the Global North uses Africa as a corridor to transfer e-waste negative externalities, where there is clear evidence of a lack of capacity to manage e-waste sustainably [27]. Considering its epidemiological and environmental effects, such as ecological injustices, and human fatalities, the e-waste movement implies the uneven transfer of the global burden and unjustifiably exposes the vulnerable in developing countries.

Due to a lack of employment opportunities, corrupt governments and underperforming economies, the urban poor and vulnerable groups have grabbed the chance to manage e-waste informally. The informal sector in developing regions such as Africa drives the demand for e-waste into the region as an active player in the e-waste value chain. The chapter considers the e-waste conundrum in Africa, its flow from the Global North, its epidemiological and environmental impact and how urban mining can assist in preserving virgin minerals and saving the planet.

### **3. The economic value of e-waste**

Urban communities in developing countries have turned the e-waste problem and emergent threat into an opportunity to manage its accumulation by salvaging

precious metals to make a living and find employment [27]. Thus, e-waste presents an excellent opportunity for the informal sector in the Global South to export high-end components to the Global North for high-tech processing, thus turning cities into rich urban mines. To harness the potential economic benefits of e-waste, countries should set up e-waste policies and acquire infrastructure for proper recycling. Only 13 African countries have e-waste policies [28].

The world produced 53.7Mt of e-waste in 2019, and revenue from recycling was estimated at around \$65 billion, higher than most African countries' gross domestic product (GDP) [28]. Less than 1% of rare earth minerals used to manufacture devices and components are recycled [29]. Some metals are extracted from volatile war-torn countries, and some have inconsistent policies that upset the value chain. Recycling these minerals will reduce dependency on unstable and high-risk countries while sustainably managing e-waste. By 2016, the world recycled 500 million tons of e-waste, and the precious minerals recovered and redirected into the manufacturing sector exceeded over \$160 billion [30]. This contributed immensely to the reduced exploitation of virgin minerals, although it is less than 10% of the e-waste.

Over 300 tons of gold are used annually in the manufacture of EEE, and through formal recycling, all this gold can be recovered and alleviate pressure on conventional mining [31]. China collected and recycled 88.84Mt of recyclable waste earning \$34.85 billion, which helped meet its demand for raw materials [32]. High-yield components include printed circuit boards (PCB), processor chips, wind turbines and batteries. PCBs contain 40% of all valuable materials embedded on all the boards [33]. A ton of PCBs can contain up to 1500 kgs of gold and 210 kgs of copper [34].

Collaborations between the Global North and South have seen Rwanda, Tanzania and Kenya partner with Wordloop in setting up recycling plants, resulting in over 25 tons of PCBs being exported to Unicore in the Global North for high-end recovery of precious metals [27]. This has the potential to recover gold worth millions. The economic value of e-waste is incredible; recycling a million discarded phones produces 24 kgs of gold, 250 kgs of silver and several minerals such as palladium and tantalum [35]. Developing countries should turn the e-waste burden into viable economic activities to sustain livelihoods. Although unregulated, informal e-waste activities in Ghana play a vital role in economic development. The sector realises nearly \$268 million in annual revenue, and over 200,000 people sustain a livelihood directly from managing e-waste [36]. Of all the informal sector jobs in the Global South, e-waste is proving to be one of the most lucrative, where scrap dealers make \$50 per day, intermediaries make \$35, and waste pickers make \$3.50 per day, almost three times the daily average earnings [37]. Developing countries should enact policies and set up infrastructure that supports the collection, aggregating and intermediary processing of e-waste. At the same time, rich and highly toxic waste can be exported to developed countries for optimal recycling. Aggeri [29] proposed leaner manufacturing, repairing and recycling end-of-life products to recover materials which can be used for manufacturing new products, forming an endless loop. Developing countries must embrace the circular economy, which creates a closed loop where resources flow and re-circulate through the economy.

#### **4. Environmental impact and health hazards**

Several toxic elements are used to manufacture EEE, which, if not handled appropriately, is deleterious to public health and the environment. Maphosa and

Maphosa [38] highlight that over 1000 substances are used to manufacture EEE; these include toxic elements such as arsenic, polybrominated flame retardants, cadmium, lead, barium, lithium and mercury. Sabra et al. [39] report that over 50 tons of mercury and 71 kilotons of flame retardants are released annually into the air, land and water through informal e-waste recycling. Research reveals that informal recycling activities in Africa released 9.4Mt of CO<sub>2</sub> and 5.6Kt of brominated flame retardants from illegally imported e-waste [23]. Perkins et al. [13] reported that toxic elements contaminate the environment as informal e-waste workers recover precious metals through burning and incineration, threatening the habitat and public health. Research reveals that a cell phone battery contains lithium and cadmium, which can pollute 600 litres of water [38, 40]. E-waste workers and communities living around dumpsites are unaware of the toxic chemicals found in e-waste. Virgin mining and illegal dumping of e-waste are some human activities causing the planet's deterioration.

When e-waste is indiscriminately recycled using rudimentary tools without environmental consciousness, toxic leachates flow into the environment, contaminating potable water sources and poisoning vegetables and fruits in the surrounding dumpsites and landfills [41]. Research reveals that Ghana's Korle Lagoon and Odaw River are heavily contaminated with e-waste toxins, which has heavily impacted the marine life ecosystem and supply of portable water [42], and poisoned fruits and vegetables. Up to 20% of farming and grazing land has been wiped out by irregular e-waste recycling in China, Ghana and Nigeria [38]. Heavily contaminated soils have infertile top soils, which decreases crop yields leading to malnutrition, hunger and various diseases. Around the Agbogbloshie, lead concentration was 18,000 parts per million against the 400 parts per million recommended by the United States Environmental Protection Agency [42]. Open incineration and burning of plastics release carbon and other toxic elements that damage the ozone layer, leading to global warming [43].

Communities engaged in informal e-waste management are exposed to diseases such as blood disorders, congenital disabilities, nausea, asthma, lung diseases and depressed immune systems. Pregnant women miscarry due to high exposure to lead [44]. Exposure to toxic fumes from acid leaching and incineration damages the respiratory system. Fatalities are high among communities living in the periphery of dumpsites and landfills [45]. Cadmium is a heavy metal found in e-waste, human exposure through inhalation and ingestion results in damaged liver, lung and testis. It may cause dysregulation of blood pressure, disturbed metabolism and the immune system while affecting the bone formation and structure [46]. The World Health Organisation (WHO) reports that 12.9 million women engaged in informal recycling are exposed to toxic elements that harm them and their unborn babies [47]. Studies in Bangladesh revealed that 36.3% of women involved in informal recycling and those living in the surrounding sites experienced stillbirths due to exposure to toxic elements. Additionally, 64% had hearing and visual problems [48].

Another study in China's Guiyu province, which has the largest dumpsite in the world, revealed that women living around the site suffered more stillbirths than expected [49]. E-waste workers at the famous Agbogbloshie dumpsite suffer from gastrointestinal, respiratory and various cancers [50]. Urine and blood samples from informal recyclers in Ghana revealed high levels of lithium, zinc, arsenic, copper and barium, all heavy and toxic metals [42]. Scholars have advocated for tighter penalties and forbidding the illegal transboundary influx of e-waste into emerging economies from the West due to the catastrophic effects on the environment and health.

## **5. Bottlenecks to managing e-waste**

E-waste collection is a fundamental phase of urban mining and the approach to the circular economy; if managed properly, it can support the formal sector by aggregating high-end and material-rich components [51]. Developing countries do not have policies and legislation to guide the gathering, separation and disposal; therefore, e-waste is discarded with municipal waste into urban dumpsites [38]. Scholars note that if information is lacking and infrastructure is unavailable, it becomes difficult for consumers to dispose of e-waste [52] responsibly. The informal sector is vital in organising e-waste according to its status and channelling repairable products into the second-hand market, where they are reused. In contrast, unreparable EEE is directed for formal recycling [53].

In the Global South, e-waste management is spearheaded by the informal sector, but one of the key challenges is developing sound recycling and disposal systems [54]. Africa's expansive and highly organised informal sector is a critical bottleneck for its management. Restricting the movement of e-waste in Africa is difficult due to inadequate regulatory framework and porous borders, where 80% of the countries have no policies, which also stifles internal e-waste management [55]. Some African government e-waste policies need fine-tuning to integrate the informal sector into formal recycling for maximum efficiency and effectiveness [16]. Africa's borders are porous and riddled with corruption. Effective e-waste management will require a collaborative effort between customs officials, environment ministries and other arms of government.

To effectively manage e-waste, the narrative that labels informal e-waste recyclers as polluters of the environment has to be changed through raising awareness and training to encourage the sound disposal of e-waste. Such cynical imaginaries are critical in re-arranging circuits and influencing material and financial outflows [56]. It will be impossible to do away with the informal sector in Africa; policies being crafted should aim to integrate it with the formal sector. This will enable the informal sector to collect, separate and perform low-level recycling while allowing the formal sector to perform high-level recycling, thus promoting efficiency and harmony in the supply chain [57]. Other scholars lament using terms such as scavenging and informal as pessimistic, biased, and wrongly portraying the e-waste phenomenon [58].

The informal sector creates many job opportunities for the local communities. It assists in supplementing municipal services in keeping the cities clean and should, therefore, be integrated into the formal structures [59]. Actors in the Global South must begin to recognise e-waste as a supply of rare earth metals capable of extending and creating new business opportunities. Appropriate infrastructure to recycle e-waste will reduce the continent's dependence on virgin minerals and extend their availability to other generations.

## **6. Urban mining**

EEE manufacturing uses precious metals extracted through virgin mining, threatening environmental sustainability. The mining operations often upset the earth's core resulting in natural disasters. Humanity is challenged to innovate and use natural resources sustainably, recover minerals from e-waste and preserve virgin minerals that face extinction. Urban mining is the recovery of precious minerals contained in anthropogenic materials and discarded gadgets thrown into landfills in urban environments [6]. Extracting virgin minerals is sometimes impossible or

very expensive; urban mining becomes a viable method to extract rare earth minerals from anthropogenic materials [60]—urban mining results in environmental, economic, and social catastrophes without regulation and control. When regulated and controlled, urban mining creates employment opportunities and supports the livelihoods of communities that recycle e-waste. China has built 109 state-of-the-art formal recycling plants nationwide, certified based on strict environmental protection standards and financially supported by government subsidies [61]. The Chinese model is ideal for Africa, where 90% of the e-waste is collected by the informal sector for formal recycling plants, which comprise waste pickers, intermediaries and dealers. Informal recyclers sift, separate and classify e-waste components as usable, repairable or ready for recycling [27].

Urban mining is part of a broader concept known as reverse logistics, which encompasses the reuse and sustainable recovery of materials through the collection, dismantling and processing of used products which become raw materials in an environmentally sustainable manner [62]. Urban mining ensures the recovery of precious materials, minimises improper disposal of e-waste, creates formal employment, reduces health challenges from improper handling, and increases consumer and institutional awareness. Urban mining creates ‘green jobs’, supporting a circular economy. Urban mining will reverse the environmental ills caused by indiscriminate e-waste disposal [63]. Raw materials are reclaimed from discarded goods and reintroduced into the economy through recycling, reducing the waste of finite resources and prolonging the lifespan of products and resources. The growth of cities in developing countries due to rapid urbanisation is exponential to the e-waste quantities and burden.

Urban mining ensures resource sufficiency by tapping into the rich stream of critical raw materials recovered from e-waste, protecting the environment and human health [64]. Governments are battling with the gobbling up of non-renewable resources, depletion of natural materials, dependence on minerals from conflict zones and the need to reduce the catastrophic effects of improper e-waste handling on the environment and human health [65]. Urban mining can save gold and silver deposits destined for interment, worth \$21 billion annually destined for dumpsites and landfills [44, 66]. Billions are lost in revenues annually as only 15% of e-waste is recycled [63]. Reverse logistics transform e-waste into urban mines, rich in the concentration of rare earth metals [27]. As cities are primary markets for EEE, discarded EEE provides concentrated ore of rare earth metals; StEP reported that mineral ores in urban mines were 50 times richer than traditional ones [66]. Urban mining creates jobs and sustains livelihoods by reclaiming raw materials and introducing them into the manufacturing industries [67].

To continue extracting finite virgin minerals, novel ways will be required to exploit deeper and more complex natural deposits, proving uneconomic. Extracting minerals from landfills will become cheaper and more feasible. Research reveals that mining a ton of conventional ore will yield 5 grams of gold, compared with 300 grams of gold recovered from a ton of discarded cell phones [63]. Urban mining is likely to be 50 times richer than conventional mining. A ton of PCBs contains about 800 times more gold and 40 times more copper than a ton of conventionally mined ore [68]. The recovered materials are reintroduced into the production lines by exploiting anthropogenic stocks destined for landfills and dumpsites [65]. It is 13 times cheaper to recover metals from e-waste ore than conventional ore; thus, urban mining is an alternative to virgin mining and promotes a circular economy where resources

re-circulate [69]. Urban mining saves on electricity and CO<sub>2</sub> emissions. About 1.1 tons of CO<sub>2</sub> are emitted to extract an ounce of gold through conventional mining, and 220 kgs of CO<sub>2</sub> per ounce of gold through urban mining [7]. Researchers revealed that it costs \$1591 for a one-kg ingot of gold through urban mining and \$33,404 for a one-kg ingot of gold through conventional mining [70].

China is extensively exploiting urban mining to meet its mineral requirements for manufacturing EEE [71]. The informal sector dominates most African economies, which is the primary driver of the circular economy. Decent jobs can be created through urban mining, in line with the International Labour Organisation's goal of transforming the informal sector and creating formal jobs for many people in developing countries [72]. The recovery of rare earth metals is currently low; failing to extract the precious resources efficiently will strain dependence on virgin materials [73]. Urban mining can transform the e-waste burden into sustainable waste management that creates jobs, protects the environment, reclaims recyclables and recirculates rare earth minerals into manufacturing industries [68].

The informal sector in the Global South can partner with high-tech recyclers in the Global North for high-value processing. Urban mining integrates informal and formal e-waste recyclers, whereas the informal sector does manual disassembling. The formal sector handles the final recovery of precious metals and disposal [59]. Oteng-Ababio and Amankwaa [74] proposed a federated model where the advantages of each method are integrated, where the informal sector collects, dismantles and segregates e-waste. Meanwhile, the formal sector uses high-tech equipment for the final recycling of complex e-waste [74]. Urban mining assists in creating formalised jobs in the informal sector, where it becomes easy to train and educate on e-waste management [5]. This will be ideal as it will allow the informal sector to be part of the global e-waste ecosystem. It is difficult to eliminate the informal sector in emerging economies; in the Global North, formal recyclers worry that the informal recyclers illegally strip high-value waste components, depriving formal recycling channels of the minimum quantities required to operate [60]. Optimal and high-end processing is done in high-tech refineries in the Global North [75].

The first step in urban mining is waste picking, where e-waste is reclaimed and channelled to recycling centres. Most waste pickers are vulnerable members of society who may face stigma and hostility and require protection through policies legalising their work. E-waste is assessed, with some gadgets being repaired and re-used in repairing broken components and creating functional devices, while some waste is destined for recycling. Plastics, glass and metal are recovered through disassembling and incineration and sent for recycling. At this stage, recyclers use rudimentary tools to dismantle e-waste. The waste is sorted based on the usability of the components or the presence of toxic compounds [76]. Basic techniques such as hydrometallurgy and pyro-metallurgy recover the precious metals [76]. Thus, e-waste is transformed from waste to raw materials used to manufacture different products. Complex e-waste components, highly toxic and rich in deposits of rare earth metals, would be exported to the Global North, where the final processing is done using state-of-the-art facilities [59]. Although complete recycling of complex e-waste is limited in most African countries, collaborations with partners with state-of-the-art equipment are necessary to complete the process [76]. Recyclers reported marginal profits of between 25 and 30%; hence, urban mining can be a source of livelihood, aggregating different players in the e-waste value chain [44].

## **7. Conclusions**

Africa is witnessing increased demand and ownership of EEE as the continent actively participates in the knowledge economy. Rapid changes in product design, the Internet, and social media have increased the use of EEE within Africa. Due to poor economic activities in most African countries, citizens afford second-hand EEE, rapidly fuelling e-waste accumulation. The demand for second-hand EEE is not balanced against environmental concerns, as these quickly become e-waste. About 80% of African countries have no regulatory framework to effectively manage the growing e-waste burden and increase reuse and recycling. The lack of import restrictions on e-waste, the ever-increasing urban population, and the lack of formal employment opportunities have presented e-waste as a treasure trove to the informal sector, which has crafted ways to eke a livelihood. As e-waste management is unregulated, the informal sector often prioritises supporting livelihoods against sustainable means of recovering precious metals found in e-waste. Research shows the tremendous overall value of recycling through reduced environmental impact, employment creation and supporting the livelihoods of millions of urban dwellers. The lack of policies, infrastructure, financial resources and skills, and knowledge makes managing e-waste a difficult task in the Global South.

Countries in the Global North are exporting about 80% of their locally generated e-waste to the Global South. The informal sector in developing countries drives demand for used EEE, which creates employment for millions in informal recycling. Informal e-waste workers know little about the epidemiological and environmental impact of irresponsible e-waste disposal. The lack of formal recycling infrastructure results in using rudimentary tools to recover precious minerals, burning and incineration to separate plastics from metals, releasing toxic elements into the environment. It exposes workers through inhalation, ingestion and dermal exposure. Soils, water bodies and the environment are polluted, resulting in many respiratory diseases, cancers and human organ failure. Illegal e-waste dumping and the exploration of virgin minerals are depleting the planet. The informal sector views e-waste as a resource for sustaining their livelihoods; attempts to enhance the management of e-waste must embrace informal sector activities in an environmentally sound and sustainable way.

Urban mining can potentially halt the planet's deterioration by reducing the burden of raw materials from virgin mining and ensuring that e-waste is correctly disposed of. Developing countries must enact policies that address their local needs. For most African countries, such regulations must recognise the role played by the informal sector in the e-waste management ecosystem. The informal sector should be partnered in collecting, segregating and classifying e-waste, where low-level recycling in safe environments is permitted. The informal sector collects e-waste for channelling into the formal system, which requires planning to ensure constant supply to the formal sector. Once the informal sector has been integrated with the formal sector, there is a need for continuous education and raising awareness of its potential and epidemiological concerns. The informal sector must have better access to funding and technical support and equipped with the right tools. E-waste components that require high-end processing will then be sold to the formal sector with state-of-the-art recycling equipment. If such technologies are not yet available in developing countries, partnerships with recyclers in developed countries can be accessed to complete the loop. This portrays e-waste management as a partnership and shared responsibility to protect the planet. Regulating urban mining will be critical to achieving a circular economy that preserves resources and protects the earth.

## 8. Recommendations

To transform African e-waste landfills into urban mines for extracting rare earth minerals to be used as raw materials, the epidemiological and economic dichotomy must be addressed to manage e-waste in Africa effectively by considering the following:

- Policies should aim at integrating the informal and formal sectors and account for the operational dynamics to transform e-waste into a treasure trove.
- Regulators must not disrupt the current model and realities but ensure that current practices are environmentally sound through training and awareness and provide access to finance for equipping the informal sector and tightening porous borders.
- The EPR model will not work in Africa, and therefore, a hybrid model that appropriates e-waste management responsibility to importers, exporters, and consumers should be considered.
- Governments should provide tax rebates for e-waste recycling infrastructure and promote research and development.
- Environmental management courses incorporating e-waste management should be taught at lower and higher levels of education.

## Conflict of interest

The authors declare no conflict of interest.

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## Chapter 4

# Treatment of Industrial Wastewater

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### Abstract

In industrialized countries, there is a great diversity of the specificities of manufacturing processes and means used for industrial wastewater treatment. The developments that these processing problems can allow are immense, given the many production sectors. Faced with this situation, we have developed in this work the essential ideas concerning the problems of the treatment of very particular effluents from industrial establishments, the conditions to be met by the discharges and the different treatment methods: primary, secondary and tertiary. Examination of these types of treatment allowed us to divide industrial effluents into four categories.

**Keywords:** industrial wastewater, treatment methods, industrial sludge, requirements, processing plant

### 1. Introduction

In a number of regions, industrialization is developing which requires a call for labor and the formation of large groups of people, at the same time many buildings, houses, shops, and factories are being built [1]. The resulting discharges of domestic and industrial wastewater are abundant and the region is therefore naturally affected by pollution. The gross pollution produced by industry must be equivalent to a population of 90 million. It is currently estimated that 1/5th of the industrial water is connected to public networks, the 4/5th being isolated and probably treated inside the plant [2].

Collective sewerage is the preferable solution, as far as possible, for urban wastewater and, under certain conditions, for industrial effluents, which by their qualitative characteristics, are likely to transit through the public network [3]. All mixed water can then be treated by the community's wastewater treatment plant. It is then said that this is a mixed treatment [4].

First, we must be aware that industrial development is changing rapidly in terms of quality and quantity. Attention should be paid to the quality characteristics of industrial effluents and their nature by classifying wastewater and waste liquids:

- Wastewater is used for washing appliances and machines, refrigeration...; may contain chemicals;
- Waste liquids result from manufacturing, such as acidic substances from emptying metal pickling tanks or toxic chemical solutions.

Wastewater can often be treated more easily than waste liquids, however, these can contain interesting products to recover. The growing interest in the recovery of industrial waste and by-products is linked both to the energy crisis, the reduction of the world's raw material resources, and for many countries the need for increasingly expensive imports, and finally the legislation, which is becoming very strict concerning the protection of nature and the environment [5].

Each production sector can work to reduce pollution and optimize waste. To this end, it can:

- In particular, recovering settling sludge with a view to saving energy, composting or recycling raw materials;
- Detoxify certain sludge materials through incineration or biodegradation.

## **2. Source of effluent**

Effluent from mills is of two kinds:

- Domestic effluents including storm water and water from the sanitary services and canteens of the establishment;
- Effluents of a clearly industrial nature originating from workshops and due to the plant's own activity are wastewater of different origin requiring either specific treatment, mixing, or recycling (mineral washing water, cooling water, etc.).

Public sewers under the same conditions must receive the former as water of identical nature from the other funds of the agglomeration; of course, this presupposes the existence within the establishment of a separative network.

The second part of the effluent can be received in the sewer system under certain conditions, pre-treatment, with the agreement of the community and sanitary services or be refused in the public network.

## **3. Conditions to be met by wastewater discharges**

### **3.1 Evacuation routes**

There are various ways of discharging this wastewater, including:

- Public sewerage networks provided downstream of a treatment plant;
- Natural environments used directly or through a public sewerage system without a treatment plant;

Discharge of industrial effluents into the natural environment	1st case: Discharges far from city water supply intakes, beaches, shell beds		2nd case: Discharges near the water intakes of town beaches, bank of shells	
	Industrial pollution-load			
	Weak	Important	Preponderant	
a <sub>1</sub> ) pH-General case	5,5 < pH <8,5	5,5 < pH <8,5	5,5 < pH <8,5	5,5 < pH <8,5
a <sub>2</sub> ) pH in the case of lime neutralization	5,5 < pH <9,5	5,5 < pH <9,5	5,5 < pH <9,5	5,5 < pH <9,5
b) Maximum temperature	30°C	30°C	30°C	30°C
c) Cyclic hydroxyl compounds and their halogenated derivatives	Prohibited	Prohibited	Prohibited	Prohibited
d) Substances likely to promote the manifestation of odors, flavors and abnormal coloring in natural waters used for human consumption	Prohibited	Prohibited	Prohibited	Prohibited
e) Substances liable to ignite	Prohibited	Prohibited	Prohibited	Prohibited
f) Total suspended solids	100 mg/L	50 mg/L	30 mg/L	30 mg/L
g) Substances capable of causing the destruction of fish downstream of the discharge	Prohibited	Prohibited	Prohibited	Prohibited
h) Radiation hazard substances	Prohibited	Prohibited	Prohibited	Prohibited
i) Additional requirements for physical criteria:				
• Conductivity				
• Decantable materials				
j) BOD <sub>5</sub>	200 mg/L	100 mg/L	40 mg/L	40 mg/L
k) Total Kjeldahl Nitrogen (TKN)	6 mg/L in N	30 mg/L in N	10 mg/L in N	10 mg/L in N
	80 mg/L in NH <sub>4</sub>	40 mg/L in NH <sub>4</sub>	15 mg/L in NH <sub>4</sub>	15 mg/L in NH <sub>4</sub>
l) Additional requirements for chemical criteria:				
• Dissolved oxygen, oxidability to potassium permanganate,				
• Phosphates				

Discharge of industrial effluents into the natural environment	1st case: Discharges far from city water supply intakes, beaches, shell beds		2nd case: Discharges near the water intakes of town beaches, bank of shells
	Industrial pollution-load		
	Weak	Important	Preponderant
m) Dilution $d$ (ratio spill in 24 h between the flow of the watercourse and the flow of the effluent) according to the duration of the industrial discharge spill in 10 h	$d > 300$ $d < 720$	$150 < d < 300$ $360 < d < 720$	$d < 150$ $d > 360$

**Table 1.** Requirements for discharges of industrial effluents to the natural environment.

- Specially constructed engineered absorbent wells (filter wells);
- Soil used by application under certain conditions for natural purification, but does not include deep geological layers.

Releases of industrial effluents to the natural environment must meet the requirements summarized in **Table 1**.

### 3.2 Discharge requirements

According to the general requirements, it is stipulated that in all cases, liquid industrial discharges must have the following characteristics [6]:

- a. pH between 5,5 and 8,5 (if the effluent is neutralized by lime, the pH may be between 5,5 and 9,5);
- b. Temperature less than or at most equal to 30°C;
- c. Absence of hydroxylated cyclic compounds from the phenol series and their halogen derivatives;
- d. Absence of any coloring substance or substance likely to give off foul odors and abnormal flavors;
- e. Absence of any substance likely to ignite directly or indirectly after mixing with other effluents, or to release toxic vapors;
- f. Absence of floating materials or any substance harmful to the proper functioning of the evacuation and treatment works;
- g. No substances that may affect aquatic wildlife downstream of the point of discharge;
- h. No risk of radiation to the neighborhood;
- i. There are also additional requirements for physical criteria, such as conductivity, decantable materials in cm<sup>3</sup>/L in 2 h;
- j. Chemical or biochemical criteria such as nitrogen and dissolved oxygen in mg/L, BOD<sub>5</sub> in mg/L, and oxidability to potassium permanganate in mg/L.

It should be added that some wastewater has high concentrations of phosphates. Phosphorus removal is essential to prevent eutrophication of lakes.

## 4. Industrial wastewater treatment methods

From the point of view of terminology, we say “purification” when it comes to domestic or rainwater wastewater, but we say “treatment” when dealing with industrial wastewater; these two words each represent a particular specialization.

Since industrial wastewater does not have the characteristics of a domestic-dominated effluent, it is often necessary to impose pre-treatments or treatments on manufacturers. For this wastewater, after settling for 2 hours:

- COD greater than 750 mg/L;
- COD/BOD<sub>5</sub> report 2,5;
- Suspended solids > 300 mg/L.

The processes of pretreatment and treatment of industrial wastewater have a large number of points in common with urban water treatment processes. Thus, the techniques used in the treatment of industrial effluents obviously include those used in urban wastewater, but they also include processes that are more specific to them. The latter processes include settling, sieving, flocculation, flotation, electrocoagulation, ion exchange, lagooning [7], physicochemical processes [8], and reverse osmosis.

All these considerations lead to consider two treatment hypotheses:

- The first is that of mixed treatment, that is to say that industrial effluents are discharged into an urban wastewater network and that an appropriate pre-treatment deemed essential; very often, industrial waste effluents and urban wastewater are located in the same area, at first glance, it may be interesting to carry out their respective purification using a common structure. But the problem is not so obvious for several technical, operational and financial reasons that are interpreted at the level of reciprocal responsibilities. The operation of the public wastewater treatment plant must remain as permanent as it was initially, so the contribution of the industrial effluent must not profoundly upset the nature of the wastewater to be purified.
- The second is the case of a major industrial establishment discharging its effluents directly into the natural environment, treatment is ordered by the health regulations of the department and the municipality.

Each of these two eventualities must be examined [9]. The definition of any treatment must take into account [10]:

- From the drainage system of public sewers and the possible separation of effluents, it is often useful to isolate certain effluents, this is necessary when the flow of industrial wastewater contains a high concentration of toxic materials;
- The nature of the effluents, that is to say the daily volume, the minimum and maximum hourly flow rate, the continuous or discontinuous manufacture of plant products, the extent and periodicity of the pollution peaks, and the possibility of separation of the discharge circuits;
- Of the nature of all pollutants, without forgetting one, otherwise the proper functioning of the station will be disrupted;
- Optimum choice between the various treatment systems.

#### **4.1 Pretreatment (case of mixed treatment) homogenization basins**

If it is accepted that the treatment of urban wastewater is generally satisfactory through the application of biological processes, the treatment of the mixture must be possible without complications for the municipality. It is then necessary to ensure that the extreme characteristics of the effluents are known and respected and that the dissolved oxygen (O<sub>2</sub>) content is always sufficient. It is also essential to specify the dilution rate of domestic wastewater and industrial water, in order to regulate flows, by creating “homogenization basins”. It is also essential that the normal operation of the public network and treatment plant is not disrupted.

Physical pretreatment devices such as desalination, screening, sieving, degreasing or de-oiling can also be installed in the plant.

It is also possible to clarify raw water pH between 6,5 and 8,5 to reduce BOD<sub>5</sub> and COD. Prior neutralization by lime or NaOH soda is essential if the pH of the raw water is outside the 6–9 interval. De-oiling is very important because the greases reduce the water-air exchanges necessary for biological purification and clog the pipes.

In some cases, the elimination of toxic substances by flocculation-oxidation processes by chemical means is required.

It is reasonable to note that the implementation of the joint treatment of industrial effluents and urban wastewater only seems possible if there is a good understanding between the industrialist and the communal community.

#### **4.2 Treatment processes specific to industrial effluents (case of release into the natural environment)**

As in the case of urban waste water, these special treatments for industrial waste water make it possible to separate, on the one hand, the treated water and discharged into the natural environment and, on the other hand, to collect a certain number of wastes in the form of sludge. This design can be modified if the manufacturer intends to recover a significant number of reusable products. It is therefore understandable that this situation justifies the diversity of specific treatment processes for industrial waste effluents [11].

##### *4.2.1 Preliminary treatments*

They include:

- Screening, desalination by settling in ponds or by centrifugation or by cyclonation;
- Degreasing using the grease separator;
- The de-oiling by means of oil interceptors or by flotation, the latter process consisting of producing, in an effluent containing fine particles of oil in suspension, an upward flow of gaseous bubbles capable of capturing the particles in passing, and drive them to the surface where they are mechanically skimmed. Flotation can be improved in some cases by the development of commonly applied aeroflotation or electro-flotation; in the latter process, gaseous bubbles are produced by the electrolysis of effluent [12].

#### *4.2.2 Primary treatment*

These processes are available:

- Settling by gravity with or without coagulation and flocculation, and settling by separation by overflow in an upward circulation of the effluent;
- Effluent electrolysis flotation (electroflotation);
- Sieving by passing water through sieves with more or less fine meshes;
- Centrifugation with coagulation of suspended matter;
- The so-called stripping process for the elimination of gases (phenol, nitrogen) and the elimination of odors;
- Neutralization of too acidic or too alkaline waste water, chemically (lime or sulfuric acid, soda);
- Physical and chemical elimination of SS (coagulation-flocculation).

#### *4.2.3 Secondary treatments*

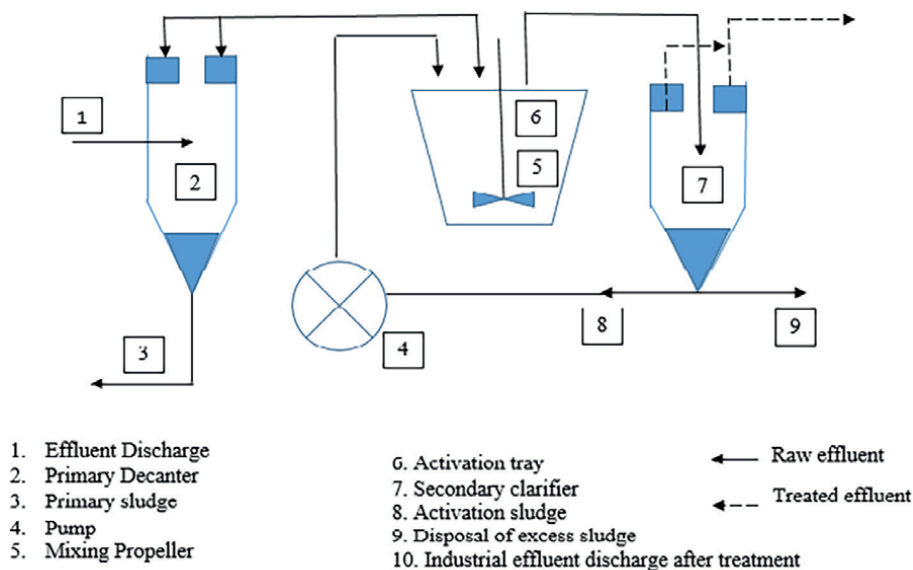
These include, but are not limited to:

- Chemical processes that make it possible to obtain recoverable substances; physico-chemical treatments, such as coagulation-flocculation, seem by far the most efficient processes with a simple implementation, they eliminate a multitude of substances, but they represent high reactive expenditure;
- Natural biological processes such as spraying on permeable soils, aerated or not;
- Artificial biological processes by high-load percolating bacterial beds and, in some cases, activated sludge processes (**Figure 1**), biological disks, oxidation channel, and stabilization basin are all means to be used within the limits of the nature of the effluents.

#### *4.2.4 Tertiary treatments*

Tertiary treatments, which are also called advanced purification or finishing purification, are a complement of wastewater treatment to regenerate these waters and adapt their new qualities to the use that we want to do. In any case, tertiary treatment plant must use as a source of water to treat wastewater after preliminary, primary and secondary treatments. On average, the three successive treatments above eliminated 80–98% of biochemical oxygen demand (BOD<sub>5</sub>) and suspended matter [13]. They have reduced, but not eliminated, microbial contamination. However, they left many mineral salts and did not eliminate many undesirable substances.

It should be noted that approximately one secondary effluent has the following characteristics (**Table 2**):



**Figure 1.**  
 Schematic of an industrial wastewater treatment plant using activated sludge.

COD	From 50 to 150 mg/L
Total organic carbon	From 20 to 50 mg/L
Azote (in NH <sub>3</sub> )	From 5 to 30 mg/L
Color	pale straw
Odor	variable
Turbidity	From 30 to 60 Jackson units

**Table 2.**  
 Characteristics of a secondary effluent.

Among the tertiary treatment processes likely to be used are:

- a. Filtration on materials such as clinker, gravel and sand and possibly also active coals, with the aim of reducing suspended matter, avoiding clogging; filtration is recommended for better adaptation of groundwater recharge;
- b. Chemical, physical or biological purification of the following processes:
  - Lime precipitation;
  - Artificial aeration;
  - Lagoon systems, where available land permits;
  - Finally sterilization for the rapid destruction of pathogenic microorganisms, especially if the effluents come from hospitals or slaughterhouses.

## **5. Technological advancements**

### **5.1 Possibility of wastewater treatment using pure or oxygen-enriched air**

Until recent years, atmospheric air has been the only source of oxygenation used directly in biological wastewater treatment plants. In fact, if water is brought into contact with a large quantity of bacteria, the degradation of organic matter is rapid; but, at the same time, the demand for oxygen increases considerably.

Therefore, a closed biological reactor fed with pure oxygen allows a very high purification efficiency. The dissolution energy expenditure is considerably reduced compared to the conventional provisions. The residence time in the oxygen activation tank is reduced to 1,33 h. The elimination rate of BOD<sub>5</sub> is 88–94%, which of COD reaches 84% and that of suspended matter: 97%.

As for the purified effluent, the BOD<sub>5</sub> decreases to 14 mg/L; the COD does not reach 90 mg/L and the suspended solids do not exceed 12 to 15 mg/L; it is easy to understand that all this is important from the point of view of the protection of the receiving environment.

Of course, if the supply of atmospheric oxygen is free, it must be agreed that the use of pure oxygen is expensive. The essential advantages of using pure oxygen are not sought economically, but much more in terms of flexibility, operational safety and ease of operation. Environmental stresses are very favorable to processes using pure oxygen.

### **5.2 Other possible solutions**

Possible solutions involve types of treatment that can be classified as follows:

- Physical: settling, filtration, sieving, micro-filtration;
- Chemicals: lime-based, flocculation, nitrogen and phosphorus extraction;
- Biological: lagoon, activated sludge, discharge to soil;
- Bacteriological: by use of chlorine, chlorine gas, chlorine dioxide, chlorine bromine mixture, or ozone, by adsorption using activated charcoal or fly ash and by ultraviolet radiation.

These difficult and expensive types of treatment are currently implemented, in very specific cases. But the principle of water regeneration can be applied on a large scale, if one wishes to ensure better protection of the natural environment, or reduce the prohibitive supply of water to the inhabitants of a city, when this work requires the costly construction of a very long network.

## **6. Industrial sludge**

Industrial sludge is most often predominantly mineral, but in some industrial branches, it is predominantly organic. Urban sewage sludge treatment does not apply to industrial sludge with some special modifications adapted to thickening or mechanical dewatering [14].

Sludge thickening is practiced by settling and very variable loads of 50 to 700 kg of solids per m<sup>2</sup> and decimeter thickness are often encountered.

Sludge dehydration does not justify thermal conditioning, which is why chemical conditioning is used using calcium carbonate, synthetic polyelectrolytes or simply sawdust. Filter strips [15] are suitable for the proper dewatering of carbonate sludge or fibrous materials.

Sludge from physicochemical purification is more abundant than sludge from biological purification and can be used as follows:

- Non-toxic mineral sludge may be spread outdoors on land;
- Toxic mineral sludge must be stored in controlled landfills on impermeable waterproofed soils (corroi of clay in specialized centers);
- Fermentable organic sludge, must be stabilized before spreading or incinerated;
- Oil-rich sludge is incinerated;
- Finally, sludge can be taken back for recovery of raw materials if possible.

## **7. Areas for future research and potential advancements**

### **7.1 Problems and composition of sludge**

The effluents admitted to a wastewater treatment plant emerge mainly as sludge, organic or mineral pollution (dissolved or suspended in purified water) and various gases.

Domestic and industrial wastewater treatment technology results in the production of large quantities of sludge during the various phases of purification and primary and secondary treatment.

Sludge production is related to the pollution load of the raw water and the proper functioning of the plant and the treatment system; it is recognized that the activated sludge process generally results in high sludge production.

Today, we must consider that the disposal of sludge must be thought and resolved within the framework of the recovery of urban waste, which allows the reduction of expenses. Indeed, sludge treatment represents an investment of 30 to 50% of the construction cost of the wastewater treatment plant with very significant operating expenses (50% on average).

The primary and secondary sludge in mixture most often contain 95% water and sometimes up to 98%. Translated into dry sludge, 0.8 kg per kg of BOD<sub>5</sub> was eliminated (0.3 kg for primary sludge and 0.5 kg for secondary sludge). In other words, the dry matter content is in the range of 40 to 60 kg per m<sup>3</sup> of sludge.

### **7.2 Sewage sludge incineration and energy recovery**

Organic matter forms the calorific value of sewage sludge. The lower calorific value is 4000–4500 kcal/kg organic matter for fresh sludge and 3500–4000 kcal/kg for digested sludge. The main purpose of incineration of urban or industrial sludge is the elimination of organic components by oxidation, and this is therefore valid from a certain organic matter content.

Thus, given the evaporation of the residual water contained in the sludge, it appears that this process of operation is interesting if:

- In assets, sufficient useful heat is available in the fuel materials;
- Passively, the heat input required for water evaporation is expected.

In other words, the self-combustion of sludge depends on the drying of the cakes and the organic matter content.

The self-burning limit is between 60 and 70% humidity. It should be added that to prevent the release of intolerable odor-producing volatile matter into the fumes released into the atmosphere, combustion must be increased to 800°C. Of course, at such temperatures, there is destruction of all pathogens.

### **7.3 Agricultural sludge recovery by composting**

One of the main items of expenditure on wastewater treatment is the disposal of sludge produced.

The mixed treatment of pre-hydrated sludge carried out simultaneously, with the composting of household waste (atmospheric composting or accelerated composting in reactors) constitutes an interesting solution from the point of view of national and agricultural economy, because it contributes to the contribution of humogenic product to the land, in the same way, and even better than conventional manure. This common composting method therefore allows substantial savings for public authorities.

The main difficulty lies in the high water content of the sludge; the humidity of the sludge-garbage mixture ensures the best aerobic fermentation must not exceed 50 to 55%. This handicap can be overcome by using sludge free of excess water through special filters before adding it to the garbage.

### **7.4 Trend for agricultural sludge recovery in liquid form**

At the outlet of the sewage works, the sludge is in a very liquid form containing about 1 to 2% dry matter. In this state, the sludge is spread on the agricultural land by means of tanker truck or per ton slurry and a group of pump motor.

However, it should be noted that good soil suitability for spreading often occurs during a short period of the year, in autumn, which does not always allow good environmental protection.

In order to be successful in the disposal of sewage sludge by agricultural spreading, it is necessary to know the following data:

- The origin, composition, and volume of sludge to be disposed of on agricultural land;
- Terrain, soil and subsoil characteristics, and the presence of groundwater;
- Regional rainfall patterns and climate;
- The nature of the crops and the needs of the fertilizer elements;

- The study of odor inconveniences in the vicinity of populated areas and roads;
- Finally, the implementation of information for farmers who may be interested in the project.

When these studies of evaluation of practical and economic conditions are positive, it is permissible to say that the sludge disposal system by spreading is interesting for the municipality and for the farmers.

## 8. Industrial pollution elements and treatment methods

**Table 3** shows lists of some most important elements of industrial pollution and the appropriate treatment methods.

## 9. Types of industries and appropriate treatments

Industrial wastewater is so diverse that specialists have agreed to draw up a list of very characteristic industries grouped by pollution analogy, which makes it possible to gather the means of treatment of these particular effluents. **Table 4** provides information on some industries [16, 17].

The examination of the appropriate types of treatment in **Table 4** divides industrial effluents into four categories:

Category 1: Industrial effluents of a dominant organic nature make biological purification possible; this mainly concerns the agricultural and food industries.

Category 2: Industrial effluents likely to be purified by the biological sector, but containing toxic products; this is the case of the leather industry.

Category 3: industrial effluents whose treatment can be carried out by physical or chemical treatment, but can be improved by biological purification, this is the case of effluents from the textile industry.

Category 4: industrial effluents of no interest in biological purification; this is the case for the coal, refining and petrochemical industries, the automotive and surface treatment industries, as well as the steel and metallurgical industries and establishments dealing with radioactive liquid elements.

Polluting elements	Modes of treatment
Fats, oils, tar, sand	Insoluble but decantable materials
Fibers, suspended solids	Physical, by flocculation of raw water or reverse osmosis
Biodegradable elements	Biological treatments by aeration
Toxic elements, phosphates, sulphides	Treatments by precipitation or physico-chemical
Dyes, detergents	Treatment by adsorption
Alcohol, phenols, H <sub>2</sub> S	Stripping treatment
Acid salts and bases	Ion Exchange Processing

**Table 3.**  
*Polluting elements and appropriate treatment methods.*

<b>Industries</b>	<b>Effluent characteristics</b>	<b>Appropriate types of treatment</b>
Agricultural and food industries	<ul style="list-style-type: none"> <li>• Significant and biodegradable pollution;</li> <li>• Releases variable over time;</li> <li>• Rapidly fermentable substances;</li> <li>• Substances causing clogging;</li> <li>• Tendency to acidification or organic dominant</li> </ul>	<ul style="list-style-type: none"> <li>• Essential preliminary treatments: screening, sieving, desalination, degreasing;</li> <li>• Provide for homogenization basins;</li> <li>• High-efficiency biological purification processes using selected bacteria;</li> <li>• Low-load cleaning processes</li> </ul>
Manufacture of paper and paperboard	<p>Cellulose pulp feedstocks are biodegradable substances;</p> <p>Waste leaching is very polluting and contains chemicals that are not very biodegradable (carbonates, sulphides) or toxic (phenols, cyanides). High water consumption requires intensive recycling</p>	<ul style="list-style-type: none"> <li>• Preliminary treatment: screening, screening, flotation, primary and secondary settling;</li> <li>• Acid neutralization;</li> <li>• Activated sludge treatment;</li> <li>• Natural biological secondary treatment in stabilization ponds with aeration by floating turbines;</li> <li>• Tertiary treatment in lagoon</li> </ul>
Iron and steel industries	<p>Highly polluting effluents by separable suspended solids, but current technical developments tend to result in significant quantities of dissolved mineral substances and chemical materials (carbonates, sulphides) or toxic (phenols, cyanides). The very high consumption requires intense recycling.</p>	<ul style="list-style-type: none"> <li>• Primary treatments with settling;</li> <li>• Secondary treatments mainly chemical (neutralization) and decyanurization with chlorine for the elimination of toxic materials;</li> <li>• Treatment focuses on pollution prevention and product recovery</li> </ul>
Textile industries (natural or artificial fibers)	<p>Wastewater receives chemical products (soaps, acids, lime carbonates, soda sulphate) from oxidants (chlorine, hydrogen peroxide), organic matter (starch, albumin), detergents, toxics;</p> <p>The multitude of washes promotes dilution.</p>	<ul style="list-style-type: none"> <li>• Preliminary treatments essential by sieving,</li> <li>• Primary treatments (settling, degreasing);</li> <li>• Chemical secondary treatments most often and biologically in some cases;</li> <li>• Stabilize pH changes;</li> <li>• Interesting combination of physicochemical and biological processes;</li> <li>• For artificial fibers (viscose), the treatment corresponds to that of a chemical plant effluent.</li> </ul>
<b>Indications on some industries (suite)</b>		
Automotive and surface treatment industries	<p>Currently, the pollutants are quite well known, they are made up of dissolved mineral substances, by organic bodies in emulsion or in solution, more or less biodegradable. Effluents are often recycled.</p>	<ul style="list-style-type: none"> <li>• Primary treatments for the demineralization of heavy substances;</li> <li>• Physico-chemical treatments;</li> <li>• Chemical neutralization; oxidation of cyanide compounds;</li> <li>• De-oiling, flocculation, flotation, ion exchangers. Organic products can be fixed by adsorbents such as activated charcoal.</li> </ul>

Industries	Effluent characteristics	Appropriate types of treatment
Refining and petrochemicals	<p>Oil pollution is considerable. Petroleum refinery water is either manufacturing water (waste liquids) or cooling water (wastewater).</p> <p>They are loaded with oil that can be partially eliminated physically—chemically. They are toxic and have a penetrating odor. They contain more or less emulsified oils and hydrogen sulphide, as well as detergents.</p>	<p>The multiplicity of substances likely to be encountered in these waters requires treatment in two or three stages, depending on the nature and concentration of the pollutants.</p> <ul style="list-style-type: none"> <li>• Preliminary screening and de-oiling treatments;</li> <li>• Primary flocculation accelerated settling treatment;</li> <li>• Removal of smelly gases by stripping;</li> <li>• Secondary treatment by biological dephe-nolization, bacterial beds filled with plastic materials, activated sludge with high load;</li> <li>• Tertiary treatment by filtration on activated coal, sludge settling, ozonation;</li> <li>• Aerated lagoon in basins equipped with aeration turbines.</li> </ul>
Radioactive effluents	<p>Liquid effluents are only a small part of radioactive waste. They include cooling water from radio-active ore (uranium) extraction and processing facilities and nuclear reactors.</p> <p>The pollution generated is very particular and dangerous. It manifests itself in two forms: irradiation (radiation exposure) and contamination (fixation of radio-elements on living tissue).</p>	<p>Radioactivity cannot be destroyed; Treatment consists of limiting the doses corresponding to the limits not to be exceeded, to be sure not to harm human health; In plants where radio elements are handled or used, liquid effluents must first be divided into separate networks according to their concentration of radioactive substances; Precipitates are formed giving sludge; the adsorbent power of charcoal is also used; ion exchangers such as clay or synthetic resins are also used. Decontamination of radioactive materials involves solid residues and liquid products; It is possible, under certain conditions, to incinerate radioactive sludge, otherwise, they are kept in reinforced concrete crates</p>

**Table 4.**  
*Indications on some industries.*

## 10. Conclusion

The specificity of industrial manufacturing requires to note today the increasing importance of toxic materials contained in the discharges of industrial effluents, from the agricultural and food industries as well as the refining and petrochemical industries (Table 4).

However, these toxic materials, very diverse, are excessively dangerous for the natural environment and difficult to treat.

This is why the treatment methods to be implemented make the application of specific techniques of organic and mineral chemistry adapted to each manufacturing process, which justifies the reason why these treatment plants, very particular to industrial effluents, are integrated into the manufacturing plant itself.


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## Chapter 5

# Renal Toxicity Due to Lead Reduced by ACF

*Jyotsna Patil, Arun Patil and Mandakini Kshirsagar*

### Abstract

Unorganized lead acid battery workers are exposed to lead. It causes the most occupational heavy metal toxicity. High lead affects several organs and systems of the body. Activated carbon fabric respiratory mask is known to reduce absorption of lead. The study was designed to see use of activated carbon fabric respiratory masks (ACF) in reducing lead-induced nephrotoxic effects among workers. A total of 36 male subjects aged 20 to 65 years were included in this study. Blood lead, renal markers, calcium, phosphorous, sodium, and potassium were investigated. Increased blood lead ( $P < 0.001$ ), significantly decreases after using ACF mask. Renal function markers showed significant alteration in serum creatinine ( $P < 0.01$ ), urea ( $P < 0.01$ ), and uric acid ( $P < 0.001$ ), in the study group after using ACF respiratory mask. Significant improvement in the mean levels of sodium ( $P < 0.0001$ ), potassium ( $P < 0.05$ ), calcium ( $P < 0.0001$ ), and phosphorous ( $P < 0.001$ ) after using ACF mask. Increase in generalized aminoaciduria was seen in battery workers before using ACF mask, but there was no decrease in excretion of amino acids after using ACF mask. The symptoms of lead acid battery workers did not significantly decrease after using ACF mask. Present study concludes that significant change in renal function parameters using ACF mask regularly indicates decreasing absorption of lead.

**Keywords:** heavy metal, renal toxicity, occupational exposure, aminoaciduria, activated carbon fabric mask

### 1. Introduction

Lead is a naturally occurring malleable and corrosion-resistant heavy metal. It can be used in building materials, automobile spray paints as protective coatings, acid storage batteries, and gasoline additives [1, 2].

It is used in lead acid battery factories in various processing steps like breaking, smelting, recycling, old batteries, and making new acid batteries. Extensive use of lead causes environmental contamination, and significant public health problems [3].

Toxic effects of lead have been known for centuries. Occupational exposure to lead results in poisoning be it asymptomatic or clinically symptomatic [4].

Clinical signs of lead toxicity are decreased libido, abdominal cramps, anorexia, nausea, constipation, diarrhea, restlessness, fatigue, irritability, sleep disturbance,

headache, and difficulty concentrating. Symptoms like tremors, toxic hepatitis, or acute gouty arthritis are observed occasionally. Severity of symptoms worsens with increasing blood lead levels.

Increased lead level affects several organs of the body. Renal toxicity in humans has been recognized in earlier studies [5–8]. Acute lead poisoning has been observed as disruption of proximal tubular architecture, with disturbances in proximal tubular function [9–12], and manifested as Fanconi syndrome-like signs observed by glycosuria, aminoaciduria, and phosphaturia [13–17].

The renal manifestations of acute lead poisoning are usually reversible after chelation therapy and cessation of lead exposure [10, 18]. But for chelation therapy, it is very important to select dosage of chelating agent.

It has been observed in earlier studies that lead absorption is reduced by using activated carbon fabric respiratory mask [19, 20].

We have carefully chosen method for reduction of blood lead from absorption which is non-invasive and easy to apply. In the present study, we have provided activated carbon fabric mask to the lead acid battery workers and observed that it is useful in decreasing renal toxicity.

## **2. Material and methods**

### **2.1 Materials**

*This is interventional study. We had planned for pre and poststudy, hence control subjects were not included.*

The study selected with aim to reduce renal toxicity due to lead by the intervention of using protective gears, which suits battery manufacturing workers more feasible and comfortable.

This study comprises 36 male workers of lead acid battery manufacturing factory in the Western Maharashtra, India. The selected workers were nonalcoholic, nonsmoker, and of age range 20–45 years. Subjects on medications were excluded from the study. By using questionnaire and interview, the demographic, occupational, clinical data, socioeconomic status, dietary intake, and food habits were collected. The written informed consent from all participants was collected in regional language.

The study objectives and health hazards of lead exposure and its toxicity were informed.

### **2.2 Ethics declaration**

Protocol committee and institutional ethics committee approval were taken prior to enrollment of study participants and as per the 1964 Helsinki Declaration [21].

### **2.3 Strategies for study**

Lead acid battery workers were selected from unorganized lead acid battery manufacturing factories from Karad MIDC, Maharashtra, India. These workers are exposed to lead while smelting and plating of batteries.

Activated carbon fabric mask was provided to all lead acid battery workers and guided them about the use of this mask. The regular use of activated carbon fabric

mask was ensured through weekly telephonic communication with all these battery workers. The workers were trained to clean the masks (recharge) every week. ACF can be easily recharged by opening the valves and filter should be removed and dipped in boiling water for 5–10 minutes and dry under the sun. This instruction was given by the authorities of Environ Products Ltd.

The activated carbon fabric mask is a respiratory full-face mask with activated carbon fabric device, which acts as barrier against chemical and biological impurities.

*A unique property of an ACF fabric is the possibility to “reactivate” the fabric when it has become saturated so that it can be reused. Weak bonds are formed by physical adsorption mechanism between pollutants and activated carbon fabric surface at low temperatures. Providing heat energy, pollutant molecules can be removed from the activated carbon fabric surface [19, 20, 22]. This mask has a superior quality activated carbon fabric, which has excellent adsorbent property, removes environmental toxin, and atmospheric pollutant.*

*Earlier effectiveness of use of ACF masks in reducing blood lead levels of battery workers was studied for 1 month [19, 22]. Hence, we planned the study protocol for short duration, that is, for 2 months.*

Blood sample was collected from battery workers. Then instructed them to use ACF masks for two months regularly. After 2 months, blood sample was collected and biochemical parameters were studied and statistically analyzed.

## 2.4 Biochemical laboratory tests

### 2.4.1 Blood lead

Ten ml blood was collected in tube containing heparin and EDTA for estimation of lead and various biochemical parameters.

Blood lead was estimated by using lead care II blood lead analyzer (Magellan Diagnostics, USA). The principle of this instrument is based on Anodic Stripping Voltammetry (ASV) to measure the blood lead level. Red blood cells (RBC) are lysed by using lead care treatment reagent, which releases the lead from RBC. To accumulate lead atoms on the test electrode, a negative potential was applied to the sensor. For releasing the lead ions, the potential was rapidly reversed, which generated the current and it was directly proportional to the amount of lead in the blood sample [23].

### 2.4.2 Kidney function tests

Kidney function tests were estimated by using EM360—Transasia fully automated biochemistry analyzer.

Blood urea was measured by Glutamate Dehydrogenase (GLDH) method. The rate of decrease in absorbance measured at 340 nm [24–26].

Serum uric acid was measured by Uricase-Peroxidase (POD) method. Uric acid is oxidized to allantoin by uricase with the production of  $H_2O_2$ . The absorbance of quinoneimine dye at 546 nm is proportional to uric acid concentration in the sample [27–29].

Serum creatinine was estimated by enzymatic method. The absorbance of produced complex at 546 nm is proportional to the creatinine concentration in the sample [30–32].

#### *2.4.3 Minerals in blood*

Serum calcium was measured by Arsenazo method. The absorbance of which is measured at 650 nm and is proportional to calcium concentration [33, 34].

Serum phosphorous was measured by UV molybdate method. The formation of reduced phosphomolybdate is measured at 340 nm and is directly proportional to the concentration of inorganic phosphorous [35, 36].

#### *2.4.4 Serum electrolytes*

Serum electrolytes like serum sodium and serum potassium are measured by method of ISE theory. Erba XL 640 fully auto analyzer is an automated, microprocessor-controlled analytic analyzer that uses ISE (Ion Selective Electrode) technology for the direct measurement of ions [37].

#### *2.4.5 Thin layer chromatography on urine*

Urine samples of subjects were collected in dark amber color bottle. Amino acids were detected in urine by using thin layer chromatography technique. Precoated cellulose sheets and butanol: acetic acid: water solvent system used. In total, 0.2 ml of urine in eppendorf tube was collected and 1.0 ml of methanol was added and vortexed, centrifuged. Supernatant was used for chromatography. A total of 5ul of supernatant was spotted on TLC sheet. TLC sheet was then kept for activation at 60°C for 10 min. TLC plate was then placed in solvent tank and allowed to ascend to 2 cm from the top of thin layer sheet. TLC sheet was removed and allowed to dry at room temperature for 10–15 min. Ninhydrin reagent sprayed over the TLC sheet and allowed to dry at room temperature. The plate was transferred to a hot air oven set at 100°C. Purple colored spots on TLC sheet were observed. These spots are amino acid spots, detected and compared with Rf values from reference values of standard in literature and also with normal urine sample [38].

### **2.5 Statistical analysis**

Statistical comparison of blood lead, renal function markers and serum calcium, phosphorous, sodium, and potassium of lead acid battery workers were done after using activated carbon fabric mask. Unpaired “t” test applied using InStat GraphPad software. Two tail p value was calculated and was set to  $P < 0.05$  statistically significant.

### **3. Result**

Activated carbon fabric (ACF) respiratory masks were provided to lead acid battery workers. We ensured that they were using it regularly in telephonic communication.

**Table 1** shows that there is decrease in blood lead level significantly ( $p = 0.001$ ) after using ACF mask.

Renal function markers like blood urea, serum uric acid, and serum creatinine decrease significantly after using ACF mask ( $p = 0.015$ ,  $p = 0.0037$ ,  $p = 0.011$ ). Minerals like calcium and phosphorous increase significantly after using ACF mask ( $p < 0.0001$ ,  $p < 0.0001$ ). Electrolytes like sodium decreases ( $p < 0.0001$ ) and potassium increases ( $p = 0.0012$ ) significantly after using ACF mask.

Thin layer chromatography for amino acid in urine shows increased excretion of general amino acids like glycine, alanine, cysteine, histidine, leucine, isoleucine, etc. in urine as compared to normal urine sample shown in **Figure 1**.

From lead acid battery workers, symptoms were observed. These were muscle cramps, irritability, lethargy abdominal discomfort, and are categorized on the basis of blood lead.

**Figure 2** shows mild symptoms (Adult PbB level > 60 mg/dl) like, muscle pains, prickly itchy feeling, mild fatigue, aggressiveness, irritability, lethargy, abdominal discomfort, and severe symptoms (PbB level = 70–80 mg/dl), joint pain, general fatigue, poor concentration, tremor, headache, abdominal pain, and constipation.

#### 4. Discussion

In this study, mainly unorganized sector of lead acid battery manufacturing workers were enrolled and they were involved in smelting, recycling, and plating of lead batteries. These workers were highly exposed to lead, which resulted in increased blood lead levels. In our earlier study, we observed that increased blood lead affects liver and kidney functions [39, 40].

Mainly lead enters the body through inhalation and ingestion of contaminated food at the site of workplace. Therefore, we have provided activated carbon fabric mask to these workers and requested all these workers to use this special mask regularly for 2 months. We have ensured that all workers were using this mask regularly by telephonically talking every week to these workers and owners of industries. Blood lead level ( $p < 0.01$ ,  $-15.76\%$ ) was significantly decreased after using 2 months of activated carbon fabric masks, which clearly indicates that the absorption of lead decreases (**Table 1, Figure 1**). It is observed that the regular use of activated carbon fabric mask is really useful to reduce the blood lead levels.

Earlier study found that significant increase in serum uric acid, serum creatinine, and serum urea levels in lead-exposed Korean workers [41]. Also in our recent study, we found there is an increased level of renal parameters [39].

Urea is the marker of the kidney function, concentration of which in the plasma tends to increase in impaired kidney state.

Accumulation of lead (Pb) in the kidney increases serum urea. This could be due to impairment of glomerular membrane [1]. After using ACF mask, we observed that there was a decrease in ( $-14.16\%$ ) in urea level. Using regular ACF mask could decrease lead absorption, which may prevent impairment of glomerular basement membrane.

Increased plasma accumulation of uric acid may be due to deposition of lead in the proximal tubules of the nephron. These effects of lead (Pb) can subsequently lead to gouty arthritis [42]. It is observed that use of ACF mask for 2 months decreases serum uric acid ( $-14.98\%$ ). Uric acid is considered one of the antioxidants in plasma [43]. In this study after using ACF mask, decrease in uric acid level may spare the antioxidant property of uric acid.

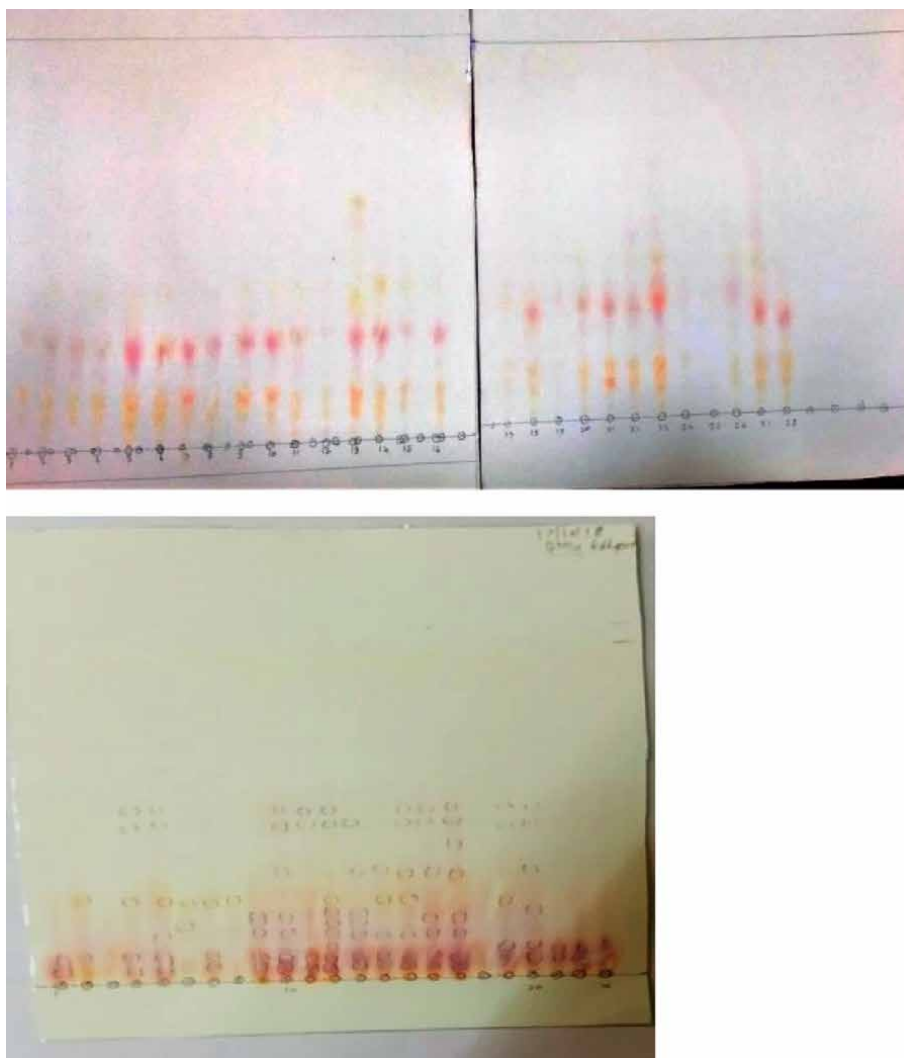
In our study, we observed that high levels of serum creatinine level in unorganized battery workers decreased ( $-13.91\%$ ) after use of ACF mask, which is beneficial for reducing renal toxicity.

Lead inhibits the  $1\text{-}\alpha$ -hydroxylase enzyme in renal tubules resulting in decreased calcitriol formation [44]. Decreased calcitriol synthesis results in reduced calcium-binding proteins, which impair the calcium absorption across small intestine. Lead

Sr. No.	Biochemical parameters	Before using ACF masks (N = 36)	After using ACF masks (N = 36)	P value	Percentage change
1	Blood Lead Level (µg/dl)	88.31 ± 18.16 (47.6–130.20)	74.39 ± 20.16** (36.7–126.98)	0.001	-15.76
2	Blood urea (mg/dl)	26.77 ± 6.70 (16.8–47.80)	22.98 ± 6.27* (12.60–36.80)	0.015	-14.16
3	Serum uric acid (mg/dl)	7.21 ± 1.59 (3.90–10.9)	6.13 ± 1.48** (2.80–8.90)	0.0037	-14.98
4	Serum creatinine (mg/dl)	1.15 ± 0.27 (0.76–2.38)	0.99 ± 0.26* (0.60–2.10)	0.011	-13.91
5	Serum calcium (mg/dl)	8.29 ± 0.35 (7.60–8.80)	8.98 ± 0.36*** (8.07–9.70)	P < 0.0001	7.36
6	Serum phosphorous (mg/dl)	2.998 ± 0.37 (2.27–3.89)	3.59 ± 0.68*** (2.27–5.51)	P < 0.0001	19.75
7	Serum sodium (mEq/L)	139.57 ± 4.28 (124.53–145.30)	129.82 ± 3.76*** (121.85–139.78)	P < 0.0001	-6.99
8	Serum potassium (mEq/L)	3.08 ± 0.43 (2.50–4.31)	3.44 ± 0.49** (2.69–5.15)	0.0012	11.69

Values in parenthesis shows reference ranges, \* P < 0.05, \*\* P < 0.01, \*\*\*P < 0.001, figures indicate mean and SD, values in parenthesis shows minimum and maximum range.

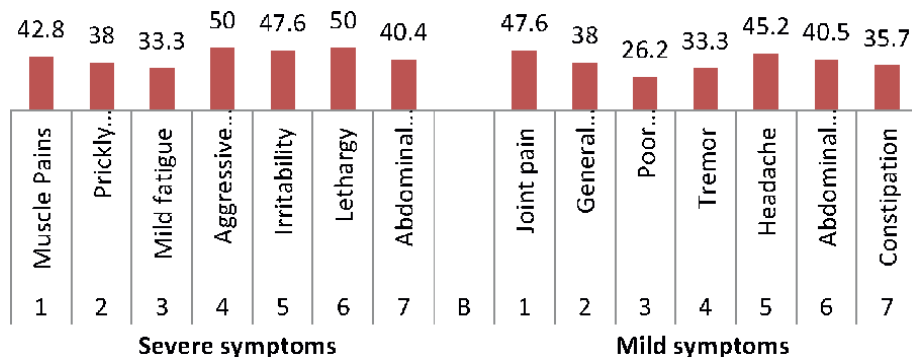
**Table 1.** Blood Lead level, renal functions, serum calcium, phosphorous, sodium, and potassium of lead acid battery workers before and after using ACF masks.



**Figure 1.**  
*Thin layer chromatography for aminoacids in urine of lead acid battery workers.*

toxicity also causes prolonged hyperphosphaturia and hypophosphatemia in children could result in bone demineralization and rickets [15]. As mentioned in literature, same mechanism may be observed in adults and may result in osteoporosis. In our study, decreased serum calcium and phosphorous, increased by 7.36 and 19.75%, respectively, indicates ACF mask is useful in improving calcium level. Use of ACF mask decreases absorption of lead and may lead to increase in the activity of 1- $\alpha$ -hydroxylase enzyme resulting in synthesis of calcium-binding proteins, which have role in absorption of calcium and phosphorous from the intestine. Use of ACF mask may reduce excretion of phosphates in urine.

The effect of lead toxicity on kidney is disruption of proximal tubular architecture. This results in disturbances in proximal tubular function with laboratory evidence [9–12]. Rats' exposure to lead shows that statistically significant difference in serum mean levels of  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Cl}$  [45].



**Figure 2.** Percentage of mild and severe symptoms of lead acid battery workers.

We also observed disturbance in sodium and potassium levels in unorganized lead acid battery workers. After use of ACF mask, there is an improvement in sodium (−6.99%) and potassium levels (11.69%).

Renal manifestations of acute lead poisoning in animal models and in humans are observed as glycosuria, aminoaciduria [13, 14], and phosphaturia, collectively representing the Fanconi syndrome [15–17]. A generalized aminoaciduria observed in unorganized lead acid battery workers is indicated in **Figure 2**. After use of ACF mask, there was no reduction in the level of aminoaciduria this may be due to high concentration of lead in blood.

Battery manufacturing workers had severe complaints of lead toxicity like nausea, loss of appetite, constipation, intermittent abdominal pain, diarrhea, and joint pain. The acute and chronic symptoms of lead toxicity observed in battery manufacturing workers before using activated carbon mask were depicted in **Figure 2**. However, after using 2 months of activated carbon fabric mask, there was no significant decrease in acute and clinical symptoms, which may be due to high concentration of lead in the blood, soft tissues, and bones. The early recognition of these symptoms of lead exposure can minimize the toxic effects by using ACF mask. The acute and chronic clinical symptoms are reduced by decreasing the blood lead level.

*This study is done for short duration as per study protocol. For long duration, we may get better results. We found use of ACF mask reduces blood lead and lessens renal toxicity. If the lead acid battery workers use such masks during working hours for long duration, definitely risk of lead toxicity is reduced.*

*In this study, activated carbon fabric mask was chosen because it is three-layered whereas other masks are two-layered. So ACF masks are better to protect from lead toxicity.*

*This is part of our study where we have studied effects of ACF on liver function, oxidative stress, and also on heme biosynthesis in occupational lead exposure which was published recently earlier. In our study protocol, neurological and cardiovascular studies are not included but in future we can plan.*

*In this study, Urine lead we could not do. Because blood lead level measured by using lead analyzer Leadcare II machine. Which gives blood lead value within three minutes which was easy and most reliable. We did other biochemical parameters like urinary delta aminolevulinic acid. Urinary porphobilinogen these are biochemical markers for lead exposure. But our work on occupational lead exposure effect on heme biosynthesis and hematological properties published (Patil JA 2019 IJCB) hence not included.*

## 5. Conclusions

Lead exposure is recognized as a risk factor for many of the diseases in battery manufacturing workers. This situation is worse in developing countries. Programs for the prevention and treatment of lead toxicity are poorly established [46]. Lead is environmental and occupational nephrotoxic cause of kidney disease, the present study aimed to reduce the renal toxicity.

Lead toxicity results in nephritis, which may be in association with hypertension. The symptoms of lead intoxication are variable. The assessment of workers with renal disease is important to identify the factors that may be leading to lead nephropathy. These factors are indications and risks of present or past lead exposure. Assessment of environmental and industrial lead is recommended to incorporate into programs for the prevention of chronic renal failure in countries where occupational lead exposure and toxicity still remain unchecked and burden of renal failure is increasing [46].

Therefore, it is essential to reduce the lead exposure by using special mask, apron, goggles, and even shifting the place of workers from high lead exposure to low lead exposure. In addition, unorganized lead acid workers need to be educated about the lead sources, hazards and that may cause lead toxicity. This is very important step in preventing further exposure to lead and its adverse health effects [5, 47]. Further prevention measures that involve the early detection and treatment of lead toxicity need to be started and also the targeted screening of workers with high risk of occupational lead exposure as this is likely to help early diagnosis and treatment of persons with lead nephropathy [47].

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We acknowledge Late Dr. Arun Jalindar Patil, Deputy Director of Research, Executive Editor of JKIMSU, and Professor Dept of Biochemistry, who guided this project intellectually. We regret his absence.

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## Appendices and nomenclature

ACF	Activated carbon fabric mask
TLC	Thin layer chromatography
BPb	blood lead


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## Chapter 6

# The Role of Industrial Sector in Pollution Control in the Context of Sustainable Development Goals

*Abdulkarim Hasan Rashed*

### Abstract

The sustainable development goals (SDGs) constitute an opportunity to engage the industrial sector to enhance its role in preserving the environment. The industrial sector has an essential role in economic growth, job creation, innovations, and sustainability. No matter the scale of the industry, it is small or large; thus, all companies can contribute to the SDGs toward a better future. Pollution problems are the root cause that hinders attain sustainable development in the industrial sectors. Thus, global challenges are climate change, water pollution and scarcity, air pollution, and resource depletion needs to be tackled collaboratively, and the industrial sector can contribute to the solution through pollution control and sustainable innovations. In the rapid transformations of business models and systems for the future and the fourth industrial revolution, the industrial sector has a crucial role; without it cannot save the environment and improve the economy and human health. To transform the current industrial systems toward a more feasible eco-friendly needs significant cooperation and coordination among concerned stakeholders. To do so, firstly, industries need to adjust their strategies and plans to be consistent and coherent to start the transformation process toward sustainable industrial development.

**Keywords:** sustainable industrial development, SDGs, sustainable innovations, industrial revolution 4.0, industrial ecology and ecosystems

### 1. Introduction

There is a consensus that industrialization is an integral part, but rather the heart of the process of economic growth. Alarmingly, human impacts on the earth planet have grown very deep that we have entered the Anthropocene era in which human activities are the root reason for significant environmental changes [1] where since the beginning of the industrial era, the primary focus has been on achieving economic growth merely, which has caused a set of major challenges facing human society including pressures on natural resources (e.g., non-renewable resources), waste, water scarcity, climate change, and various types of pollution (air, water, land), and biodiversity loss. Accordingly, conflicts arose between the economic development that led to rapid industrialization and the serious negative effects of the destruction

and unsustainable consumption of natural resources and extreme pollution [2]. For instance, in the 1960s, the Best Available Techniques (BAT) notion appeared as an essential environmentally friendly industrial policy tool to control and prevent industrial pollutants releases, and that led to industrial transformation based on bi-solutions technological and managerial that provides cleaner production and better sustainable economic growth that utilizes raw materials, energy, and water efficiently [3]. The industrial sectors play a fundamental role in the adoption of sustainable development toward a better future. Thus, it draws great attention to a sustainable development approach to meet those challenges. Lukin et al. point out that one of the top reasons companies decided to adopt sustainable strategies is that the demand for environmentally friendly products is increasing in nearly all industrial sectors [4].

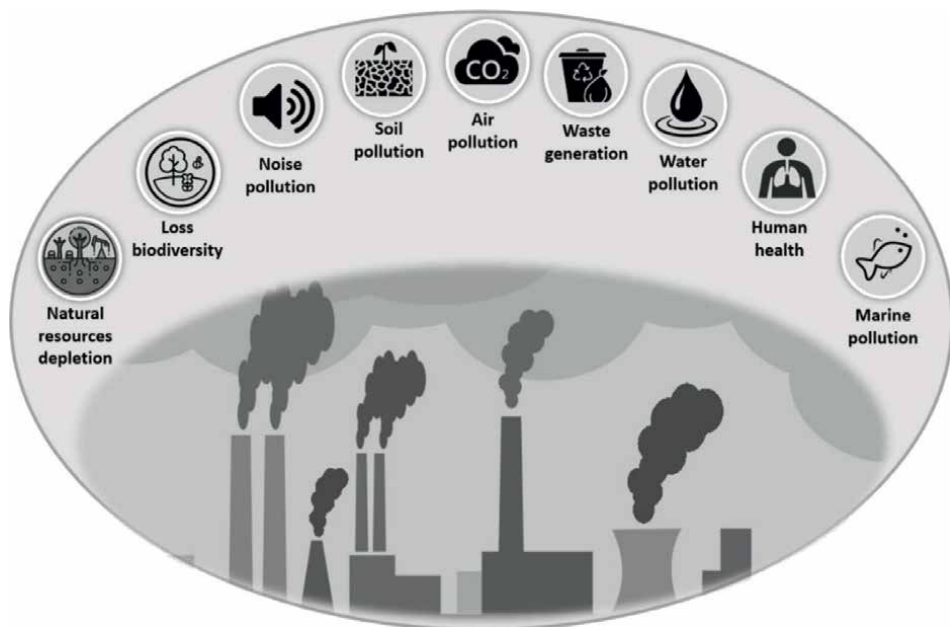
Therefore, economics and competitiveness are not the sole drivers, whereas ethical, social, and environmental are essential drivers toward sustainable growth [5]. Therefore, a wide range of sustainable actions was adopted in the industrial sectors to control the pollution impacts on the environment such as corporate sustainability [6], end-of-pipe technologies [7], corporate social responsibility [8], green supply chain management [9], sustainable supply chain management [10], sustainable manufacturing [11], life cycle assessment [12], the product life cycle supply chain [13], best available control technologies and best environmental practices [3], the sustainable operations [14], cleaner production [15], and circular economy [16].

This chapter builds a relationship between the industrial sectors and sustainability, given the essential role of this sector in implementing sustainable development goals (SDGs) and providing innovative solutions to stop the deterioration of the environment and save human health. In addition, this chapter reviews a range of technologies that contribute to reducing the adverse pollution impacts resulting from manufacturing processes. It concludes that the industrial sectors should transform from linear to circular ecosystems toward accomplishing sustainability.

## **2. Industry and environment**

Remarkably in the past two centuries, the negative impacts of pollution emissions of industrial activities on the environment and human health have grown exponentially [17, 18] and environmental degradation has become a major issue [19]. Thus, this sector is liable for environmental degradation. Therefore, the attention toward global sustainable industrial development has increased [10]. In this vein, Kopnina stated that the cumulative effects of rapid industrial development and unsustainable production and consumption patterns that aim to prioritize economic benefits over preserving the environment, therefore, led to impeded attained environmental sustainability and caused damage to ecosystems. **Figure 1** summarizes the environmental and health impacts of industrial sectors [20].

The world, in the period 1979–1989, witnessed significant environmental crises that called the private sector to take urgent actions to localize sustainable development issues [21]. As a case in point, chemicals, textiles and garments, and mining sectors are considered the most polluting industries, and their negative impacts adversely led to environmental degradation [22–24]. For example, the textile industrial sector accounts for about 20% of global industrial wastewater pollution [25], both the mining and energy sectors consume more than 70% of water, and the food and industrial manufacturing sectors consume more than 50% of water [26], and oil and gas sector consume more than 57% of total global fuel [27]. Globally, energy consumption is



**Figure 1.**  
*The impacts of industrial sectors on the environment.*

the largest (73.2%) emitter of greenhouse gases, and the industrial sector is the major contributor [28]. Further, the main environmental impacts of the mining industry include hazardous waste, acid mine drainage (wastewater), sedimentation and metal deposition (soil contamination), and loss of biodiversity, and it has significantly impacted global warming potential; and human health, either carcinogenic or non-carcinogenic [29]. Furthermore, paper, rubber, and wood manufacturing sectors pose a risk to the forests, natural habitats, and biodiversity [30].

There are severe impacts of industrialization on the environment; climate change has significantly affected the environment due to the high consumption of energy resources. The industrial sector is one of the main contributors to carbon dioxide emissions [31], which constitute the highest percentage of greenhouse gases. In recent years, the severe impacts of climate change were considered a major crisis of environmental degradation [32], where greenhouse gases reached much higher concentrations (50%) than at the kickoff of the industrial age [33]. Therefore, there is an essential need to take urgent action concerning the negative aspects of economic growth that have caused adverse effects on the environment and human health [34]. According to Antoci et al. that the estimated cost of industrial pollution impact on rural societies is very high in monetary terms [19].

### **3. Industrial ecology and ecosystems**

Industrial ecology and industrial ecosystems are emerging concepts in environmental policy, environmental economy, and environmental management [35]. The importance of the ecosystem concept has increased in the management field of technology and innovation [36]. Industrial ecology implies utilizing the design of

ecosystems to steer the redesign of industrial systems; where the concept of industrial ecosystems includes cleaner production in the companies' interactions in a specific industrial area within their local and global ecosystem, while industrial ecology is a comprehensive framework for leading the industrial system transformation toward a sustainable basis [37].

Erkman stated that an industrial ecosystem “studies the whole of the industrial system material and energy flows and interaction with the environment, as does industrial metabolism, it further seeks to move beyond description and use the model of sustainable ecosystems in unsustainable industrial systems” [38]. The system definition limits are essential for industrial ecosystems; thus, it studies complete systems consisting of companies, institutions, raw materials, and energy flows, and the information and data link all these components to each other and with social, economic, and environmental systems [35], that will yield multiple benefits such as improving industrial activities, attracting new companies to the system, increasing the number of synergies, creating employment, reducing industrial emissions, and increasing inclusive sustainability [39].

Graedel classified the industrial ecosystem activities into three types: Type I is linear materials flow, Type II is quasi-cyclic materials flow, and Type III is cyclic materials flow [40]. Where that classification is similar to concepts currently in circulation, the first type represents the “linear economy”, the second type represents the transitional stage, and the third type represents the “circular economy”.

Figures 2 and 3 are open systems; the plentiful resources flow from input to output without control and convert to waste. Thus, the mismanagement of this system will lead to depleted resources and continuously generate waste and pollution; as a result, it will impose economic costs. Further, in the long run, it will impact the availability and sustainability of resources, especially non-renewable finite resources.

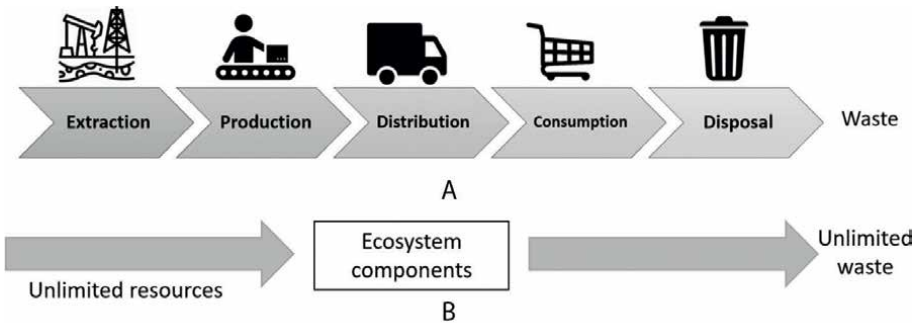


Figure 2. A. Linear economy. B. Quasi-cyclic materials flows [40]

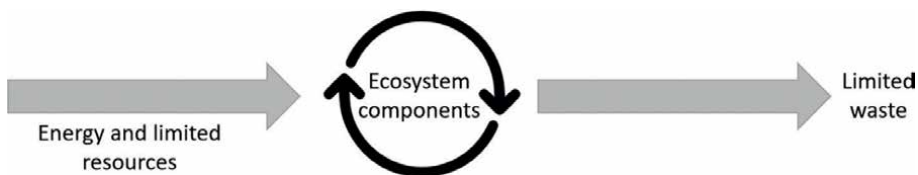
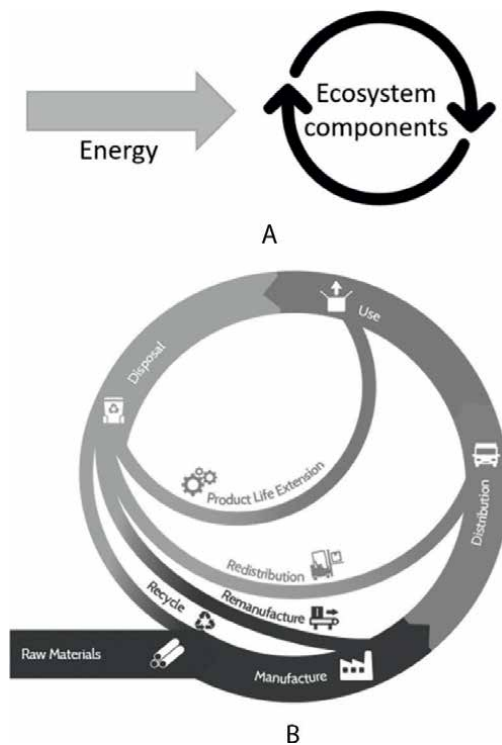


Figure 3. Linear materials flows [40].

The industrial systems began to develop due to the deterioration of the environment. As shown in **Figure 3**, the resource control features appeared in the type II system, which makes it better and more efficient than the type I; since the flow is still in one direction; thus, this system is not sustainable in the long run. Further, this system paved the way for the shift from a linear to a cyclic system which is evident in the reduction of waste generation.

**Figures 4A** and **B** resemble one concept and both closed systems and illustrate the transformation of manufacturing from Type I to Type III, and their cyclic loops consider waste a resource. The advantages of the closed cycling loops of this system will save finite and scarce resources, adopt resource efficiency, and minimize pollution. Further, it will drive progressive change in manufacturing processes toward sustainable industrial innovations. Both ecosystems characterize completely grown systems where most of the resources used are contained and reused within the same ecosystem, which will lead to avoiding or minimizing extracting more virgin resources. That also will sustain and conserve the resources. Thus, the pollution emitted from the raw materials extraction processes will be avoided or reduced primarily.

Unsustainability use of limited resources is a crucial concern hindering attaining sustainable development, and circular resource utilization is one of the significant positive responses. The circular economy pledges to integrate aspects of both the industrial ecosystem and the ecological ecosystem [42]. The circular economy is the most recent approach to sustainability and the most widely used concept, and it is a comprehensive concept ultimately aimed at zero waste of resources and minimizing



**Figure 4.**  
A. Cyclic materials flows [40]. B. Circular economy [41].

the production's negative impacts on the environment. Also, it is a good sign of transformation toward sustainability and beat pollution.

#### **4. Industry and SDGs**

The industrial sector is an integral part of the economic growth process and constitutes a core part of the business sector, and its direct and indirect negative impacts on the environment hinder attaining sustainability. Manufacturers globally have growingly recognized the significance of sustainability; mainly the necessity to integrate sustainability strategies within current company practices [11]. All industrial companies can contribute to the SDGs regardless of their size [43] and the sharing economy can contribute effectively to attain SDGs [44]. One of the significant challenges on the track to sustainable development is the industrial production transformation [45]. The SDGs enhanced “sustainable industrialization” and “sustainable use of land” concepts, and almost all the SDGs address the environmental dimension directly and indirectly by controlling and preventing environmental degradations, various types of pollution, climate change crisis, waste management issues, and encouraging resource efficiency [46].

According to the 2030 Agenda, the SDGs related directly to industrial sectors are 8 (Decent Work and Economic Growth), 9 (Industry, Innovation, and Infrastructure), 12 (Sustainable Consumption and Production), 13 (Climate Action), 14 (Life Below Water), and 15 (Life on Land) [47]. In the context of SDG 9, by evidence, innovations and SDGs are closely interlinked, specifically in industrial sectors [48]; further, innovation is considered an essential driver for following SDGs at all phases [49] and there is an opportunity to link it to each goal [50]. According to van Zanten and van Tulder that most economic activities have a positive impact on SDGs 8 and 9 [51].

The KMPG study of 2022 on corporate reporting of the SDGs revealed that the reporting increased from 24% in 2017 to 63% in 2022 in the industrial, manufacturing, and metals sectors, and in the oil and gas sector reporting increased from 39% in 2017 to 83% in 2022, similarly increased to 83% in 2022 compared to 38% in 2017 in the automotive sector [52].

Another study by UN Global Compact revealed that 84% of companies and industries acting on the SDGs, where the strong focus—ranked respectively—is found on SDGs 8, 9, 12, 13, and 3 (Good Health and Well-being), and only 46% of them embedded the SDGs within their core businesses strategies. Therefore, to take a step of necessary transformation toward sustainability, there is a need to accomplish more and go faster through specific relevant SDGs, standards, and practical guidelines to harmonies the company's and industries' efforts toward attaining the SDGs by 2030 [53].

At the national level, environmental policies should be coherent and holistic management approach consistent with the SDGs, considering the international conventions' commitments to enhance sustainable practices [54], and sustainable manufacturing practices are the primary strategies for sustainable development [55]. Therefore, there is an urgent need to control industrial pollution by implementing sustainable practices such as resource efficiency, zero waste, sustainable products, and innovative environmental approaches to lessen environmental impacts and improve the social state [14, 56–58]. In addition, industrial strategies and policy tools should be more encompassing by comprising environmental and societal development, besides economic development, which will ensure improved environmental status and societal welfare and gain better economic growth [59].

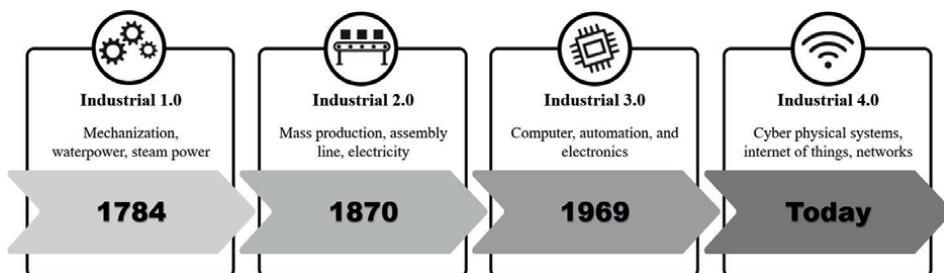
The sustainability trend in industrial sectors has gained more attention, especially in large sectors. Thus, the SDGs are considered a window of opportunity to enhance more sustainable practices and promote eco-friendly technologies to beat pollution and conserve the environment and human health, which will yield to balance between the environment and the economy. Moving forward requires an efficient nexus between industrial activities and the SDGs to build a resilient industrial sector to enhance its ability to improve its environmental footprints.

## 5. Industrial Revolution 4.0 and SDGs

An important component linking the SDGs to technological innovation is the adoption of industrial innovation through Industry 4.0. Where industrialization, resilient infrastructure development, and technological innovations are the most feasible paths to attain sustainable growth in the industrial sector and the SDGs of the 2030 Agenda. Thus, technology is considered the most important subject during the industrial revolution [60], and Industry 4.0 is an advanced technological revolution promising broad environmental conservation [61]. Therefore, when the Industry 4.0 concept considers the fundamental aspects of sustainability, it will guide to more sustainable development [45]. In this vein, Fritzsche et al. point out that there are high anticipations concerning Industry 4.0 contribution to sustainable development and the SDGs attainment, specifically among decision-makers, policymakers, and industrial sector representatives [62].

As depicted in **Figure 5**, the first industrial revolution focused on energy primary renewable and non-renewable sources, such as oil, gas, coal, steam, nuclear, solar, geothermal, and wind. Industrial 2.0 improved the production of goods more efficiently from mechanization to mass production with assembly lines, whereas Industry 3.0 witnessed advanced improvements by introducing computers, automation, and electronics into production lines. While Industry 4.0 outperformed the rest of the industrial revolutions, it is a rapid innovation revolution toward automation and data exchange in advanced manufacturing technologies, such as artificial intelligence, cyber-physical systems, and the Internet of Things.

Industry 4.0 provides essential technological solutions and a driver for achieving SDGs 7, 8, 9, 10, 11, 12, and 13 [63–65]. The role of Industry 4.0 in achieving SDG 7 (affordable and clean energy) will provide technologies with sustainable energy efficiency to improve quality and cost-saver for consumers [66] and SDG 8 (decent work and economic growth) will provide advanced technologies for protecting the



**Figure 5.**  
*The timeline of industrial revolutions.*

environment that led to better economic growth, create more decent jobs, more business opportunities with high efficiency and quality work [67–70]. Concerning SDG 9, Industry 4.0 will enhance sustainable industries, invest more in scientific research and innovations, and improve infrastructure [71, 72], while through SDG 12, technologies will advance production and consumption patterns; and the adoption of a circular economy [45, 73]. The opportunities of SDG 13, advanced technologies will speed up adopting net-zero emissions, which lead to reduced CO<sub>2</sub> emissions through data-centric and traceable carbon footprint analysis [67, 74].

The rapid technological advancement is oriented toward a better world for people and the environmental ecosystem. In this context, Agenda 2030 emphasizes the plans to attain an integrated sustainable infrastructure, technological innovations, and sustainable industrial development. Certainly, Industry 4.0 will contribute more to SDGs accomplishment, where SDG 9 is the core of industrial innovation and infrastructure. The successful SDGs adoption to tackle environmental problems, such as increasing energy demands and climate change issues, will foster technological innovations and improve manufacturing processes; therefore, enhancing sustainable industrialization and growing the investment in research and innovation.

## **6. The industrial pollution management controls**

Environmental pollution is a necessary evil in any industrial revolution; thus, industrial activities without control are unsustainable in the long term due to their accumulation of negative impacts on the environment and human health. Industrial pollution management controls are the measures or actions taken to prevent or reduce all kinds of pollution impacts from the source caused by industrial operations and activities. There is a broad range of control measures, such as cleaner production technologies, waste reduction and recycling, waste-to-energy, and various pollution prevention technologies. Therefore, green, and sustainable innovations are essential to enhance economic, technological, and social development [75]. In the same vein, green innovation has a crucial role in leading sustainable development practices and enhancing circular economy practices [76].

Introducing new technologies in industrial sectors is not an easy issue and often faces some obstacles; in this context, Frondel et al. mentioned some include lack of top management support, organizational measures (e.g., environmental management systems (EMS)), type of inputs raw materials, technology cost, nature of environmental aspects, and the rigor required measures of the environmental policies [7]. The severity of the environmental impacts of industrial processes depends on production effectiveness, raw material components, water and energy consumption, and the pollutants type of the manufacturing and recycling processes [77].

Therefore, the industrial sector's technological and innovation capacity is necessary with their commitment to support the implementation of the SDGs [78]. For example, the chemical industry sectors provided dual scientific and technological solutions to prevent pollution and tackle several global challenges [79]; the carbon footprint impacts can be significantly reduced by shifting to employing renewable power sources (e.g., solar and wind) and using recycled materials as raw materials [28]. **Table 1** summarizes the implementation of best environmental practices, best abatement technologies, and approaches to control pollution from sources.

<b>Control pollution technology/approach</b>	<b>Aim</b>	<b>Examples</b>	<b>References</b>
Cleaner Production (CP)	Lessen the environmental hazards effects at the source by replacing or modifying the least clean technologies.	Recycling materials, using eco-friendly materials, and modifying the combustion chamber system	[7, 15]
End-of-pipe	Additional measures to comply with environmental obligations.	Waste incineration facilities, wastewater treatment plants, and noise-absorbent techniques.	[80]
Sustainable end-of-life 'Extended supplier responsibility'	Capture the product, materials, and parts value - energy and cost - by extending their service life by maintenance and support services to customers.	Managing product guarantee returns/replaces, providing recycling support services, and hazardous waste treatment.	[11]
Corporate Sustainability (CS)	Enhance and adopt sustainability aspects at all levels of the company and activities.	Enforcement of the environmental norms, enhance sustainability practices, reduce environmental footprint.	[6, 81]
Corporate Social Responsibility (CSR)	It is represented as one of the sustainable development pillars. It is the commitment to balance the requirements of financial profits and society at large. Involve various stakeholders that influence the company's actions and make pressure on the company to act on some policies.	Moral business practices, improve environmental performance, good governance, enhance sustainability practices develop sustainable solutions, reduce environmental footprint, and meet social needs.	[76, 81, 82]
Life cycle Assessment/ Analysis (LCA)	An environmental analysis tool to examine the likely impacts of environmental aspects of products and services through their life cycle.	Carbon footprint, water footprint, eco-efficiency, material flow analysis,	[77]
Circular Economy (CE)	It is a multi-level system of resource use that stipulates the locked loops of all resources, ultimately no waste of resources.	Recycling, reuse, reduce, resource efficiency, redesign, repurpose, remanufacture, refurbish, waste exchange materials, durability products.	[42, 83]
Best Environmental Practice/Best Available Techniques (BEP/BAT)	Technological and managerial solutions aim to prevent and control industrial emissions to air, water, and soil, and foster more efficient operations.	Maximizing resource efficiency, enhancing energy efficiency and reduce GHGs emissions, minimize hazardous waste, strengthening industrial policy, and encourage industrial innovations.	[3, 84]

<b>Control pollution technology/approach</b>	<b>Aim</b>	<b>Examples</b>	<b>References</b>
Green/Sustainable supply chain management	Manage the activities and services of the entire supply chain to avoid and reduce damaging the environment and human health.	Reduce air pollution and global warming impacts, promote eco-friendly production, improve healthy and safe work conditions, adopt recycling, reduce waste, improve environmental performance, and promote resilient sustainability practices.	[9, 10]
Sustainable manufacturing	“the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound” [85]	design for: (less material consumption, repairability, rework, refurbishment, maintenance, recover obsolete products, removes hazardous materials and material recovery); and cleaner production.	[11]

**Table 1.**  
*Control pollution technologies and approaches.*

There is a need for a multidisciplinary study to examine the interactions between environmental pollution issues and the industrialization processes as a source of pollution. Thus, the evolution of pollution control approaches and technologies in the field of the industrialization process should be oriented to beat environmental pollution, innovative products, and cleaner process development.

## **7. Conclusions**

Industrial sectors face challenges to compliance with environmental regulations and policies, which request control of the pollution sources within certain limits. Consequently, the companies’ environmental performance represents their compliance level in certain environmental aspects such as hazardous-waste generation reduction, air and water pollution control measures, hazardous chemicals consumption records, reduction in environmental incidents, and adopting sustainable practices and resource efficiency.

An accumulation in pollution stock will lead to negative impacts such as the complexity of environmental problems, increasing pollution treatment costs, reduced labor productivity, loss of reputation, loss of competencies, experts, and skilled workforce, and loss of competition. Therefore, pollution problems are the root cause that hinders attain sustainable development in the industrial sectors. Thus, the emphasis on including sustainability in manufacturing processes is essential alongside the best pollution control measures. In this regard, environmental policy instruments play a significant role in sustainable industrial development; therefore, sustainable strategies are the base for the adoption of clean technology and enhancing innovative technology in industrial sectors.

In pursuit of the SDGs, those goals are a voluntary sustainable global framework; that companies can adopt to improve their current environmental situation and implement sustainable practices. One of the key principles of the SDGs is to reform industrial ecosystems toward a better and sustainable future by adopting eco-friendly technology with minimal impacts on the environment. In this vein, SDG 9 plays a crucial function in promoting innovative technologies through revitalizing and strengthening the significant role of the industrial sector in innovations and advancing clean technology.

Furthermore, it should functionalize the circular economy concept to actively implement the applications of the sustainability concept in the industrial processes to increase industrial environmental efforts for better natural resource management, implementing sustainability strategies, and planning for advanced eco-technologies. As a result, that will contribute significantly control of pollution and promote more sustainability innovations. Transform the current industrial systems toward a more feasible eco-friendly needs significant cooperation and coordination among concerned stakeholders. To do so, firstly, industries need to adjust their strategies and plans to be consistent and coherent to start the transformation process toward sustainable industrial development.

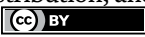
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# Air Pollution from Industrial Emissions and Its Control in Pakistan: Current Situation, Challenges, and Way Forward

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## Abstract

Own to its negative effect on the global ecosystem, air pollution has been a growing concern. Developed world had taken it on top priority long before, now they breathe the air of much better quality. Contrarily, air pollution was not on the priority list of developing worlds. Consequently, air pollution in regions such as South Asia is 5–9 times higher than in the developed world and the world's topmost polluted cities lie in South Asian countries including Pakistan. Now, due to the apparent and widespread, effects and pressure from the local and global community, Pakistan has started taking the air pollution problem more seriously. The governments have taken multiple initiatives concerning monitoring and control of air pollution from industries. However, due to several challenges, the implementation is slow. To increase the pace of air pollution management in the country it is imperative to explore the underlying factors. This chapter synthesizes the available knowledge on the status of air pollution from industrial sources, its control, treatment technologies, and factors slowing the air pollution control and then in the light of this knowledge, provides suggestions to improve the pollution management problem in the country.

**Keywords:** air pollution in Pakistan, industrial fuels, criteria pollutants, factors affecting air pollution, challenges to pollution control, air pollution management

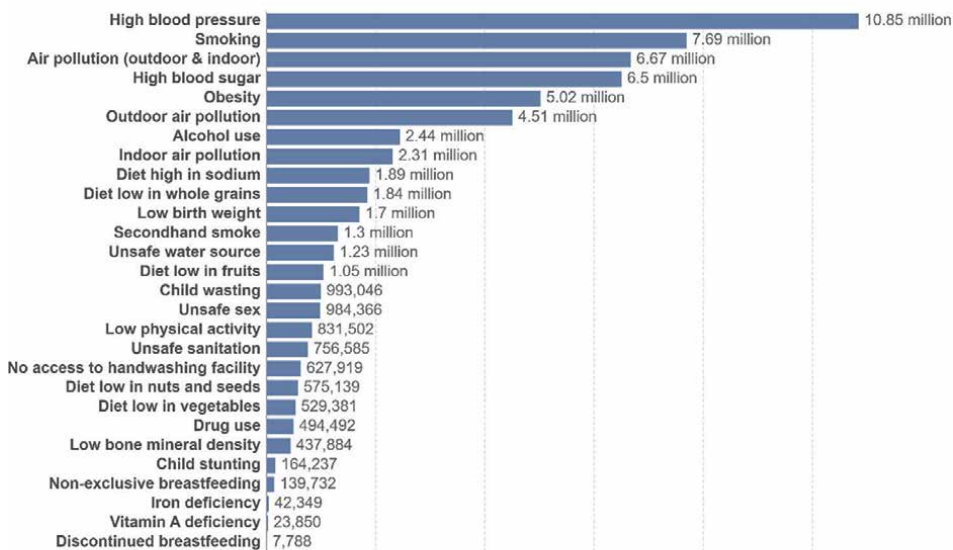
## 1. Introduction

Air pollution is attributed to the release of harmful pollutants into the atmosphere which are inimical to human health and other living organisms. According to the World Health Organization (WHO) report published in 2019, every year 7 million deaths occur in the entire world due to air pollution (**Figure 1**). Air pollution (indoor & outdoor) particulate matter is the main factor causing many diseases like heart problems, stroke, lower respiratory infections, lung cancer, diabetes, and chronic obstructive pulmonary disease (COPD) [1]. The global burden of disease shows that about 4.9 million premature deaths were caused by air pollution in 2017. WHO

### Number of deaths by risk factor, World, 2019



Total annual number of deaths by risk factor, measured across all age groups and both sexes.



Source: IHME, Global Burden of Disease (2019)

OurWorldinData.org/causes-of-death • CC BY

**Figure 1.** Number of deaths by risk factor (Our World in Data, 2021).

estimates about 7 million premature deaths in 2016. Stockholm Environment Institute studies the effects of air pollution on human health. In 2010, a global assessment of pre-term birth revealed that 2.7 million pre-term birth occurs due to exposure to PM 2.5 in outdoor environments [2].

As reported in the World Air Quality Report (WAQ, 2019) Asia is highly polluted with the highest particulate concentrations compared to the rest of the world. Among its four sub-regions i.e., South Asia, Southeast Asia, East Asia and West Asia, South Asia has the highest pollution concentrations with four out of the top five polluted countries in the world and thirty out of forty most polluted cities in the world. In Bangladesh, India, Nepal, and Pakistan the air quality is much worse (44%) than it had twenty years ago, especially in Pakistan where air quality has remained poor since 1990. One of the leading reasons which are causing air pollution in Pakistan is the emission of industries like carbon dioxide, sulfur dioxide, nitrogen dioxide, smoke, etc. Pakistan’s industrial sector is very broad and deals with textile, leather, chemicals, fertilizers, petrochemical, pharmaceutical, paper and board, electric, sugar, food, automobile, cement, and heavy engineering industries. These industries bring about capacious hazardous waste, noxious gaseous pollutants, and other emissions which are poisonous to human health. Under the World Trade Organization administration, there are some strict rules and regulations set by ISO for the safe disposal of hazardous substances, effluents, and waste. Pakistan is included in those Asian countries where industrial pollution is at high and unaccepted levels. About 6.5 million people are hospitalized each year due to diseases caused by industrial pollution.

Air pollution emitted from different sources has different effects. To understand the basic concept of sources first, we need to understand their origin, how much they

are affecting people, and which are the most polluted cities. Since most of the air is polluted due to industrial activities, it is vital to understand the concept of air pollution in connection with industries. This chapter intends to comprehend information on air pollution from industrial sources. To achieve this goal, we have outlined this chapter in the following sections. In the first section, we have described the mechanisms of pollutant formation, the second section describes the current situation of air pollution in Pakistan, in the third section we comprehend challenges being faced by the enforcement agencies in ensuring compliance from industries, and in the fourth section, different options to ensure compliance by industries and pollution control are described.

## **2. Mechanism of pollutant formation in industrial processes**

Criteria of air pollutants are those pollutants upon which we set the limit range of exposure which is tolerable. There are a total of six criteria pollutants carbon monoxide, sulfur dioxide, nitrogen dioxide, particulate matter, ozone, and lead [3]. Based on their composition air pollutants are divided into two types, particulate matter, and gaseous pollutants. Particulate matter consists of solid airborne particulates like dust, fly ash, smoke, fog, soot, and fumes. While on the other hand, gaseous pollutants consist of carbon monoxide, sulfur dioxide, and nitrogen dioxide. Pollutants are also classified into primary and secondary based on their formation process. Pollutants that directly exit from combustion processes are known as primary pollutants. Among criteria pollutants, carbon monoxide, sulfur dioxide, nitrogen dioxide, particulate matter, and lead are the primary pollutants. When these primary pollutants encounter each other in the presence of moisture, energy, and volatile organic compounds (VOC) in the atmosphere, they form secondary pollutants such as particulate matter ozone, and other reactive materials. Primary particulate matter is solid while secondary particulate matter is liquid [4]. Since sulfur and nitrogen oxides released from industries are the primary constituents of secondary particulate matter. Almost 30% of sulfur dioxide and 90% of nitrogen oxides in the atmosphere transform into secondary particulate matter. Moreover, the nature, type, and quantity of primary pollutants from industrial sources largely depend on the type and quality of fuel used. Therefore, formation mechanisms are described based on the type of fuels as well.

### **2.1 Growth of the industrial sector in Pakistan**

With a 19% share of the gross domestic product (GDP), the industrial sector is the second largest sector in Pakistan [5]. Throughout recent history, it has been growing owing to local and global factors. According to the Pakistan Bureau of Statistics, there were 4474 large-scale manufacturing industries (LSMI) in 1995. The number grew to 8680 in 2005–2006 and rose exponentially to 42,578 in 2015–2016. Industrial growth in Pakistan is associated with globalization and the growth of personal remittances received [6, 7]. The industrial sector has been one of the major contributors to air pollution in Pakistan. As reported by [8] over the past two decades between 1977 and 1998 the SO<sub>2</sub> emissions from the industrial sector had increased by 52 times (**Table 1**). Their growth will further deteriorate ambient air quality, making it imperative to synthesize the status of industrial emissions in the recent past.

Sector	1977–1978		1987–1988		1997–1998	
	SO <sub>2</sub>	NO <sub>x</sub>	SO <sub>2</sub>	NO <sub>x</sub>	SO <sub>2</sub>	NO <sub>x</sub>
Industry	19	N/A	423	N/A	982	N/A
Transport	52	N/A	57	N/A	105	N/A
Power	4	3	95	N/A	996	76
Domestic	5	N/A	16	N/A	40	N/A
Agriculture	5	N/A	28	N/A	40	N/A
Commercial	11	N/A	13	N/A	25	N/A

Notes: N/A = not applicable; SO<sub>2</sub> = sulfur dioxide; NO<sub>x</sub> = nitrogen oxide.

**Table 1.**  
Air pollutants from the industrial sector (modified from [8] (thousand tons)).

## 2.2 Commonly used fuels in the industrial sector

The main factors which control pollutants loaded from industries into the atmosphere are the type, quantity, and quality of fuels. Besides emission loads, the nature and type of pollutants also depend on fuel characteristics [9]. Keeping in view their imperativeness to pollutants characteristics this section describes the type and chemical characteristics of fuels which are commonly used in Pakistan. As per the energy outlook of Pakistan report coal, diesel, firewood, furnace oil, compressed natural gas (CNG), liquid petroleum gas (LPG), and petrol (gasoline) are the major fuels being used in the industrial sector [10]. Among these fuels coal and firewood are solid, diesel, furnace oil, LPG, and petrol are liquid, while CNG is a gaseous fuel. The industrial use of fossil fuels (coal, diesel, firewood, furnace oil, CNG, LPG, and petrol) has been increasing in Pakistan. As reported by [11], the total industrial use of fossil fuels in 1990 was 5.71 million tons of oil equivalent (Mtoe), and it rose to 18.07 Mtoe in 2019.

It is the quality of fuel that determines how much of the fuel will transform into pollutants. The quality of solid fuels is characterized based on their chemical properties such as the percentage of moisture contents, volatile matter, fixed carbon and ash contents, and concentration of hydrogen, carbon, nitrogen, oxygen, and sulfur contents [12]. In the case of liquid and gaseous fuels, their quality is determined based on flash point (Table 2), density, ignition point, kinematic viscosity, heating value, and ignition temperature [13]. The chemical properties of solid fuels are determined by using proximate and ultimate analysis. While of liquid and gaseous fuels, they are determined by using analytical techniques [14].

## 2.3 Mechanism of formation

This section describes the mechanisms of pollutant formation from commonly used fuels in industries in Pakistan.

### 2.3.1 Oxides of sulfur

Oxides of sulfur are formed when sulfur-containing fossil fuels are burned. During the formation of coal and oil, a small part of sulfur fused into fossil fuel.

Type	Fuel	Flash point (°C)	Density (kg/m <sup>3</sup> )	Kinematic viscosity (m <sup>2</sup> /s)	Heating value (MJ/kg)		Ignition temperature (°C)
					HHV	LHV	
Liquid/ gaseous fuels	Gasoline	-42	750	$0.5 \times 10^{-6}$	45.7	42.9	246-280
	Diesel	50	830	$3.0 \times 10^{-6}$	47	43	210
	CNG	-187	0.72	$7.8 \times 10^{-6}$	55	50	537
	LNG	-188	430	$1.6 \times 10^{-6}$	50	45	537

**Table 2.**  
*Qualitative characteristics of major industrial fuels [9].*

Sulfur is discharged into the atmosphere as sulfur oxide when fuel is burned. In the case of coal, sulfur is present in inorganic compounds like pyritic sulfur and sulfates. In coal, about 0.2–5% sulfur is present in dry form. Sulfur is emitted when high temperatures occur which is basically during the gasification process [15]. In the case of oil, sulfur dioxide converts into sulfur trioxide during combustion. This process is carried out by vanadium oxides and iron which play the role of catalysts [16].

### 2.3.2 Oxides of nitrogen

Oxides of nitrogen released from industries are a blend of nitrogen oxide and nitrogen dioxide. Most oxides of nitrogen are formed by human activities like fossil fuel burning, the formation of nitrogen acid and nitrogenous fertilizers, and some other industrial processes. There are two types in the case of fuel combustion, one is thermal NO<sub>x</sub> which is released when oxygen and nitrogen are burned at high temperatures. Second, is fuel NO<sub>x</sub>, formed by decomposed and oxidized compounds of nitrogenous compounds in fuel like pyridine (C<sub>5</sub>H<sub>5</sub>N) and carbazole (C<sub>12</sub>H<sub>9</sub>N) at high (1204°C) temperatures [17].

In fuel type NO<sub>x</sub>, about 0.3–2% nitrogen is present by weight. These fuel compounds which have nitrogen emit in the form of gas when the particles of fuel are burned in the devolatilization process. Which results in the formation of HCN, NH<sub>3</sub>, and N [18]. In coal type NO<sub>x</sub>, coal consists of organic nitrogen compounds which discharge into the atmosphere as volatile gases. These compounds react with the oxygen present in the air in the boiler combustion zone [19].

### 2.3.3 Oil combustion

Major boiler constellations for fuel oil combustors are water tubes, fire tubes, cast iron, and tubeless designs. Boilers are based on the orientation of heat transfer surfaces, burner shape, and size. In fire tube boilers, hot combustion gases pass through the tubes while water heated revolves outside the tube. High-pressure steam in the fire tube unit is carried by the very strong boiler wall. Fire tube boilers are small, and they are used where boiler load is relatively constant. In the case of a cast iron boiler, combustion gases level up through a vertical heat exchanger and discharge through an exhaust duct. Such types of boilers are used in commercial or residential areas (internal layout of fire tube boiler) [20].

In the diesel combustion process, hydrogen and carbon make the lineage of diesel fuel work like fossil fuel. When the combustion process is complete it will

make carbon dioxide and water in the combustion chamber. During the combustion process, a lot of dangerous products are released [21]. Pollutants that are emitted from diesel fuel are mostly CO, HC, NO<sub>x</sub>, and PM. NO<sub>x</sub> contributes (50%) more to polluting the air than other pollutants. After NO<sub>x</sub>, PM plays a vast role in polluting the air [21].

#### *2.3.4 Carbon monoxide*

Carbon monoxide is formed when organic materials like firewood, coal, and gasoline are partially burned. Due to an insufficient amount of O<sub>2</sub>, oxidation rate from CO to CO<sub>2</sub> is very slow. In the case of industries, the formation of CO is completely different, which is called steam reformation. Methane gas is mixed with steam gas in the presence of a catalyst at a high temperature which results from hydrogen gas and carbon monoxide [22].

#### *2.3.5 Particulates matters*

These are small solid particles present (PM 2.5 and PM 10) in the atmosphere. These particles originated from fire ash, dust particles, industrial plants, and asbestos (20). In industries, these particles are formed through the combustion process or the complex reactions of oxidation in gases like sulfur dioxide and nitrogen dioxide [23]. Particulate matter released from diesel is known as diesel particulate matter (DPM). It is made of elemental carbon, PAHs, and nitro PAHs [24]. Particulate matter released from firewood burning is microparticles that form when organic matter and wood burn [25]. Asbestos particulate matter is different from others because its length is greater than its width. The mechanism which is the main source causing the particulate disposition is impaction, diffusion, and sedimentation [26].

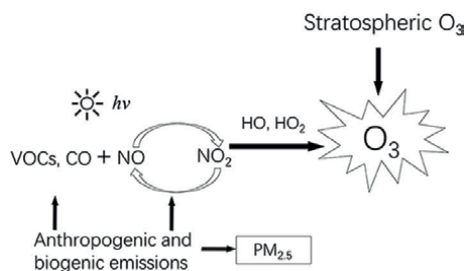
#### *2.3.6 Coal combustion*

Coal is an inorganic fuel. When coal is heated the organic matter of coal is pyrolyzed which develops as volatile. The remaining solid is a mixture of carbon and mineral matter, which is known as char. The combustion of coal is primarily the combustion of carbon as well as volatile matter. Combustion of coal has three basic steps. (1) Discharge of volatile matter in response to heating of coal, (2) volatile matter, which is released burn, and (3) burning of the remaining char. The flaming process of volatile matter and coal combustion takes place at the same time (Partitioning of coal combustion mechanism) [27].

#### *2.3.7 Ozone*

When NO<sub>x</sub> and volatile organic compounds discharge into the atmosphere they react with each other in the presence of sunlight which causes the formation of ozone (**Figure 2**). Triplet oxygen is formed when dioxygen and singlet oxygen react with each other in the existence of a third body molecule that can absorb the heat discharge during the reaction. Ozone lies in both the troposphere and stratosphere [28].

Ozone is not formed directly but it is a series of complex chemical reactions. Ozone formation from coal is taken by different reactions between reactive organic compounds and nitrogen oxides. A high concentration of ozone is released during a



**Figure 2.**  
*Formation of ground-level ozone [28].*

photochemical reaction [29]. Ozone is released during the burning of oil by a reaction between volatile organic compounds and nitrogen oxide. VOCs such as paints, industrial solvents, and cleaners [30].

### 2.3.8 Lead

Lead (Pb) is known as heavy metal which is found in both natural and manufactured items. The emission of lead into the air is in the form of suspended particles. Exposure of humans to lead is through breathing or the lead present in the air comes in contact with soil or dust [31].

Tetraethyl lead is a lubricant oil that acts as an anti-knocking agent for petrol and gas. It is formed when ethyl chloride reacts with a powdered alloy of sodium and lead [32]. Lead is formed in coal by monosulfides (known as galena), silicates, and pyrite. Its concentration depends on the type of coal like low-rank coal or high-rank coal [33].

## 2.4 Factors affecting the rate of pollutants generation

Besides the combustion process and fuel type, some other factors moisture content, fuel variety, temperature, and ash contents also affect the rate of pollutants generation in coal fuel (**Table 3**). The effect of moisture content on the pollutant (SO<sub>x</sub>, NO<sub>x</sub>, PM, Ozone, Pb, and CO) generation is defined as the increase in the devolatilization rate, and the moisture rate increases [34]. Four coal varieties (anthracite, bituminous, lignite, and sub-bituminous) are commonly being used as industrial fuels. Anthracite does not produce any pollutants during combustion while bituminous, lignite, and sub-bituminous produce pollutants [35]. In the case of temperature, the generation of pollutants increases with the increase in temperature [36]. Likewise, with the increase in the ash content, the concentration of pollutants increases [37].

In oil combustion, an increase in moisture content causes the combustion rate to decrease which means pollutant emission will also decrease [38]. There are different types of fuel like diesel, LPG, LNG, and crude oil. All of them emit air pollutants that have hazardous effects on the environment except LPG. Diesel fuel increases the production of SO<sub>x</sub> in the environment while crude oil and gases contribute ozone, and VOCs in the environment [39–41]. Temperature increases, increase the amount of pollutants, especially nitrogen oxide [42]. Ash content contributes more pollutants into the environment like particulate matter, sulfur, etc. [43].

Sr	Factors	Change in magnitude or type of fuel	Effect on rate of pollutant generation
1	Moisture content	Increase	Increase
2	Temperature	Increase	Increase
3	Ash content fuel	Increase	Increase
4	Type of coal	Bituminous, lignite, and subbituminous	emit pollutants except anthracite coal
5	Type of fuel	Diesel, LNG, and crude oil	emit pollutants except LPG

**Table 3.**  
*Effect of different factors on the rate of pollutant generation in coal and fuel oil combustion.*

### 3. Current situation of air pollution in Pakistan

In this section, we discussed the results of air quality monitoring performed in different cities of Pakistan, their health impacts on people, and some regulatory framework policies implemented in Pakistan for air pollution.

#### 3.1 Air pollution from industries

The rate of urbanization increases with the increase in population which contributes to an increase in the number of transport and industrial sector.

##### 3.1.1 Punjab, Pakistan

In 2015, air quality monitoring was performed in two cities of Punjab Faisalabad and Gujranwala as both are industrial cities to check the pollution load index, pollution index, geo-accumulation index, and integrated pollution index. Results indicate that Faisalabad has more pollution index (of 91.43%) while Gujranwala has less pollution index (of 85.29%) [44].

In 2017 Lahore, Punjab Pakistan research work was conducted to check out monthly and diurnal patterns of air pollutants. As Lahore lies in the semi-arid region it means low rainfall and cold dry winter. The air quality index is high during the winter season (November to February) which represents low temperature and humidity. On the other hand, the air quality index is low during the summer season (June to August) due to high temperatures and high wind speed [45].

Oxidative potential, chemical characteristics, and sources of PM 2.5 were measured in Lahore and Peshawar, Pakistan in February 2019. The level of exposure is estimated to be high in both cities. Major sources which deteriorate the quality of air or contribute the PM 2.5 in the atmosphere are carbonaceous species. Peshawar is under a high range of DTT (carbonaceous species) while Lahore has less. Road dust and traffic pollution play a huge part in the expansion of oxidative potentials [46].

In Faisalabad, Pakistan spatial and temporal changes were observed in aerosol particulate matter at nine different sampling sites from June 2012 to April 2013. Results indicate that the concentration of these PM is 20 times higher than the standard limits set by WHO. Fine particles are in high concentration during winter, coarse particles represent high concentration during summer time [47].

In Lahore, Pakistan air quality monitoring is performed in 15 households in different seasons with the help of DusTrak aerosol quality monitor. Monitoring is

performed for seventy-two hours in the kitchen and living rooms. PM concentration is observed to be high during winter and autumn seasons while low during monsoon and summer seasons [48].

### *3.1.2 Islamabad, Pakistan*

In 2017 air quality monitoring was performed in Islamabad and Rawalpindi, Pakistan. The combined population of both cities is about 15 million. The main objective of this monitoring is to identify the concentration of SO<sub>x</sub>, NO<sub>x</sub>, Ozone, PM 2.5 and PM 10, and carbon dioxide. Results indicate that all pollutants are present within permissible limits except PM 10 and carbon dioxide. PM 10 and carbon dioxide caught high concentrations at Saddar, Rawalpindi, and Blue Area, Islamabad [49].

### *3.1.3 Sindh, Pakistan*

Air quality monitoring was performed (post-monsoon and pre-monsoon) in different sites in Karachi, Sindh Pakistan from 2017 to 2019. Monitoring areas are Landhi Industrial Area, Korangi Industrial Area, and North Karachi Industrial Area. Most criteria pollutants are focused on checking their concentration in these polluted areas. Results show that the concentration of pollutants is less observed in post-monsoon while these pollutants have high concentration during pre-monsoon season. Korangi and Landhi have more exposure to these pollutants (especially PM 10 and PM 2.5) than other areas [50].

### *3.1.4 Peshawar, Pakistan*

In Peshawar, KPK Pakistan density of particulate matter has exceeded the WHO average PM limits. In November 2016 monitoring results show that the average mass concentration of PM 2.5 and PM 10 is 252.6 and 771.8 micrometers. The concentration level is 10 to 16 times more than the recommended WHO limits [51].

In Peshawar, Pakistan particle size distribution and mass concentration measure by aerosol spectrometer GRIMM (Durag Group, Hamburg, Germany) spectrometer data. The positive matrix factorization model helps to mark the suitable sources (Industrial, brick kiln, and vehicular emissions) which contribute to the PM in Peshawar. Data was collected for 20 days both morning and evening in April 2011. Results show that the volume size distribution of aerosol is high during the morning and afternoon. Especially during the rush hours [52].

### *3.1.5 Baluchistan, Pakistan*

Air quality in Quetta, Baluchistan Pakistan is more harmful than in other provinces in Pakistan. PM, Sox, NO<sub>x</sub>, and carbon dioxide these parameters' concentrations are more than the actual normal limit. Lead petroleum fuel usage is higher because of smuggled petrol from Iran and Iraq. Studies reveal that the presence of lead in the blood level of people of Quetta is 28.3 µg/dL while in Tokyo it was 6 µg/dL. About 25 brick kilns are available around Quetta city as well as some small industries. The range of SPM of ambient air quality is 170 µg/m<sup>3</sup> (at station Qta-2) to 500 µg/m<sup>3</sup> (at Qta-1) with an average concentration of 370.52 µg/m<sup>3</sup>. This concentration surpassed the permissible limit of 200 µg/m<sup>3</sup> provided by (NAQS) [53].

Air monitoring is performed in the Quetta Valley to analyze the concentration of lead in the ambient air. Calculate the ratio of vehicular emission emits from the exhaust

pipe of vehicles and results indicate that it is four times higher than WHO limits. The concentration of lead peaks during springtime while low during summertime [52].

According to the Global Alliance on Health and Pollution, around 128,000 people die each year in Pakistan from pollution caused by air. Around 80% contribution of power, industry, and transportation causes the photochemical haze in Punjab [54].

#### **4. Challenges faced by Pakistan in air pollution management**

In this section, we will discuss the challenges Pakistan is facing in dealing with the air pollution problems. These problems are the main reason behind the deterioration of the air quality in the whole country.

##### **4.1 Unawareness**

The crucial reason behind the environmental issues and major threats related to health caused by air pollution is simply the lack of awareness among the people of developing countries like Pakistan. Indoor air pollution is a major threat to women and children especially in kitchens with the use of biomass fuel stoves. This causes acute respiratory infections in children (less than 5 years of age). Another issue is the availability of accurate information, there is a lack of awareness of the current information about the air quality of Pakistan [55]. Indoor air pollution in industries poses serious problems to the workers. Like in the textile industry during the processing, there is the emission of acid and oil mists, dust, odors, and solvent vapors. In the paper and pulp industry emission of chlorine from the bleaching unit is the most common indoor air pollution [56].

Information related to atmospheric pollution is known in cities of Pakistan but people who live in small towns are unaware of the air pollution. A study was conducted to check public awareness and WTP (willingness to pay) about the removal of atmospheric pollution in small towns of Pakistan by conducting interviews. Analysis of data is performed by the interval regression model. Results indicate that the main sources of information are the newspaper, TV, and radio. About 46% state that the severity of pollution is at an intermediate level. Other 48% believe that sources of this air pollution are vehicular emissions and industrial emissions. In the case of eco-friendly measures, about 37.7% gave concerns about using public transport and 27.7% gave an idea about using equipment on solar. People of towns want the government to perform preventive measures and stop atmospheric pollution [57].

##### **4.2 Weak policies and regulations of government**

Policies related to health, monitoring, and industrial rules are not strict in developing countries, especially in South Asia. In Pakistan, rules and regulations on air quality standards are not properly implemented. Pak-NEQs are introduced but still no feedback on such standards because of govt weak policies and unsatisfactory legislation.

##### **4.3 Usage of unfavorable fuel**

Poor quality fuel makes the quality of the air worse. Due to energy crisis problems in Pakistan usage of fuel has increased in the energy sector which pollutes the air. Pakistan introduces some high-quality fuels like (EURO 5) for vehicles but these are

available in some parts of the country. Due to the economic condition of the country, govt. is focusing on using Thar coal instead of importing oil. This will make the condition worse and there will be high emissions of SO<sub>x</sub> and NO<sub>x</sub> [55].

#### **4.4 Agricultural practices**

Agricultural practices are the primary source of air pollution in Pakistan. The burning of crops or agricultural residue is the main contributor of carbon dioxide in the atmosphere. Emission of nitrous oxide from synthetic fertilizer. Crop residue, agriculture machinery, and cereal production are the intense causes of air pollution in Pakistan [58]. Stubble burning also causes smog in cities like Lahore and Karachi. According to FAO in 2018, about 20% of air pollution contributes to crop burning in Pakistan [59].

#### **4.5 Deforestation**

Deforestation causes environmental problems like air pollution, climate change, and soil erosion. It means the cutting, and burning of the trees for cooking or medical purposes [60]. Policy management in the case of forestry is not so good in Pakistan. Deforestation is at a high level in northern areas of Pakistan due to poor provincial governance and illegal usage [61]. Some brick kilns use wood as fuel which has a significant effect in causing deforestation and air pollution [62].

### **5. Modern air pollution treatment technologies**

In this section, we will discuss the current modern technologies which are being used to treat air pollution. We will discuss each technology for all criteria pollutants (particulate matter, ozone, SO<sub>x</sub>, NO<sub>x</sub>, lead, and carbon monoxide).

#### **5.1 Particulate matter (cyclone separator)**

There are many technologies to remove particulate matter but the simple one which is used by most the industries is cyclone separator. Cyclone separators are also known as dry scrubbers. It works on the principle of inertia (centrifugal force makes the particles suspend and isolate them in the gaseous phase while the large particles move inside the cyclone due to inertia). Cyclone separators are used to remove the large particulate matter. Its efficiency depends on the density and size of the particles. Cyclones are cheap, their physical appearance is cone-shaped with no moving parts, and can endure high temperatures and pressure [63].

##### *5.1.1 Mechanism*

As discussed above there are many cyclones available but the best one for use is the reverse-flow cyclone. It reflects the thoughts on a new cyclone design which has a cone under a cylindrical body with a tangential inlet. The performance of the separation process depends on the length and the structure of the double vortex. In this design, vortex length and separation performance increase by decreasing friction losses in cyclones. This type of cyclone has inner and outer cylinders without any vortex limiter and conical parts. Through the outermost cylinder, the flow spirals

down toward the inner cylinder without hitting wall friction before reversing course through the limiter plate in the path of the exit pipe. The vortex length is unable to be adjusted by moving the vortex limiter up or down. By way of example, the vortex limiter can be lowered downward to expand the vortex length and attain maximum efficiency if the rate of flow or inlet velocity increases. The centrifugal force allows the particles to travel toward the outer cylinder wall, which is where they become separated from the vortical flow and aggregate at the outer cylinder bottom. This is the initial process of segregation that takes place in the outer cylinder. The positive aspects of the new design include low cost of upkeep and ease of fabrication (Cyclone design) [64].

## **5.2 SO<sub>x</sub> (flue gas desulfurization)**

There are three methods available to reduce sulfur dioxide emissions. (1) Remove the sulfur from the fuel before combustion. (2) Remove the sulfur dioxide during combustion. (3) Eliminate the sulfur from the flue gas after combustion. Fuel desulfurization and the selection of low sulfur are discussed in pre-combustion controls. In furnace injection, sorbents are utilized in combustion control, which is for conventional coal-fired plants. The flue gas desulfurization process is post-combustion control.

Flue gas desulfurization has been operated through wet scrubbers, spray dry scrubbers, sorbent injection, and regenerable processes. The mechanism of limestone scrubbing is based on the wet scrubbers.

### *5.2.1 Limestone scrubbing*

Wet scrubbers are used mostly to treat sulfur dioxide emissions. To react to the SO<sub>2</sub> in the flue gas, a slurry mixture with calcium sodium-based sorbents is put into a vessel which is particularly built. The removal efficiency of the wet scrubber is about 99%. The main reason behind this process is to make gypsum, a high-quality product which can be used as a raw material in many industries.

All the chemical reactions take place in a single integrated absorber to reduce the cost and energy usage. The integrated single-tower system occupies less space and can be fitted easily in already existing plants. Rubber, nickel alloy, or stainless-steel interiors are typically required for the absorber structure to avoid corrosion and abrasion. Scrubbers for fiberglass are also in use.

The main process of the preparation includes the formation of raw materials, pollutant absorption, maintaining the scrubber suspension pH, oxidation of sulfite to sulfate, separation of gypsum, and the last step is the treatment of wastewater. Limestone is utilized to make the absorber suspension. To produce a homogenous suspension, this is mixed with demineralized or municipal water in the absorber feed tank. The suspension is injected into the absorber with pH of 7 and 20% (by mass content) CaCO<sub>3</sub> concentration. Air pumped from the absorber's bottom enables the generated sulfite to oxidize to sulfate, causing forced oxidation. Upon being reheated above 72 degrees centigrade, the clean exhaust gases escape out into the station flue system. As the solubility of SO<sub>2</sub> declines at low pH values, the absorption rate is highly reliant on pH. To sustain the pH value between 5 and 6.5, fresh feed sorbent solution is introduced to the suspension to cancel out the effect. This retains the quality of the gypsum manufactured and ensures suitable chemical absorption. The bottom of the absorber provides the gypsum suspension, which has 7–18% (by mass) solid matter

concentration. Most of the water content drains off the gypsum suspension when it is introduced into the gypsum separator. Gypsum is collected as fine crystals after the water is removed by using a centrifuge (flow diagram of limestone scrubbing method) [65].

### **5.3 NO<sub>x</sub> (selective catalytic reduction)**

Selective catalytic reduction is such a technology that is applied especially on stationery combinations units where the discharge level of NO<sub>x</sub> is high. SCR system might theoretically develop with a high NO<sub>x</sub> removal efficiency of 100%. In the SCR system, reagents which might be used for the reduction of NO<sub>x</sub> are ammonia and or urea. Before using urea as a reagent, transform it into ammonia.

#### *5.3.1 Mechanism*

The catalytic reactor ammonia injection grid and ammonia storage and delivery system are the main parts of selective catalytic reduction. Post-combustion flue gas is introduced with a nitrogen-based reducing agent, which can be ammonia or ammonia produced from urea. Within a specific temperature range, in the presence of oxygen and the catalyst, the reagent effectively reacts with the flue gas NO<sub>x</sub>, decomposing it into molecular nitrogen and water vapors. SCR operation takes place across a wider and lower temperature range. On the other hand, a significant increase in capital and operational expenditures coincides with the drop in reaction in response temperature and a rise in efficiency. The significant amount of catalyst required to perform a reduction reaction is the primary cause of the increases in capital costs. Ammonia reagent and maintenance catalyst expenses make up more than half of SCR's operating cost. Whereas the catalyst replacement cost was traditionally high, the reagent cost has risen to be the most significant element of running cost for most of the SCR. By an injection grid installed in the ductwork, the reagent is introduced into the flue gas downstream of the combustion unit and economizer. For ease of injection, the reagent is usually dissolved with steam or compressed air. After the reagent and the flue gas combine, they both approach a reactor chamber that contains the catalyst. The NO<sub>x</sub> in the flue gas chemically reduces nitrogen and water when the heated flue gas and reagent permeate through the catalyst and encounter active catalyst sites. The reaction is driven by heat from the flue gas. In the meantime, the SCR reactor discharges nitrogen as well as any other components of exhaust gas (SCR flow process diagram) [66].

### **5.4 Ozone (thermal catalytic method)**

Ozone is known as a pale blue pollutant whose concentration increases as the altitude increases. There are some methods used to remove the ozone like adsorption with activated method, thermal decomposition, and thermal catalytic removal of ozone. It is one of the best catalytic techniques. Use of different nanosized catalyst metals like platinum, gold, and palladium are used as active catalyst components. The catalyst is usually placed on the metallic and ceramic honeycomb support. Ozone should be shifted to the catalyst surface which meets the catalyst and decomposes as the catalyst reaction is a surface reaction. Ozone must diffuse first via the outer surface, then move through the porous network and engage with the catalyst to stop the conversion.

#### *5.4.1 Mechanism*

One through experimental design (used in bleeding air purification of aircraft cabin) is used to remove the ozone. High pressure zero is produced by a zero-air generator driven by an air compressor. For regulating the mass flow rate of the zero gas (ThermoEnvironmental Inc. Model 146C) is used in conjunction with the zero-air generator. To add the ozone into the experimental setup, an ozone generator with three UV lamps and a primary wavelength of 254 nm is used. UV lamps are used to control the amount of ozone that enters the system. A specific concentration of ozone reached the reactor, which was set up in the middle of the electric resistance furnace after the flow rate and the ozone concentration remained steady for more than an hour. This transpired when the ball valve in route two opened and the valve in route one closed. To fulfill the temperature requirement of the bleed air, regulate the furnace temperature by using the temperature controller within the range of 25–500°C. A U tube manometer is used to measure the reactors' pressure drop. A thermostatic water bath is employed to the lower airstream temperature before it reaches the ozone analyzer, as the ozone analyzer air suction temperature is low. To regulate the ozone analyzer measurement, a declaration section is outfitted with equipment to lower air velocity. The reaction temperature is measured by a thermocouple that was inserted into the reactor. Single activated carbon or activated carbon loaded with palladium catalyst is rolled up and filled inside. The airflow is passed through a 3 mm opening in the middle of the rolling-up ACFs. Later, frosted glass was attached to the quartz reactor on both ends to result in a powerful sealing effect.

#### *5.4.2 Preparation of Pd/ACFs*

After being submerged in the palladium solution, the treated ACFs are run through an ultrasonic cleaner for 10 minutes. Afterwards, the palladium solution underwent 6 hours of vacuum pump suction separating to eliminate the particles of the chloride which are left behind. Eventually, the catalyst Pd/ACFs are formed by submitting (Pd/ACFs) to a twelve-hour blast oven with an electric thermostat set at 100°C (experimental setup of ozone converter) [67].

### **5.5 Carbon monoxide (biofiltration)**

The old treatment technologies for carbon monoxide are UV and photocatalytic techniques, and selective catalytic oxidation with noble metals like Au, Ru, and Rh. The main disadvantage of such technologies include it cost a lot of money. One technique is biofiltration, which is passing a stream of contaminated air through a bed filled with solid media before it is evacuated or humidified. Biofilter contains microorganisms (methanotrophs, ammonia oxidizers, oligotrophic bacteria, fungi, and algae) which break down the pollutants.

#### *5.5.1 Mechanism*

Nutrient solution (gram per liter) which is used during the study is magnesium sulfate heptahydrate (0.12), monopotassium phosphate (0.25), ammonium sulfate (1.18), sodium chloride (1.00), and ammonium chloride (0.96). Vitamins and trace mineral filter sterilized solution were added to the culture media after it had been autoclaved for 20 minutes at 120°C.

It is a glass cylindrical packed bed reactor with dimensions of 500 mm in height and 80 mm in diameter. The column that had been packed with lava rock or a mixture of lava rock or peat had an active height of 300 and 450 mm, respectively. The total reactive bed volume is either 1 or 1.5 L. Teflon has been utilized for all tubing, fitting, and connectors. The biofilters were supplied with the appropriate amount of humidified air and CO through its top. A pressurized cylinder delivered the pure CO that was placed inside the Tedlar bag. A small reglo peristaltic pump with a tube connecting the bag and silicon tubing was used to control the pump's rotation speed to keep the CO input concentration within the range of 24–8830 mg per meter cube. An empty bed residence time (EBRT) of 85 seconds is given by the gas flow rate of 42 L/h. The range of residence time for the gas flow rate is 0.5–12 minutes.

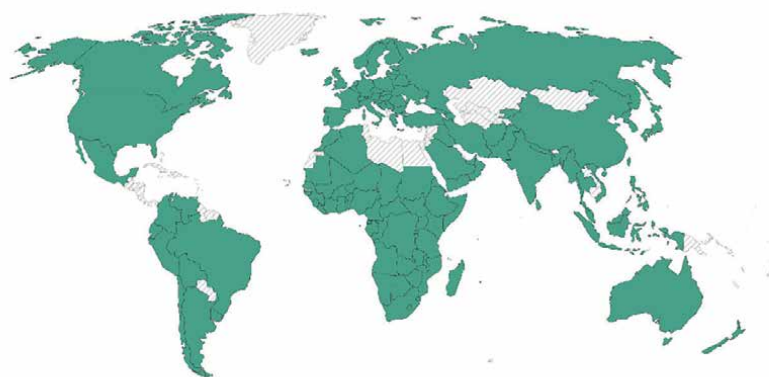
### 5.5.2 Biofilter inoculum

First, 250 ml of aerobic activated sludge from a facility that produced synthetic resin wastewater treatment plant is added to the reactor as an inoculant. Following that, a pure culture of the CO degrader is also injected into it. Before use, a flask of activated sludge with a CO-degrading consortium was subjected to CO-polluted air. The fresh nutrient medium was added with leachate from the previous experimental bioreactor, and pure CO gas was pumped into the bottle as needed. The flask was utilized to inoculate the bioreactor after being incubated at 30°C and 120 rpm of shaking.

Gas chromatography is used for assessing the carbon monoxide gas phase contents in the biofilters. Samples were collected in the filter bed at various heights, and their pH was periodically measured. Regular measurements are made for the leachate's pH. A compatible process is followed to prepare the samples of colonized packing material exposed to CO for electron microscopy investigations (biofilter treating carbon monoxide) [68].

### Global phase-out of leaded petrol in road vehicles, 2021

All countries have banned the use of leaded petrol in road vehicles. Algeria was the final country to do so in 2021.



Still in use Banned Unknown year of ban

Data source: Collected by Our World in Data based on multiple sources

[OurWorldInData.org/lead-pollution](https://OurWorldInData.org/lead-pollution) | CC BY

Note: The specific date of phase-out could not be found for some countries, but all countries have banned its use.

**Figure 3.**  
*Global phase-out of leaded petrol (Our World in Data, 2021).*

## **5.6 Lead (technology under development)**

In the case of lead, there is no such technology which can purify the air from the lead. Overcome the concentration of lead-based air pollution by following some strategies like making lead-free materials and lead-based paint abatement.

According to world data, lead will be completely banned in 2021 (**Figure 3**) and there will be no use of lead-based gasoline in the whole world [69]. Regular gasoline has not included lead since February 1975. In 1986, all gasoline used in on-road automobiles was lead-free [70].

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Section 3

Sustainable Approaches to  
Biological and Industrial  
Waste Management

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## Chapter 8

# Biological Waste Management

*Muhammad Sajid, Ayesha Akram, Syeda Fatima Sajjad,  
Tehmina Siddique and Muhammad Arshad*

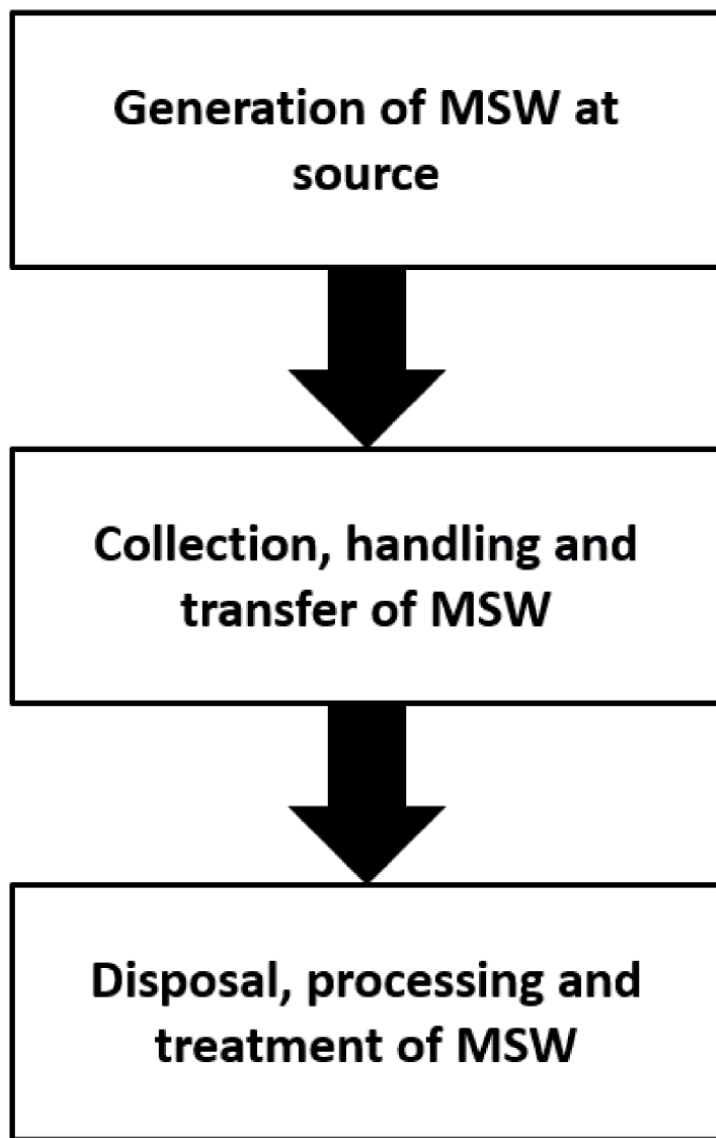
### Abstract

Biological waste management is an important aspect of environmental sustainability that requires proper disposal and treatment of biological waste produced from different sources. Biological waste is waste that comes from biological processes including wastes from plants, animals, hospitals, household, and municipal solid waste (MSW). Biological waste management involves the collection of waste from waste-producing sources, transport, processing, disposal, or recycling. The biological waste management technologies include composting, incineration, landfill, anaerobic digestion, and bioconversion to produce biofuels, i.e., bioethanol, biodiesel, biogas, etc. Urbanization, industrialization, changing lifestyles, and consumption patterns of the public have resulted in increased production of biological waste worldwide. Production of biological waste is affecting soil health and biodiversity, crop productivity in case of discharge of industrial liquid waste into the fields, and human health, and contributes to global warming and climate change. Furthermore, every year, approximately one-third of the food produced is lost from the food chain as waste, resulting in increasing hunger, economic loss, inflation, and inequality among people. Hence, biological waste needs proper treatment to conserve the environment, and the bioconversion of waste to produce renewable sources of energy like biogas, biodiesel, and bioethanol will result in the reduction of emission of greenhouse gases.

**Keywords:** biowaste, MSW, incineration, anaerobic digestion, biogas, 3R's

### 1. Introduction

Biowaste or biological waste is a waste that comes from a wide range of sources including animal wastes, plant wastes, domestic wastes, commercial wastes, ashes, biomedical wastes, construction wastes, radioactive wastes, and industrial solid and liquid wastes [1, 2]. Biological waste management is the collection of waste from the waste generation source, transport, processing, disposal or recycling, and proper monitoring of waste materials in case of hazardous nature of wastes, e.g., radioactive wastes, as shown in **Figure 1** [2]. Biological waste management is gaining attention worldwide as the amount of waste has been steadily increasing due to the increasing human population, changes in their lifestyles and consumption patterns, urbanization, food grain production, economic growth, and industrialization [1–3]. Approximately one-third of the food produced is lost every year from the food chain as waste, resulting in increasing hunger, economic loss, inflation, and inequality among people [4, 5]. Moreover, the generation of biological waste is affecting soil



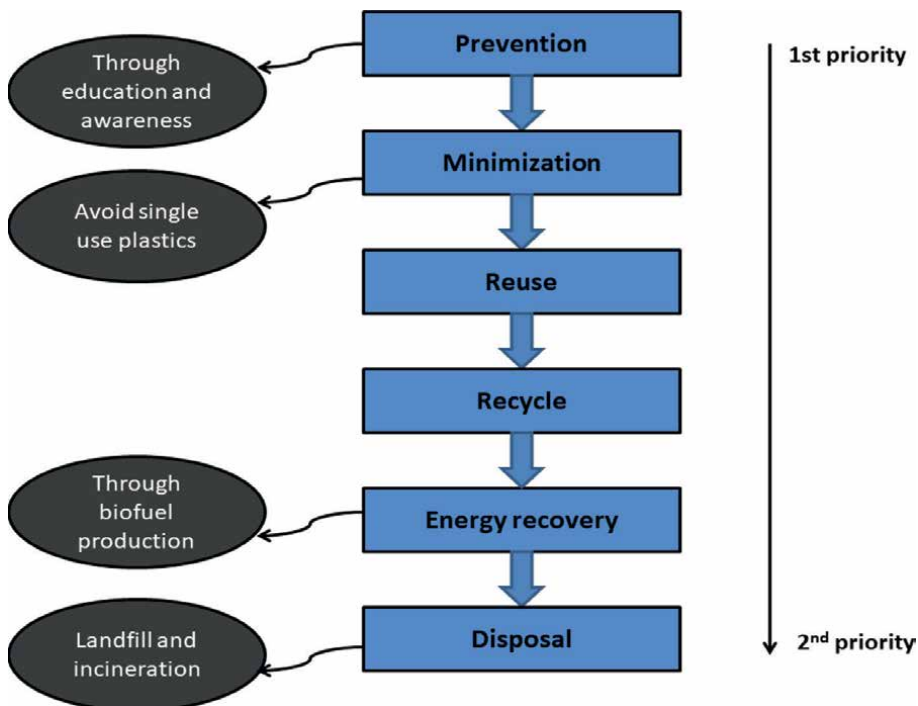
**Figure 1.**  
*General steps of a classical MSW management process.*

health, soil biodiversity, and crop productivity, as in the case of the discharge of industrial liquid waste into the fields, human health, and contributes to global warming and climate change [1].

Municipal solid waste (MSW), one of the contributors to increasing environmental pollution, is defined as waste containing organic and inorganic wastes from residential or household, commercial, and industrial sources [6]. Random urbanization, industrialization, and economic expansion have resulted in increased generation of municipal solid waste (MSW) per head. According to the recent report by the Central Pollution Control Board (CPCB) 2019-2020, currently, about 1.2 kg of solid waste per capita per day, i.e., 3 billion tons per year, are generated by 3 billion residents of the world cities [1]. Due to poor infrastructure, financial constraints, and poor regulatory

policies in developing countries like India, a huge percentage of street garbage is left unprocessed, and thus, they are major contributors to increasing global warming and climate change [7].

For the sustainable development of human society and environmental conservation, biological waste should be managed or treated properly. The waste produced can be recycled or recovered to produce renewable sources of energy like biodiesel, biogas, and biofuels and to recover other nutrients. The waste material can be recycled by the processes of physical reprocessing, biological reprocessing, and energy recovery [2]. The world is shifting from non-renewable energy sources, i.e., fossil fuels, to renewable sources of energy, i.e., biogas, bioethanol, and biodiesel. Burning of fossil fuels releases huge amount of greenhouse gases into the atmosphere and is major threat to the environment and thus human health, while the burning of renewable sources of energy is eco-friendly [8]. Bioconversion of solid waste into energy sources not only reduces the waste concentration from the environment but is also a good step toward the utilization of the waste in a better way. Almost 1.3 billion tons of municipal solid waste was collected worldwide in 2013 and may be expected to increase to 2.2 billion tons by 2025. Most of this is disposed of in landfills, where they may contribute to soil contamination and produce gases such as methane and carbon dioxide that cause global warming. Biological methods (such as anaerobic digestion, esterification, and fermentation) and physiochemical methods (such as gasification, incineration, and landfills) are currently in practice to transform waste into energy [2, 9]. For example, biodiesel is produced by the esterification reaction of restaurant oils and bioalcohols from organic wastes using fermentation. The waste management hierarchy is shown in **Figure 2**, which shows that prevention from



**Figure 2.**  
*Waste management hierarchy.*

creating waste should be our first priority, while the disposal of waste should be the second or last choice.

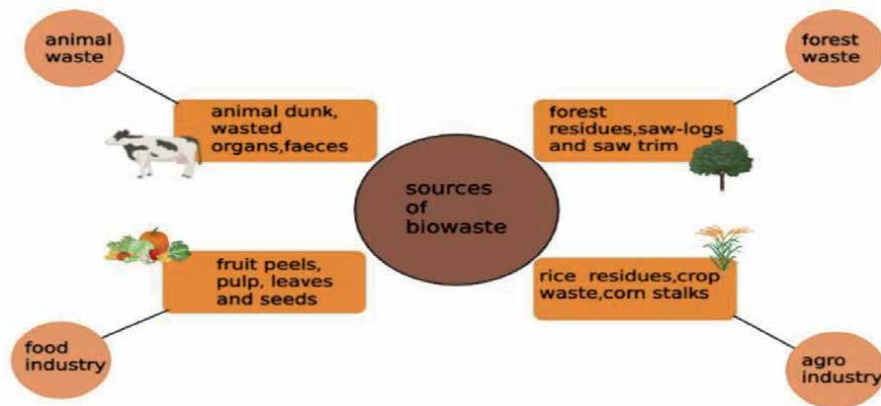
The biological waste management technologies are composting, incineration, landfilling, anaerobic digestion, disposal methods, and bioconversion for biofuel production [2, 4]. Composting is an aerobic conversion of organic waste such as fruits and vegetable scraps into nutrient-rich soil through natural decomposition that can be used to nourish plants [10]. Incineration is the combustion of waste material. A landfill is a container-like body for the disposal of wastes. Anaerobic digestion is a process employed to convert the organic material directly into biogas carried out by a group of microorganisms in the absence of oxygen [9].

Managing biowaste should be cost-effective in order to protect the environment and improve living standards. Secondly, education and awareness regarding waste management are very important from a global perspective of pollution control and resource management [2]. The concept of a sustainable environment should be introduced to the youth to reduce the amount of waste that is discharged into the environment by reducing the amount of waste generated, i.e., amount of waste discharged  $\leq$  amount of waste generated. Burning of waste in open fires should be avoided to prevent human health and environmental risks. Furthermore, a detailed overview of the types and sources of biological wastes, along with their management methods, are discussed below.

## 2. Classification of biological waste on the basis of its sources

On the basis of sources of waste, they are generally classified into (1) domestic wastes, (2) animal wastes, (3) biomedical or medical wastes, (4) commercial wastes, (5) ashes, (6) construction wastes, (7) industrial solid wastes, (8) sewer, (9) hazardous wastes, (10) agricultural residues, (11) biodegradable wastes, and (12) non-biodegradable wastes [2] as some are mentioned in **Figure 3**.

*Domestic wastes* include household wastes that contain fabrics, plastic, paper, vegetable and fruit scraps, polythene, ceramics, etc. A case study was done in Dhanbad, India, to predict household solid waste production. According to PIB (Press Information Bureau, Government of India), in 2016, 165 million tons of waste



**Figure 3.**  
*Different sources of biowaste.*

were produced yearly, which is continually increasing [11]. *Animal or livestock wastes* include livestock manure. According to a report by EPA in 2015, about 55 billion tons of animal waste is generated by animal categories [12]. *Medical or biomedical waste* is generated in the diagnosis, treatment, or immunization of animals and human beings [13]. According to a study, total medical waste generated by healthcare facilities was 28.8% in 2011 [14]. *Commercial wastes* include packing materials, polythene, spoiled goods, printer papers, and vegetable and meat remains that are generated in commercial places like shops, offices, etc. A case study was done in Austria in 2000 to predict the commercial waste generation from different sources. This study tells us that about 20–50% of the waste comes from commercial sources [15]. *Ashes* are generated as waste from the burning of wood, coal, fossil fuels, etc. *Construction wastes* generated at the construction sites, e.g., cement, roofing materials, concrete, metal roads, bricks, etc. About 44% of the waste contributes to construction waste, according to a case study to minimize construction waste generation in 2017 [16]. *Industrial waste* is generated by various small or large-scale industries like the textile industry, food industry, pharmaceutical industry, cigarette factories, etc. According to a report by FAO in 2015, between 20 and 50% of food is wasted and produced for human consumption [17]. *Sewer* from the sewerage poses various health hazards to the public. *Hazardous wastes* include radioactive wastes, which may come from the hospitals or energy sectors [18]. *Agriculture residues* include crop residue, husks, straws, wood, etc. *Biodegradable* (can be decomposed) wastes include kitchen garbage, animal dung, etc. *Non-biodegradable* (cannot be decomposed) wastes include plastics, glass, etc.

### 3. Waste management methods

#### 3.1 Disposal methods

For the management of large quantities of a diverse range of biological wastes in an energy-efficient and environment-friendly way, there should be proper disposal. The proper disposing of the waste require the keen examination of the nature of the wastes from their generation sources such as the raw materials for their manufacture, manufacturing process, their hazardous nature, possible reuse of items, and proper disposal of the wastes in general [2]. An integrated waste management system is key to the proper management of biological waste. For integrated waste management, the concept of maximum output consists of 3Rs (reduce, reuse, and recycle) followed by landfill and gas to energy and waste to energy conversion. Traditionally, solid and liquid wastes are disposed of in landfills and through incineration.

##### 3.1.1 Landfill

Disposal through landfill is the most inexpensive waste management method [19]. A landfill is more likely to be a tightly sealed storage container, deprived of air and water, where organic wastes are degraded very slowly with the help of microorganisms—the decomposing bacteria [20]. It has been estimated in 2016 that approximately 16% of all the dumped municipal solid waste (MSW) is incinerated while the remaining is disposed of in landfills [21]. The decomposition of organic waste in landfills is accompanied by a series of stages, each of which is marked by the increasing or decreasing population of specific decomposing bacteria and the production

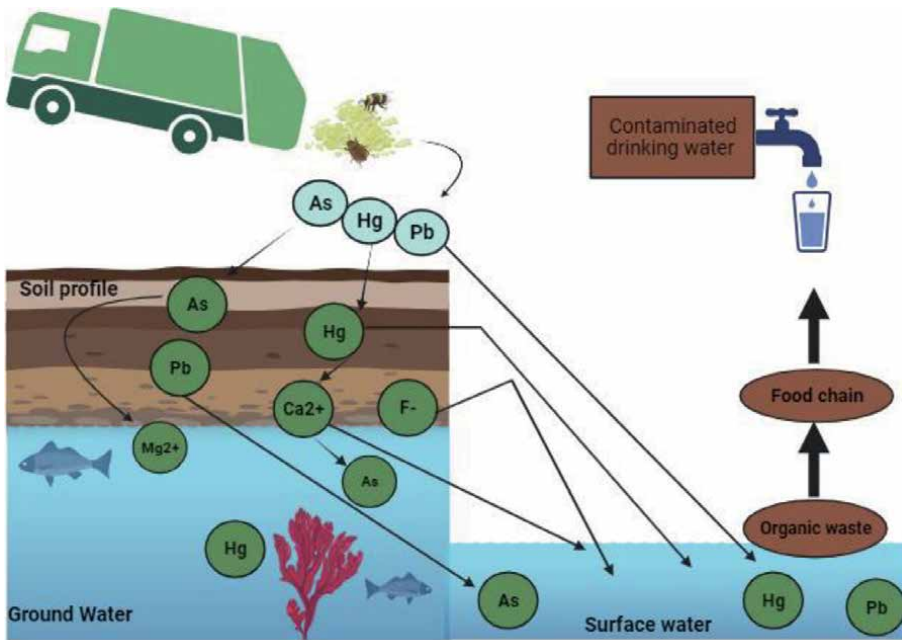
and consumption of certain metabolic products. In the first stage, the aerobic bacteria remove oxygen from the waste. This step usually takes less than a week. In the second stage, a diverse population of hydrolytic and fermentative bacteria acts on the waste and hydrolyzes polymers such as cellulose, proteins, lipids, and hemicellulose into simple monomers such as amino acids, simple soluble sugars, long-chain carboxylic acids, glycerol, etc. The second stage is also termed the anaerobic acid stage. These metabolic byproducts are the components for the generation of biogas and biofuels [2, 4].

Depending on the type of waste, as mentioned in the sectioned named classification of waste, the location and disposal facilities of landfills vary. We have classes, i.e., Class 1 disposes of waste in soil, Class 2 disposes of construction and renovation waste, Class 3 disposes of MSW, Class 4 disposes of commercial as well as industrial waste, Classes 5 and 6 dispose of underground disposal of hazardous waste, i.e., radioactive waste and medical waste, etc. [6, 22].

Effective management of the waste has become a major environmental and social concern. The medical wastes from hospitals can be very infectious as they contain expired drugs, surgical dressings, plastic syringes, blood, etc. [13, 23]. Hence, proper medical waste management is required before it may affect public health or become a source of infectious diseases.

It has been observed that waste decomposition in landfills leads to the emission of greenhouse gases such as methane  $\text{CH}_4$  and carbon dioxide  $\text{CO}_2$ , which, when released into the environment, causes pollution [24, 25]. These gases are produced when MSW is degraded aerobically and anaerobically during chemical, biological, and thermal reactions in the landfills.  $\text{CH}_4$  contributes 1–2% of greenhouse gases [26]. According to a study by United States Environmental Protection Agency (USEPA) in 2020 in the USA, landfills are the third largest contributor of  $\text{CH}_4$  in the atmosphere. Thus, if there is more concentration of combustible  $\text{CH}_4$  gas in the composition of landfill gases, there is a potential hazard of accidental explosions and fires on the site [6]. Furthermore, a case study was done in India in 2017 to analyze the contaminants released from the closed MSW landfill container. The contaminants containing the heavy metals As, Hg, Pb, and  $\text{Mg}^+$  were contaminating the groundwater, soil, and surface water. Drinking water is also get contaminated, causing human health problems after drinking, as can be seen in **Figure 4** [27].

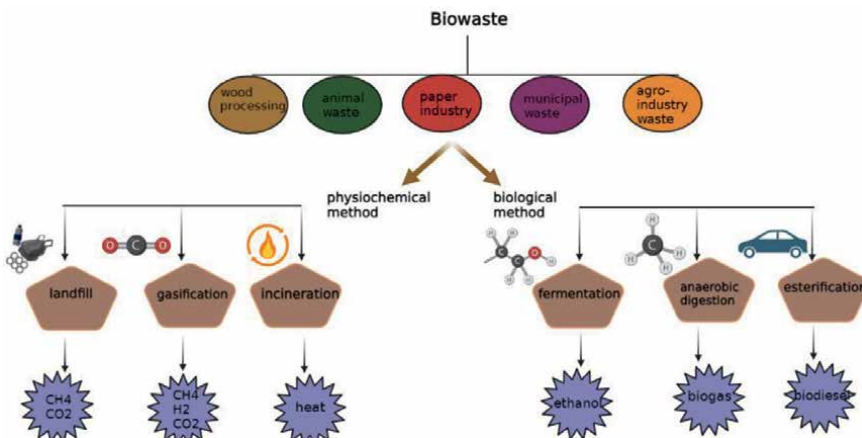
Although disposal of through landfills is the most inexpensive waste management option, it still has some associated problems. The contact of landfill leachates to the surrounding environment can create a threat to public health and nature. The methods developed for the treatment of landfill leachates are classified as physical, biological, and chemical, which are often used in combination in order to improve the efficiency of the treatment process [28]. Biological treatment methods can be aerobic, anaerobic, and anoxic and are widely used for the removal of biodegradable compounds from the leachates. For the removal of non-biodegradable substrates from the landfill leachates, physical and chemical methods are used, and they provide us with high nutrient levels. Furthermore, pretreatment methods are also used to improve the biological treatability of the leachates. EPA (provincial environmental agencies and Environmental Protection Acts) in Canada, USEPA (state environmental agencies and the US Environmental Protection Agency in the United States, Landfill Allowance Trading Scheme in the United Kingdom, Scottish Environmental Protection Agency in Scotland, Northern Ireland Environmental Agency in Northern Ireland and Landfill in the European Union are some of the government agencies which are regulating the management of landfills worldwide).



**Figure 4.**  
 Contaminants in the form of heavy metals released from the MSW landfill site.

### 3.1.2 Incineration

Incineration is another waste disposal method involving the combustion of waste material under high temperatures. It is also sometimes referred as “thermal treatment.” An incinerator is typically designed, built, and operated at specific conditions where the waste material is burnt at high temperature in the presence of oxygen and energy is recovered from combustion [29]. Combustion of waste in the incinerators produces heat, which can be used to recover energy as seen in **Figure 5**. It is used to



**Figure 5.**  
 Production of bioenergy from different biowastes sources.

dispose of solid, gaseous, and liquid waste. Biomedical wastes are also incinerated to prevent health hazards to the public. It also avoids the production of CH<sub>4</sub> gas. It is carried out on a small scale by individuals as well as on a large scale by industries. Japan, China, and the United States are using incinerators to treat the waste to produce electricity [30, 31].

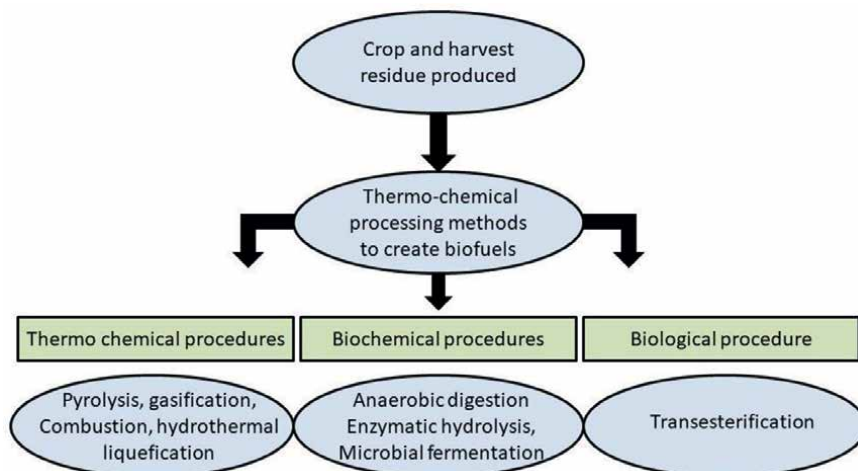
Although incineration is better than landfill disposal, especially with respect to the management of hazardous wastes, this method is considered controversial due to the emission of pollutant gases, which contribute to increasing environmental pollution. The incomplete combustion of organic matter in the incinerator results in the emission of carbon monoxide along with high content of inorganic compounds and carbon compounds [32, 33]. Toxic metals, dioxins, and furan are also released from the incinerators, affecting human health [31]. Inhalation of airborne pollutants causes respiratory problems and consuming contaminated food and water also poses serious health issues in humans [34]. Cancer and respiratory problems, congenital disorders, hormonal defects, and imbalance in the sex ratio are some of the impacts of incineration gases on human life. At the same time, its impact on the environment can be seen in the form of global warming, acidification of soil, smog formation, ozone depletion, aquatic toxicity, and eutrophication in the form of algal blooms formation [35]. A case study was done in Wuhan (China) in 2015 to evaluate the waste incineration plants to determine the impact on the environment, human health, and the site [36].

## **4. Biowastes as biofuels**

### **4.1 Agriculture residues**

Agriculture residues are generally categorized into field residues and process residues. The material left in the fields after the harvesting of the crop is field residue [2]. For example, stalks, stems, seed pods, and leaves. The material left after the processing of the crop into a usable resource contributes to process residue. For example, husks, seeds, roots, bagasse, etc., are used as components of biofuel generation, while others are used as animal feed and for soil management. For example, cereal straw is used as feed, garden mulch, and animal bedding, and the majority of it is burned into the soil. Field burning is generally practiced to dispose of straw, but now many countries are imposing bans on this traditional practice to avoid pollution generated. Likewise, corn Stover can be converted into biofuels as it has the potential for direct burning [33]. Through gasification, rice husk can be converted into fuel of uniform quality. Woody crops (poplar) and tropical grasses (elephant grass) are gaining more attention from energy crop companies due to their suitability (cellulose: lignin) for subsequent processing as energy crops.

Agriculture waste or crop residues are generally converted into biofuels by biochemical and thermochemical conversion technologies and are shown schematically in **Figure 6**. The thermochemical technologies can be combustion, gasification, pyrolysis, and hydrothermal liquefaction, while biochemical methods include enzymatic hydrolysis, anaerobic digestion, and microbial fermentation. In addition to these, sometimes transesterification, a chemical method, is used to convert the biomasses [37]. Combustion is a process in which biomasses are burnt in the presence of excess oxygen to convert them into thermal energy [38]. In a case study in Pakistan in 2016, it was showed that utilizing 70% of rice husk residues by combustion generated 1328 GWh of electricity annually. Using rice husk residues as a source



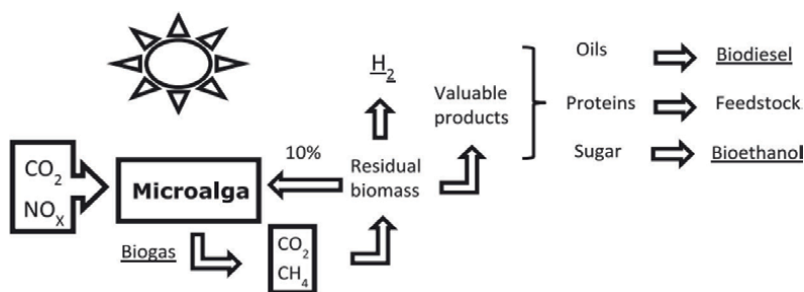
**Figure 6.**  
 Conversion techniques of agricultural residues into biofuels.

of energy, there is a great reduction in methane consumption and carbon dioxide emissions, and the provision of jobs in energy sector will reduce unemployment to some extent [39]. Gasification is a thermochemical conversion process in which we obtain a gaseous mixture of biomasses in the form of methane ( $\text{CH}_4$ ), hydrogen ( $\text{H}_2$ ), carbon dioxide ( $\text{CO}_2$ ), and carbon monoxide ( $\text{CO}$ ) in the presence of may be oxygen, steam, or a mixture of above-mentioned gases [38, 40]. In a case study in Malaysia in 2014, waste of oil palm was used to get the hydrogen to use it as a fuel by gasification process [41]. Burning of hydrogen does not produce greenhouse gases and can be used efficiently for electricity generation such as in hydrogen fuel cells [42]. Pyrolysis is a thermochemical decomposition occurring in the absence of oxygen at an increased temperature, usually at  $400^\circ\text{C}$ . An intermediate product, a liquid bio-oil, is produced and further processed into petrol, gasoline, diesel, or other fuels. Studies show that rice straw, rice husk, maize straw, and wheat straw are thermochemically converted into biofuels using pyrolysis [43, 44].

Enzymatic hydrolysis, a biochemical approach, utilizes glucose from agricultural residues and ferments it into ethanol. Under optimum pH and temperature conditions, enzymes permit yeast to produce ethanol in a fermentation reaction. This process is eco-friendly and reduces air pollution [45]. Anaerobic digestion is the breakdown of waste with the help of a group of microorganisms without oxygen [46, 47]. With transesterification, biodiesel from vegetable oil and animal fats can be obtained, which can be used as an alternative to petroleum diesel [48]. Overall, using agricultural residues as a source of biofuels reduces the emission of greenhouse gases, thus mitigating air pollution, but there is a need to work more on them to explore more crop residues to use them as a renewable source of energy thus will able to prevent them from degradation and from causing soil and air pollution.

#### 4.2 Paper and pulp industry waste

The wastes left behind in the paper and pulp industry can be used in the biofuel production process [2]. For example, pulp mill sludge, when disposed of in landfills, degrades to methane gas, which contributes to the greenhouse effect. By using it in



**Figure 7.** *Microalgae is a source of biofuels (biogas, biodiesel, and bioethanol) and feedstock [53].*

biofuel production, contamination of the land and the water can be prevented. Black liquor, another byproduct, can be combusted to produce energy in the paper mill, and electricity can be generated from the extra energy. Black liquor has a high energy content due to dissolved lignin. Almost 300–350 million tons of waste is produced by the world’s paper and pulp industry, but only a small portion of it is recycled, and the rest causes pollution, i.e., land pollution and water pollution, and blocks the water passages and gutters [49, 50]. Thermochemical and biochemical conversion techniques are frequently used to convert waste paper and pulp into bioethanol, biodiesel, and petroleum products [51]. Waste paper contains 50–73% of cellulose content, which can be enzymatically degraded to get biofuels [52].

### 4.3 Algae

The photosynthetic organisms, i.e., microalgae, are acquiring great attention for fuel use. In some algae, up to 50% of their dry mass contains oil content [2]. Thus, scientists are working on the production of algae oil for biodiesel as well as other types of biofuels, as can be seen in **Figure 7**. It has been estimated that diatom algae can produce 40 tons of oil/ha/year, 7–31 times more than the oil production from the best-performing vegetable oil palm plant and 200 times more than the soybean plant, according to a report by NREL (National Renewable Energy Laboratory) in 1998 [54]. This capability of producing high oil content can be used as an alternative renewable energy resource. However, the separation of algae from water is highly costly; there has not been any commercial undertaking so far.

### 5. Biogas from waste

Anaerobic digestion (AD) is a process employed in the production of biogas from biowaste, as mentioned in **Figure 2**. AD is the collective process of the breakdown of biodegradable waste with the help of a group of microorganisms, specifically in the absence of oxygen [4, 55, 56]. Biogas is a mixture of gases, mainly methane and carbon dioxide, with trace amount of other gases [2]. It can be used as a fuel for engines, boilers, gas turbines, or for manufacturing other chemicals after final gas cleanup. The anaerobic digestion of biowaste takes place in four basic steps: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis. In the first step, microbes produce enzymes named hydrolases that convert the complex components of the biowaste into simpler molecules like sugars, amino acids, fatty acids, etc. [57].

In the second step, the acidogenic bacteria further ferment these simple molecules into various volatile fatty acids (VFAs) and gaseous components ( $H_2$  and  $CO_2$ ). In the third step, acetogenic bacteria reduce these molecules into acetic acid. In the fourth and last step, methanogenic bacteria ferment the intermediate products of the various steps into methane,  $CO_2$ , and water [58]. The production of biogas from biowaste is gaining attention on a commercial scale. Germany is the largest producer of biogas in Europe, followed by Italy, the United Kingdom, France, and Switzerland [4]. Depending on the type and nature of the components in the biological waste, the yield of the biogas can be varied. For example, for pure cellulose, the biogas product contains 50% methane and 50% carbon dioxide. In case of mixed waste feedstock, methane percentage in biogas products will be 40–60% by volume. Fats and oils can provide us with a methane content of 70% [2].

The use of an anaerobic digestion (AD) approach to manage biowaste can not only help to solve waste management and energy problems but also generate revenue by providing side products. Furthermore, all types of biowaste (agro-industry, animal, MSW, and food) can be subjected to AD process. If we talk about the environmental problems associated with waste, air pollution, and water pollution are the two main environmental risks affecting public health. The increasing trend toward urbanization and rapid industrialization results in more consumption of non-renewable sources of energy [59]. This will not only result in the depletion of energy resources but also an additional step toward causing environmental pollution. More transportation causes more burning of fossil fuels like petrol, diesel, compressed natural gas (CNG), etc. Burning fossil fuels releases greenhouse gases such as oxides of sulfur, oxides of nitrogen, carbon dioxide, carbon monoxide, etc. [60]. Greenhouse gases cause global warming, i.e., a condition of increased temperature of the earth and climate change [61]. Water pollution is another problem which is caused by the waste. A case study in Malaysia showed that palm oil industries are a major contributor to water pollution [62]. The dissolved solids in effluent pollute the freshwater resources when they it gets enters into the rivers, streams, lakes and oceans affecting the marine life by making a layer of oil on the surface of water. The layer of oil on the surface of water trapped the light which comes from the sun, thus the photosynthetic activity of plants greatly reduces. Furthermore, bacteria utilizes the oxygen of the water, thus depletes the oxygen available for the marine life.

## 6. Conclusion

Biological waste which comes from different sources like households, plants, agriculture, paper pulp industry, hospitals, construction sites, animal waste, municipal solid waste (MSW), and industrial liquid and solid waste, need proper management and treatment to ensure a safe and clean environment. The treatment of biological waste through landfilling and incineration produces greenhouse gases. But, the recycling of biowaste and their bioconversion for the useful production of renewable energy sources like biogas can overcome the above-mentioned pollution problem. Usually, thermochemical, biochemical, and chemical conversion technologies are employed. Among them, combustion, pyrolysis, anaerobic digestion, and transesterification are mostly used to convert the biomasses into biofuels like biodiesel, bioethanol, and biogas, which are potential renewable sources of energy. Burning renewable sources of energy is clean and eco-friendly. Shifting toward renewable sources of energy from non-renewable sources such as converting biowaste into biofuels, will

reduce environmental pollution and prevent complete depletion of non-renewable energy resources like petrol, natural gas CH<sub>4</sub>, etc. Furthermore, electricity generation from biomasses is also a plus point toward increasing electricity units and decreasing electricity per unit cost. Hence, by properly disposing of and treating biological waste, we will ultimately achieve the goal of zero-waste societies.


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## Chapter 9

# Wine Production Wastes, Valorization, and Perspectives

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### Abstract

The wine sector generates high quantities of residues that are still poorly exploited as feedstock. Normally, these wastes are directly discarded into the fields or burned, thus causing environmental problems. Wine production wastes, like vine pruning and grape pomace, are available at relatively low prices and are considered prime materials for biochemical conversion into added-value products. In this context, the reutilization of these wastes is very important not only for minimizing environmental impact but also for obtaining higher profitability. The main objective of the present chapter is to address what are the possible reutilizations and valorizations of these wastes.

**Keywords:** vine pruning, grape pomace, grape stems, lees, waste valorization

### 1. Introduction

Agro-food residues with high organic content represent environmental hazards, but at the same time are sources of added-value compounds like polyphenols, carbohydrates, proteins, *etc.* In the context of circular economy, and according to the concept of reduce, recycle, and reuse, the valorization of these types of residues has become a priority in the last decade. Strategies for the valorization of food residues include their use for energy production and reprocessing the wastes for the making of functional materials, new products, and extracts. In 2021, 77 Mt. of grapes will be produced worldwide [1]. Around 70% of the grapes are used for wine production. During the winemaking process are generated different wastes that represent around 30% of the total grapes used. These wastes include vine pruning, grape stems, grape pomace, and lees. The first generated waste in the process of winemaking is vine pruning, which is calculated to be around 5 t/ha. Grape stems are the wastes from destemming the grapes and represent between 2.5 and 7.5% of the total weight of the grapes. Grape pomace (mixture of skins, seeds, and parts of stems) results from pressing the grapes and can represent between 25 and 45% of the total weight of grapes. Lees are the residual mass at the end of the fermentation process that sediments on the bottom of the fermentation vessel. It's a mix of dead yeast, grape skins, seeds, and stems and accounts for between 3.5 and 8.5% of the total generated waste [2].

Normally, a big part of the wine waste is incinerated, a process that has high operation costs and generates hazardous gases and ashes. It can be used also for animal feed

or left in fields. Wine residues are not hazardous by nature, but the fact that wine production is concentrated in a specific period of the year poses potential pollution issues and implications.

There are different studies aiming at possible solutions for valorization and further reutilization of these wastes, according to the concepts of circular economy. The main intuition of the present chapter is the systematization and recognition of the existing research carried out on wine residue valorization.

## **2. The winemaking**

The International Organization of Vine and Wine (OIV), which represents 49 member states, accounting for about 87% of world wine production, defines wine as the beverage resulting exclusively from the partial or complete alcoholic fermentation of fresh grapes (*i.e.* the ripe fruit of the vine), whether crushed or not, or of grape must, the liquid product obtained from fresh grapes, whether spontaneously or by physical processes such as crushing, removing stems from grape berries or crushed grapes, draining and/or pressing [3]. The European Union Law [4] defines wine in a similar way but is rather more restrictive. Wine means the product obtained exclusively from the total or partial alcoholic fermentation of fresh grapes, whether or not crushed, or of grape must. Fresh grapes are fruits of the vine used in winemaking, ripe or even slightly raised, which may be crushed or pressed by normal wine-cellar means and which may spontaneously commence the alcoholic fermentation. Only wine grape varieties belonging to the species *Vitis vinifera* or coming from a cross between the species *Vitis vinifera* and other species of the genus *Vitis* are allowable, except Noah, Othello, Isabelle, Jacques, Clinton, and Herbemont. But, on the other hand, the Encyclopedia of Microbiology refers to wine as an alcoholic beverage made by the fermentation of grape juice or other sugar-containing substrates including honey, sugarcane, fruit juices, and other plant juices containing sugars, such as palm tree sap, floral extracts, and Agave, the century cactus plant [5]. So, the terms rice wine, orange wine, ... are also usual. However, if the term is used alone, it must be applied only to the product resulting from the fermentation of the grape juice.

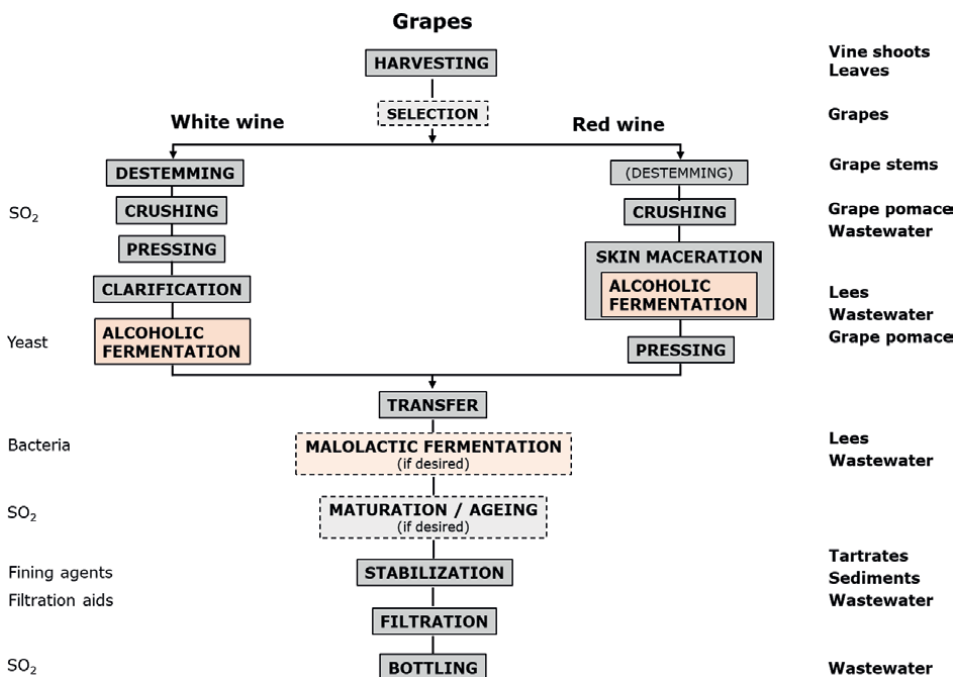
In 2022, according to the OIV,  $7,30 \times 10^6$  ha of vines, allowed the production of  $258 \times 10^8$  L of wine around the world [6]. This amount changes every year, depending on various circumstances like occasionally unfavorable climate conditions.

The two main biotechnological processes associated with wine production are alcoholic fermentation (AF), conducted by yeasts, and malolactic fermentation (MLF), by lactic acid bacteria. Alcoholic fermentation is the primary fermentation during winemaking. Throughout the AF, the fermentable sugars of the must, mainly glucose and fructose, are transformed into ethanol, carbon dioxide, and several other compounds contributing to the global taste and aroma of the wine. They belong to several chemical families: organic acids, higher alcohols, aldehydes, volatile fatty acids, ethyl esters and acetates, *etc.* [7, 8]. In practice, in winemaking, a must containing around 170 g/L of hexoses, will yield a wine with an alcoholic strength, by volume, of about 10% [9]. Malolactic fermentation (MLF) is a secondary fermentation in which L-malic acid is transformed into L-lactic acid and carbon dioxide, mainly. The main consequences of the MLF are the decreasing of the wine acidity and a subtle modification of the aroma, *i.e.* it may bring favorable organoleptic properties to the wines [9]. In terms of acid conversion, the fermentation of 1 g of malic acid per liter reduces the total acidity, expressed as tartaric acid, by approximately 0.6 g/L [9].

Normally, MLF starts when AF has finished, but co-inoculation of yeasts and lactic acid bacteria is an emerging trend in winemaking as it may reduce the length of the overall process [10].

Nevertheless, the process of winemaking includes several other steps before and after the fermentation processes [9, 11]. **Figure 1** presents the generic processes for making white and red wines, including the fermentation stages, the processes for preparing the must and finishing the wine before bottling, and also the residues, by-products, and liquid effluents generated. Although a few products are added to the must and/or wine, several residues are rejected, either as liquid or solid wastes [12].

White wine is usually produced by alcoholic fermentation of a clarified grape must. Malolactic fermentation may also occur in some wines. To obtain the most, after harvesting, and eventually selecting the bunches, the grapes should be crushed and pressed before the juice is clarified either by gravity or by dynamic processes—centrifugation, filtration, or flotation; pre-fermentative skin maceration is sometimes applied. Before alcoholic fermentation, the must usually need some specific preparation, depending on its initial composition and on the desired characteristics of the resulting wine. Sometimes the total must acidity may need adjustment of either increasing (acid addition, using for example tartaric acid) or decreasing (acidity reduction, using for example  $\text{CaCO}_3$ ) [13]. The addition of enzymes (pectinases) accelerates particle sedimentation and helps the clarification of the grape must; glycosidases may be used to enhance varietal flavor [14, 15]. Sulfur dioxide ( $\text{SO}_2$ ) is added to the grape must prevent oxidation and growth of wild yeasts and bacteria. To promote alcoholic fermentation, selected dry *Saccharomyces cerevisiae* yeasts are usually applied as fermentation starters, as this eases the control of the fermentation and can bring to the final product specific aroma compounds [9, 16]. A temperature



**Figure 1.** Generic biotechnological process of winemaking, including waste and by-products generated.

of 18°C constitutes a good compromise between the fermentation rate and the final quality of the product. Recently, the use of non-*Saccharomyces* yeasts, either used singly or combined with *S. cerevisiae* (mixed or sequentially applied), became a way to obtain sensory distinct and more complex products [17, 18]. MLF, when desired, takes typically place after AF, in environmentally appropriate conditions, by inoculation of lactic acid bacteria, usually *Oenococcus oeni*. Then, the wine must be stabilized and clarified before bottling; a maturation step may also occur.

Contrarily to white wine, the fermentation of red wines is accompanied by maceration, to maximize the extraction of color (and other relevant compounds) from the grape pomace (mainly skins). The length and intensity of the macerations are very important and depend on the grape variety and the desired type of wine to be produced [9, 16]. In order to facilitate the extraction of coloring matter, temperatures around 25°C are used. Moreover, unlike white wines, red wines usually undergo malolactic fermentation and are aged (frequently in oak barrels) before bottling.

Rosé wines are made from red grapes, by alcoholic fermentation of the must that results from the immediate pressing, or that results after a slight/controlled skin maceration; the grape variety and the maceration time influence the shade of the final product [9].

### **3. Reutilization and valorization of winemaking residues**

In the framework of the circular economy, obtaining natural components from food waste has gained interest. The disposal of winemaking residues in the environment is a serious concern and as such, in recent years, attracted much attention of the scientific community in an effort to find profitable and sustainable solutions for their reutilization and valorization. The main winemaking residues that will be addressed in the following rows are vine pruning, grape stems, grape pomace, and lees.

#### **3.1 Vine pruning**

Vine pruning is fundamental for the vineyards. It is a practice where shoots, branches, and herbaceous parts are cut to achieve good harvest and quality grapes. There are different types of grape pruning with distinctive characteristics that influence the vine and consecutively the produced grapes. Vine pruning residues (VPR) are a lignocellulosic material and even though it is known to have interesting added-value compounds with different bioactivities, this material is still economically underutilized [19]. Lignocellulosic residues are a possible sustainable substitute for fossil-based fuels, chemicals, and materials. It was concluded that VPR contains more lignin than other renewable sources like wheat straw and corn stalks. The proximal composition of VPR was found to be as follows: cellulose from 24.8 to 32.4%, hemicellulose from 9.6 to 13.8%, and lignin from 23.7 to 32.4% [20]. Moreover, VPR is a rich source of polyphenol compounds.

VPR can be used for different purposes (**Table 1**). For example, it was used as raw material for ethanol production by hydrothermal treatment, also known as autohydrolysis [21]. The autohydrolysis was used in two sequential stages in an attempt for the integral valorization of VPR. With the proposed method, xylooligosaccharides, phenolic compounds, and ethanol were obtained. In summary, 69 kg of value-added compounds were obtained from processing of 100 kg VPR. In the study from Gullón *et al.*, autohydrolysis combined with extraction with ethyl acetate was evaluated as

Compound	Method used	Reference
polyphenols	Ohmic heating	[19]
ethanol, xylooligosaccharides, polyphenols	autohydrolysis	[21]
lactic acid, furfural	Saccharification, fermentation	[22]
polyphenols	microwave-assisted extraction, subcritical water extraction, conventional extraction	[23]
polyphenols	microwave-assisted extraction	[24]
particleboard	direct use	[25]
activated carbon	physical, chemical activation	[26]
monomeric sugars, furfural, HMF, formic acid, lactic acid	enzymatic hydrolysis	[2]
solid biofuel	burning	[27]
oligosaccharides, polyphenol compounds	autohydrolysis followed by ethyl acetate extraction	[28]
Energy source	catalytic combustion	[29]

**Table 1.**  
 Valorization of vine pruning residues.

the valorization process of VPR [28]. Oligosaccharides and polyphenol compounds were obtained with the suggested process.

A biorefinery concept was used for the production of lactic acid and furfural from VPR. Moreover, the life cycle assessment of the process was performed on the selected scenario. It was concluded that with this scenario there were significant reductions in climate change, fossil fuel depletion, freshwater ecotoxicity, and human toxicity impacts compared to their counterfactual systems [22].

VPRs are rich in polyphenol compounds and frequently are used for the extraction of these valuable compounds. Polyphenols have various biological activities like antioxidant, anti-mutagenic, anti-inflammatory, antimicrobial, and anti-carcinogenic properties [19]. The composition of the recovered phenolic compounds from VPR depends on grapevine variety, age, and growth conditions. Moreover, the extraction yield and type of extracted phenolics depend on the temperature, time, and solvent composition used in the experiments. The phenolic composition of extracts from VPR from the grape varieties Touriga Nacional and Tinta Roriz were evaluated [23]. Gallic acid, catechin, myricetin, and kaempferol were the main polyphenol compounds found in the extracts. Moreover, the extracts demonstrated high antioxidant activity and inhibitory activities against  $\alpha$ -amylase and acetylcholinesterase enzymes, showing their potential to be used in the treatment of Alzheimer and diabetes's diseases [23]. In another study, the main polyphenol compounds identified in the extracts made with microwave-assisted extraction were apigenin and ellagic acid [24]. The main polyphenol compounds found in the ethyl acetate extracts of VPR were vanillin, acetovanillone, guaiacylacetone, syringaldehyde, and acetosyringone. The extracts had antioxidant and antimicrobial activities against both Gram-positive and -negative bacteria [28].

In other studies, VPR is used directly, like for example in the construction of particleboards. The experimental three-layer boards where wood particles from the

core part were substituted with 50% of VPR demonstrated good properties. However, the use of vine pruning particles as surface material should be excluded as it deteriorates [25]. VPR was used directly as solid biofuel inside the vineyard. The idea of the project was to use VPR as solid chips for the boilers inside of the vineyards, replacing the pine pellets that are usually used. This change in solid biofuel decreased the total CO<sub>2</sub> emission of the vineyard, and consecutively its carbon footprint. It was calculated that the proposed process brings economic savings for the vineyard [27]. The high combustion efficiency of VPR was also obtained using catalytic combustion (Pd catalyst) in a conical spouted bed combustor [29].

VPRs were used after being transformed into activated carbon and applied in wines as a fining agent. The produced activated carbon was able to decrease the presence of unpleasant aromas, as well as to alleviate the negative effects of browning in a white wine [26].

An integrated biorefinery concept was applied with the objective of reusing all the winery waste streams. VPR were subjected to hydrothermal pretreatment followed by enzymatic hydrolysis. The obtained compounds depended on the severity of the treatment of the material and included the compounds glucan and xylan (at milder pretreatment conditions), furans (furfural, HM-hydroxymethylfurfural), and organic acids (formic, lactic) [2].

### **3.2 Grape stems**

The grape stems (GSs), also known as grape stalks, form the skeleton of the grape bunches. GS is obtained during the destemming process. It is a lignocellulosic material with the following proximal composition: 34% lignin, 36% cellulose, 24% hemicellulose, and 6% tannins [30]. The high contents of lignin and tannins make the grape stems a challenging material for processing and reutilization [30]. Compared to grape pomace and seeds GS has fewer bioactive molecules, but it is still an important source of antioxidant compounds [31].

At the same time, it is considered that using the GS exclusively to produce ethanol is not a cost-effective and beneficial process. In this context GP was exploited as biorefinery biomass for the production of second-generation ethanol, as well as added-value compounds including cellulose, hemicellulose, lignin, and cellulose nanocrystals (**Table 2**) [31].

GS were treated physically (heat process) and chemically (mercerization) with the intuition to be included in biocomposites for the production of new products that can be used in industries like packaging, aerospace, automotive, and construction [32]. In this context, GS was used as a primary source in the process of making highly porous bricks. The obtained total porosity and pore dimensions enhanced the durability and thermal insulation properties of the produced bricks. With respect to the same type of clay, bricks produced with GS decreased heat transmission by around 40% [33]. Another utilization for GS in biocomposites formula is as filler in bioplastics while polybutylene succinate was the basic polymer. The obtained product demonstrated improved mechanical properties, and lower production costs [40]. GS was, also, used directly as a solid substrate for the growing of *R. oryzae NCIM 1299* in a fermentation process intended to produce lactic acid [39].

The antioxidant extracts of GS were considered a promising replacement for sulfur dioxide in wine preservation. However, the authors concluded that before the implementation of this process in the wineries, additional studies should be carried out [35]. The polyphenol compounds present in the GS have the capacity to bond with the iron vacant orbitals protecting them from corrosion. In this context, the extracts

Compound	Method used	References
lignin, sugars, tannins	dilute sulfuric acid, ethanol organosolv, wet oxidation,	[30]
ethanol, cellulose, hemicellulose, lignin, cellulose nanocrystals	acid and enzymatic hydrolyses	[31]
modified grape stems	heat process mercerization	[32]
to produce porous bricks	direct use	[33]
( <i>E</i> )-resveratrol	photo-molecularly imprinted sorbent	[34]
sulfur dioxide replacement	extraction	[35]
corrosion inhibitor	water extraction	[36]
polyphenols	extraction	[37]
tannins	microwave extraction	[38]
solid substrate for fungi growth	direct use	[39]
as filler in biocomposites	direct use	[40]
succinic acid	alkaline and acid pretreatment, enzymatic hydrolysis	[41]
adsorbent	direct use, activated carbon	[42, 43]

**Table 2.**  
 Examples of possible valorization of grape stem residues.

of GS were used as corrosion inhibitors of mild steel in 0.5 mol/L NaCl. The GS extract applied at 400 mg/L was found to provide maximum protection of 88% [36].

The potential application of GS extracts in the cosmetic, pharmaceutical, and food industries was also evaluated. The analysis of the extracts confirmed the presence of polyphenol compounds with catechin showing the highest concentrations. Moreover, the extracts had diverse bioactivities including antioxidant, anti-inflammatory, and anti-aging [37]. GS was directly applied in the vinification of the grapes from the variety Bonarda with the objective to increase the tannin content of the resulting wine. The result demonstrated that the use of GS in the fermentation process modified the chromatic characteristics and phenolic composition, improved the color stability, and changed the volatile and polysaccharide profile of the produced Bonarda wines [38].

GS can be used as a raw material for the production of succinic acid. Succinic acid has many applications in the pharmaceutical, agricultural, food, and chemical industries. The proposed process valorization included alkaline and acid pretreatment of the stems, followed by enzymatic hydrolyses. The sugar-rich hydrolysate was further used as fermentation broth for the production of succinic acid [41].

GS contains various functional groups (tannins, tartrate, organic acids, *etc.*) that make it a good candidate for adsorbent, that can be directly used or in the form of activated carbon. As such GS was successfully used for the removal of caffeine and methylene blue from wastewater [42, 43].

It is to refer to the fact that, grape stem extracts were evaluated for their multiple biological activities like anti-cancer (breast, colon, renal, and thyroid cancer cells) [44], anti-microbial (including digestive pathogens) [45], also against ultraviolet irradiation [46], antioxidant, anti-inflammatory, anti-aging, and others [37]. In this context, further studies are needed to find out and understand the full potential of this waste material and to project its further utilization.

### 3.3 Grape pomace

Grape pomace (also known as grape marc) is the residue after pressing the grapes. It is a mixture of grape skins, grape seeds, and some grape stems. Traditionally grape pomace is used for ethanol distillation, animal feeding, or spread in the land. The grape pomace distillation and resulting spirits are an important industrial activity in countries like France and Italy. High amounts of bioactive compounds are present in GP, especially polyphenols. Their concentration and presence depend on numerous variables like type of grape variety, type of vinification process, geographic region, and year of harvest [47].

Grape pomace (GP) was used for the extraction of oleanolic acid, a natural triterpenoid with antidiabetic properties (**Table 3**) [48]. Besides oleanolic acid other compounds like polyphenolic compounds, anthocyanins, minerals, and amino acids were also identified in the GP extracts. The most abundant polyphenols found in the extracts were catechin, epicatechin, caffeic acid, and quercetin. A sustainable production process of ethyl hexanoate (ester with flavor of pineapple) from GP was evaluated. GP was used for the production of hexanoic acid that was further converted to ethyl hexanoate [49]. The proposed process demonstrated to be a possible alternative to fossil-derived hexanoic acid.

In the context of circular economy and waste reutilization, the use of green technologies is the best possible scenario. Aqueous solutions of surfactants are green substitutes for organic solvents and were used for the extraction of polyphenols from GP [50]. The main extracted polyphenols were catechin and quercetin. Catechin and quercetin were also the main polyphenol compounds found in GP extracts made with non-ionic surfactants [55]. The study was conducted with 11 different surfactant solutions and demonstrated that the structure specificities of the surfactants influence the extraction efficiency of the polyphenols.

Compound	Method used	Reference
oleanolic acid, polyphenols, amino acids, anthocyanins	ethanol extraction	[48]
polyphenols, fibers, polyunsaturated fatty acids, minerals and protein	ethanol extraction	[47]
hexanoic acid	fermentation	[49]
polyphenols	surfactants extraction	[50]
anthocyanins	ultrasound-assisted extraction	[51]
anthocyanins	extraction with eutectic solvents	[52]
substitute for wheat flour	direct use	[53]
pectin	conventional, microwave-assisted, and pulsed ultrasound-assisted extraction	[54]
polyphenols	non-ionic surfactants extraction	[55]
animal feed	direct use	[56]
energy	pyrolysis	[57]
polysaccharides	extraction	[58]

**Table 3.**  
*Valorization of grape pomace residues.*

The eco-friendly ultrasound-assisted extraction method was used to obtain anthocyanins from red GP [51]. Anthocyanins are known to have many health benefits, for this reason in our days anthocyanin supplements are an important part of the nutrition market. Anthocyanin isolation from agro-industrial wastes is attracting much attention. Besides their bioactive properties, anthocyanins are also used as natural colorants. For this purpose, anthocyanins were extracted from GP using eutectic solvents [52]. The proposed method of isolation and stabilization of the extracted anthocyanins had low environmental impacts and economic costs compared to the conventional extraction with solvents.

GP, in powder, can be used directly in the elaboration of cakes, as a substitute for wheat flour. Cakes produced with 4% GP powder showed good sensory quality with enhanced nutritional properties, once the GP powder provided the cakes with polyphenolic compounds [53].

GP was also used for the extraction of pectin applying green technologies, like microwave and ultrasound-assisted extractions. Pectin is a polysaccharide found in the plant cell walls. Normally it is extracted from apples pomace and citrus peel using organic or mineral acids. The use of different extraction methods resulted in extracted pectin with diverse structural characteristics [54]. However, it was concluded that pectin from GP has the potential to be applied in different fields including the food industry. In another study, the extracts of GP were successfully applied as antimicrobial additives in polypropylene food packaging. The obtained materials demonstrated antimicrobial activity against Gram-negative (*Escherichia coli*) and Gram-positive (*Bacillus subtilis*) bacteria [59].

GP is rich in polysaccharides, especially the GP from white grapes. GP from red grapes is only liberated after the fermentation of the juice, so it contains less pulp and residual sugars, than the white GP. However, polysaccharides may be also obtained from red GP. The most abundant polysaccharides in extracts made with hot water were arabinose, xylose, mannose, glucose, and galactose [58].

Cheese made from the milk of ewes on a diet formula that included GP had improved sensory characteristics. GP supplement mainly affected the aromatic profile of the cheese [56].

GP was also evaluated as an energy source. The proposed idea is to use the energy obtained from GP pyrolysis in the food processing plants to reduce the final cost of energy [57].

As a final remark, we can say that grape pomace is a versatile source of different compounds and products that can be used in the food industry, in the pharmaceutical and cosmetics industries, in agriculture, as well as energy sources.

### **3.4 Lees**

Wine lees are one of the main byproducts of the wine industry. This sludge is essentially made up of dead yeast, which precipitates at the bottom tanks after the fermentation process has taken place [60–62]. According to Galanakis, 85.7 t (dry basis) of wine lees are generated for every 1000 m<sup>3</sup> of wine produced [63].

Since lees contain large amounts of polysaccharides, lipids, proteins, and other compounds with high demand for oxygen, their deposition to the environment, causes serious pollution problems, due to the high organic content and a low pH. These characteristics also make their direct use in agricultural practices inappropriate, such as the production of compost and use for animal feed.

On the other hand, since this by-product contains a wide variety of value-added compounds, the investigation of potential recovery routes has gained relevance. In this way, the deepening of this strategy would not only avoid serious environmental problems but would also reduce the costs associated with its deposition [64]. More specifically, wine lees contain both liquid and solid fractions. The first is called vinasse and contains bark, part of the seed, and dead yeast, consisting of the spent fermentation broth. In turn, the solid fractions contain organic and inorganic salts, grain, seeds, cellulose, hemicellulose, and lignin. Both fractions have the potential to produce added value by-products, with high economic relevance [60, 61].

Thus, in order to avoid the conventional applications of this by-product (agriculture and animal feed), which are not appropriate and generate environmental problems, several approaches have been applied and several studies have been carried out in order to find effective, sustainable, and economically viable alternatives.

On an industrial scale, only ethanol and tartaric acid extraction have been applied. From the wine lees distillation process, it is possible to recover ethanol and produce distilled beverages [65]. The by-product obtained from distillation (vinasses) contains several value-added components with the potential to be extracted.

Wine lees are the major source of tartaric acid and the most valuable component that can be extracted from vinasses [66]. This acidifier is widely used in the food and beverage industry, as well as in the pharmaceutical, cosmetic, and chemical industries [67, 68]. Conventional processes for obtaining tartaric acid (precipitation, crystallization, acidification, ion exchange, *etc.*) are associated with disadvantages at environmental and economic levels, essentially due to the production of calcium sulfate as waste. In this way, new studies have been carried out to try to overcome these problems, trying to reduce the consumed energy and the use of chemicals [67, 69]. New technologies being tested include membrane processes and microwave-assisted and ultrasound-assisted extraction techniques, showing improved results in terms of extraction yields [67, 70, 71].

In addition to these more developed strategies, there are other promising possibilities that have been studied and tested. One of them is the biotechnological application of remaining lees as a culture medium for lactic acid bacteria [68]. Studies have shown the possibility of integrating the production of microbial substrates from this by-product, with the extraction of ethanol and tartaric acid, in order to extract the greatest number of components and make the processes viable [64, 68].

Furthermore, the cell walls of mannoproteins and  $\beta$ -glucans from wine lees have been explored, proving to be promising for various types of applications, namely the food industry (emulsifier, fat replacers, cholesterol reducer, antioxidant) and viticulture (foam, mouthfeel enhancer). Extraction methods can vary between physical, chemical, enzymatic methods, and a combination of these [72, 73]. In turn, Iseppi studied the development of methods for yeast glyco-compounds extraction from wine lees, through physical (autoclave and ultrasonication) and enzymatic methods, demonstrating their possibility of use as winemaking additives [74].

Moreover, wine lees present a valuable opportunity as rich sources of anthocyanins and other polyphenols, showcasing the strong potential for use within the food, cosmetics, and pharmaceutical industries. This ability to foster health benefits is attributed to their well-recognized properties as antioxidants, antimicrobial agents, anti-inflammatory substances, and promoters of cardiovascular well-being [75].

Additionally, the production of biogas has been tested as a potential application of the solid fraction of wine lees. This strategy involves anaerobic co-digestion of wine lees by *Escherichia coli* under mesophilic and thermophilic conditions [76].

Compound	Method used	Reference
ethanol	distillation	[77]
polyphenols	organic solvents	[75]
polyphenols	microfiltration	[78]
$\beta$ -glucans	extraction using NaOH	[73]
microbial media	preparation for microbial media	[68]
polyphenols, polysaccharides	ultrafiltration and nanofiltration	[70]
ethanol, tartaric acid, polyphenols, microbial media	cation exchange resin	[79]
tartaric acid polyphenols	nanofiltration	[67]
ethanol, tartaric acid, polyphenols, microbial media	extraction and preparation for microbial media	[64]
biogas	anaerobic digestion	[76]
yeast glycomcompounds	ultrasonication, enzymatic, autoclave	[74]

**Table 4.**  
 Summary of the papers that studied valorization approaches for wine lees.

In short, wine lees have great potential for extracting value-added compounds. The investigation of the methods to be adopted must be deepened in order to optimize the extraction efficiency. The development of integrated approaches aimed at extracting various types of compounds for application in different sectors would be an asset to promote the valorization of wine lees, applying the circular economy in this sector and promoting environmental and economic sustainability.

**Table 4** presents the possible wine lees valorization strategies that have been studied.

As final remarks about the extraction methods used to obtain valuable products, one can see that there are various methods used. The right choice of method will depend on the desired result as well as the existing conditions in each laboratory. It is evident that the simplest and the easiest method to be implemented and used is the conventional heat extraction method. Clearly, the method of extraction to be applied will depend on the nature of the desired final compounds. The best choice is that the used method is environmentally friendly and of a low cost, *i.e.* without aggressive solvents and methods that spend a high amount of energy and are time-consuming. Some methods used additional consummatives like enzymes (enzymatic hydrolase) or membranes. Others required the use of specialized apparatus like ultrasound or microwave extraction methods. In this sense, many times the chosen method will also depend on the possibilities of the laboratory to acquire equipment and apparatus.

## 4. Conclusion

Wine residues are rich sources of various compounds of interest like polyphenols, dyes, carbohydrates, organic acids, and others. As such wine residues can be a cheap alternative for the development of new products, functional foods, pharmaceuticals, and cosmetics. Regardless of the many existing studies on the valorization of wine wastes, the proposed processes have not been widely implemented in the winemaking industry so far. There is still much work to be done until wine residues gain an established recovery pathway that brings economic benefits.

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## **Conflict of interest**

The authors declare no conflict of interest.

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*Edited by Hosam M. Saleh,  
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Hazardous waste poses one of the most complex and risky pollution challenges worldwide. As industrialization accelerates globally, volumes of toxic byproducts and emissions continue to grow, requiring urgent solutions. This book provides a practical overview of hazardous waste management approaches, technologies, and policies to reduce environmental and human health damage. The text begins by outlining Pakistan's current hazardous waste situation, including crucial pollution sources like the textile, fertilizer, and leather industries. It summarizes reduction efforts and persisting challenges around enforcement, technology capabilities, and lack of recycling infrastructure. The following chapters delve into biological waste management techniques and an innovative fertilizer production process utilizing steel slag waste. Case studies demonstrate the potential to convert industrial byproducts into economic resources. Several chapters focus on electronic waste (e-waste), examining landfill contamination risks in Africa and the push to transform these sites into urban mining operations. Technical contributions analyze tools like activated carbon filters to reduce toxic e-waste emissions. The book concludes with a look at winery waste recycling and closes with a chapter connecting hazardous waste management to broader sustainable development goals. Together, the chapters in this volume provide a multifaceted look at hazardous waste management strategies, current limitations, and the work still required to reduce ecological damage. The text is valuable for researchers of dangerous waste, industry operators, and policymakers looking to improve abatement practices. With its detailed case studies and technical analyses, the book offers both practical and big-picture insights to support the critical work of sustainable, effective hazardous waste management worldwide.

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