SUSTAINABLE MANAGEMENT OF MINING WASTE AND TAILINGS

A Circular Economy Approach

EDITED BY ALOK PRASAD DAS,
ERIC D. VAN HULLEBUSCH, AND ATA AKÇIL

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Integrating waste management, environmental sustainability, and economic development is a prime milestone in the circular economy. Critical metals recovery from mining tailings and secondary resources has significant potential, with widespread applications in high-tech industries that are critical to modern society and sustainable development. This book discusses technological advances for managing industrial and mining waste through circular economy approaches and successful critical metal recovery from secondary resources. It highlights how reprocessing of mine waste and tailings results in development of critical raw materials that significantly reduce the mining burden and ensure the lucrative use of waste materials.

FEATURES:

- Describes advances in remediation and valorization technologies for mining wastes.
- Details biotechnological methods, cutting edge research, and applications.
- Covers use of waste mining resources for economic growth and novel opportunities.
- Discusses IR4.0 and machine learning methods.
- Includes reports and case studies on mining waste in value-added products and recovery of strategically important critical minerals.

This book will be of value to researchers and advanced students working in the mining, chemical and environmental engineering, and renewable energy sectors.

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Preface

The earth's environment is a natural ecosystem that has its own remedial control, but the present rate of natural resource exploitation and depletion promotes destructive ecosystems patterns. Extensive mining activities have resulted in soil erosion, sinkholes, damage to biodiversity, and pollution of soil, groundwater, and surface water by the toxic chemicals and heavy metals released from mining processes. Mining affects fresh water through heavy use of water in processing ore, and through water pollution from discharged mine effluent and seepage from tailings and waste rock impoundments. These human activities have created inconsistencies in the ecosystems with devastating outcomes. For the sake of current and future generations, we need to safeguard the environment against increased rates of mining and mineral processing. We need to ensure the best pollution-prevention strategies are employed in cases where the risks can be managed. The universal environmental complications demand a greener solution underlying unity between the global environmental problems irrespective of their intricacy and executing solutions. Critical metals recovery from tailings and secondary resources has significant potential for the future, as its applications are widespread in high-tech industries that are critical to modern society and sustainable development.

Integrating waste management through environmental sustainability and economic development is one of the prime milestones in the circular economy. There is an exigent need for developing countries to move towards a circular economy in order to achieve their sustainable development goals. Greener technologies are a novel archetype that promotes financial progress and environmental sustainability at the same time. This book will elucidate the growing application of greener technology with a circular economic approach and examine the connections among environment, economy, and ecology for an emerging and supportable human society.

The book will focus on numerous features of environmental sustainability and identify the technologies and methods essential to managing growing volumes of mining and mineral processing wastes. It will also describe the biotechnological methods, cutting-edge research, applications, and procedures required to safeguard sustainable development along with mining waste management. This book will focus on the role of green engineering technologies for sustainable mining and mineral processing waste management in building an economically viable society as a basic need of developing countries, and will also highlight how mine tailings can be re-processed to produce critical raw materials (CRMs) that could significantly reduce the mining burden and ensure the lucrative use of mining waste materials.

Editors' Biographies

Dr. Alok Prasad Das is Assistant Professor in the Department of Life Sciences, Rama Devi Women's University, Odisha, India. With more than 15 years of research experience, he has published several books and more than 100 research and review articles in international journals of repute. He is the editor of several books, serves on the editorial boards of several reputed journals, and is an active lead guest editorial board member in top-rated journals. Dr. Das's area of expertise includes: wastewater treatment, environmental microbiology, environmental pollution and management, microplastic and microfiber pollution, and bioremediation for sustainable solutions. His current Google Scholar: Citations is 2790 and h-index 29. Dr. Das is also listed in the world ranking of top two percent of scientists for 2023, drawn up by Stanford University (USA) on the basis of subject-wise analysis.

Professor Eric D. van Hullebusch received his PhD (aquatic chemistry and microbiology) from Université de Limoges (France) in 2002. From November 2002 until October 2004 he was a Marie Curie postdoctoral fellow at Wageningen University & Research (the Netherlands), where his research focused on the optimization of anaerobic granular sludge reactors by studying the speciation, bioavailability, and dosing strategies of trace metals. In 2005, he was appointed as an associate professor in biogeochemistry of engineered ecosystems at Université Paris-Est (France). From September 2016 until August 2018, he worked at IHE Delft as Chair Professor in Environmental Science and Technology and head of the Pollution Prevention and Resource Recovery chair group. In September 2018, he joined Institut de Physique du Globe de Paris (France) as a full professor in biogeochemistry of engineered ecosystems. Professor van Hullebusch has published more than 280 peer-reviewed papers (about 14500 citations, h-index 62) in the field of biogeochemistry of metals and metalloids in engineered ecosystems. His research is currently mostly focusing on the implementation of biohydrometallurgical approaches for the recovery of technology-critical elements as well as polluted soils (bio) remediation.

Professor Ata Akçil is a professionally registered engineer with 32 years of experience in process, hydrometallurgical and biohydrometallurgical engineering, mineral processing, waste management, engineering services, teaching, research, professional service, consulting, management, and industrial plant operations. Professor Akçil obtained his Ph.D. in mineral processing and hydrometallurgy in 1999 from the Dokuz Eylul University (Turkey). He worked as Research Assistant (by 1999), Assistant Professor (by 2005), Associate Professor (by 2010), and Full Professor (by 2023) at the Akdeniz University and the SDU (Turkey). He is also Adjunct Professor (since 2023) at Beijing University of Chemical Technology (China). Professor Akçil is also a technical senior expert for critical and strategical raw materials and resource recovery. He is an active member of the editorial boards of four peer-reviewed scientific journals and author or co-author of 200 research papers, one book, ten book chapters, and 60 international conference proceedings. His work has 11,500 citations (h-index: 48).

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1 Novel Methods and Techniques for the Remediation of Mining Waste Residues

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1.1 INTRODUCTION

Due to the significant growth in population and rising demand for natural resources globally, mining activity has significantly expanded (Reichl et al., 2016). Exploration, mine development, mineral beneficiation, metal extraction, smelting, refining, reclamation, and clean-up are all part of the complicated process known as mining, and they all generate a large quantity of waste. Society demands proper management of waste (Bakken, 2007) to address the hazards generated by the waste's toxicity, flammability, reactivity, corrosivity, and other factors. Waste management practices that lessen or eliminate the dangers are necessary in these kinds of situations (Mishra et al., 2019; Fernandez-Naranjo et al., 2020).

Mineral extraction waste normally falls into three categories: (i) solid wastes such as waste rock, dust, sludge, slurries, and slags; (ii) liquid wastes such as wastewater and effluents; and (iii) gaseous emissions (Lottermoser et al., 2011; Ndlovu et al., 2017). To minimize negative environmental consequences, waste is held in tailing ponds, dams, or tips, in line with local waste-control treatment rules that apply to each mining area, or recycled if physically possible (Pasariello et al., 2002; Hudson-Edwards and Dold, 2015). Each of these methods may be considered harmful depending on how it affects the soil, surface water, groundwater, plants, and even the neighbouring human population (Tew et al., 2018; Iribar et al., 2000). Inert structures cause no harm to human health or the environment.

We have touched on the more general environmental and economic concerns related to garbage mishandling and given a quick summary of the difficulties in managing waste. Let's break down and discuss the key points we have raised:

i. Waste Generation and Mismanagement: Waste is an inevitable byproduct of industrial processes. Inadequate waste management practices, such as open dumping and burning, contribute to environmental degradation, air pollution, and health hazards. In many cases, waste mismanagement stems from a lack of proper infrastructure, awareness, and resources.

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ii. Disparity in Waste Management Approaches: While waste management strategies may be similar between developed and developing countries, the implementation and effectiveness of these strategies can vary significantly. Developing countries often face challenges in funding, infrastructure development, and public awareness, which can hinder the proper execution of waste management programs.
iii. Hurdles in Waste Management Programs: Insufficient waste management technologies, equipment, and capital investment pose significant hurdles in establishing effective waste management programs. Additionally, the lack of protective measures for workers involved in waste management can contribute to health and safety concerns.
iv. Citizen Participation and Awareness: The success of waste management programs depends on citizen participation and awareness. Lack of knowledge about proper waste disposal, recycling, and the environmental impacts of mismanagement can lead to continued dumping and burning of waste, exacerbating the problem.
v. Economic Factors: Economic challenges, such as limited funding and resources, can hinder the development and maintenance of waste management infrastructure. This can lead to a cycle where inadequate waste management affects the environment, which, in turn, can impact the local economy.
vi. Multinational Companies and Hazardous Waste: Some multinational companies' practice of relocating their operations to less developed countries can lead to disparities in waste management practices. Regulations and technologies used in their home countries may be stricter or more advanced, potentially leading to increased environmental risks in the host countries.
vii. Mining and Environmental Impact: The production of valuable geological elements from the planet and other celestial objects is known as mining. Most substances that cannot be cultivated through farming or generated artificially in a laboratory or factory must be mined. Iron ore, bauxite, copper, tin, nickel, manganese, tantalum, cassiterite, gold, silver, diamonds, oil shale, gemstones, limestone, chalk, dimension stone, rock salt, gravel, and clay are among the ores extracted by mining (Balaram, 2019). Mining is a complex process that involves various stages, from exploration to cleanup. While mining plays a crucial role in resource extraction, it can also have significant environmental impacts, including habitat destruction, water pollution, and soil degradation. Proper management and regulations are essential to minimize these negative effects (Bennamoun, 2012).

Here you might ask, why is it necessary to study this subject in such depth? Are mining wastes really so hazardous to mankind? The answer to the second question is a simple yes. Not all waste is eco-friendly and should be left unattended and exposed. The three most frequent throwaways are waste rock, tailings, and mine water. If wastes are abandoned for a long time, they leach metalloids, heavy metals (copper lead, mercury), acids, and radioactive elements into the soil, contaminating the rich top layer, surface water, groundwater, useful microbes, and so on. Furthermore, 4%

to 7% of greenhouse gas (CO, $CO_{2,}$ $SO_{2,}$ $NO_{x,}$ PM) emissions come from mining sources (Alloway, 1995; Pérez Cebada, 2016; Durucan et al., 2006).

Effective waste management is a multifaceted challenge that requires a combination of technological innovation, regulatory enforcement, public awareness, and sustainable practices. Addressing waste mismanagement in developing countries involves overcoming economic, social, and infrastructural barriers. Collaborative efforts between governments, industries, communities, and international organizations are vital to improving waste management practices, reducing environmental harm, and promoting sustainable development (Paul et al., 2023; Pradhan et al., 2023). Similarly, responsible mining practices are essential to minimize the environmental footprint of mining activities and ensure the long-term well-being of ecosystems and communities.

1.2 VARIOUS MINING TECHNIQUES

- **Artisanal mining:**—An artisanal miner, also known as a small-scale miner (ASM), is a subsistence miner who is not officially employed by a mining company but works independently, mining minerals using their own resources, usually by hand (Schwartz et al., 2021). Artisanal miners often mine seasonally; for example, crops are planted in the rainy season, and mining is pursued in the dry season. However, they also commonly travel to mining locations and work year-round (Buss et al., 2019).
- **Surface mining:—**Surface mining includes the removal of surface plants, soil, dust, and bedrock to access subsurface ore reserves. It is an alternative to underground mining, in which the overlying rock is left in place and the required mineral resources are extracted via shafts or tunnels. Surface mining is a technique for extracting sand, gravel, stones, coal, iron, and other metals.
- **Highwall mining:**—When surface mining has reached its economic stripping ratio, highwall mining is a way to enhance coal recovery, in which the continuous miner is remotely deployed beneath highwall mining with no crew access. Compared to underground mining, highwall mining has several advantages, including a higher level of safety due to the use of remote-controlled cutter heads (Ross et al., 2019). It also requires a small team of only three or four persons.
- **Underground mining:**—Underground mining is used to harvest ore from beneath the earth's surface in a safe, cost-effective, and waste-free manner. An adit, shaft, or decline is a horizontal or vertical tunnel that connects the surface to an underground mine. Underground mines are created by excavating vertical shafts or horizontal adits to reach buried ore deposits. Underground mining is more expensive than surface mining (Afum et al., 2021). Coal businesses, for example, must dig more depth and employ sophisticated equipment to collect materials.

Minerals are heavily used and exported by China, which is the biggest miner in the world. China mined over 4.1 billion metric tonnes of metals, including non-ferrous and other metals, as well as fossil fuels and iron in 2018, the most recent year for which data is available from the World Mining Congresses. Nearly 3.5 billion tonnes of coal, which is classified as a mineral fuel, were dug up, making China the single largest contributor of coal to this statistic. China mined more than 200 million tonnes of iron, the nation's second most-excavated mineral after coal. Similar to China, many of the top-ten nations in terms of mining output relied virtually entirely on mineral fuels. Saudi Arabia is known for its significant oil reserves and plays a crucial role in global oil production. Indonesia, too, is a major player in the energy sector, with coal being a notable component of its mining output. Australia and Brazil are major players in the global iron ore market, with extensive reserves and significant mining operations. The data analysis implies that, out of the total iron production worldwide, the combined output from Australia and Brazil fell within the specified range of 47% to 62%. Therefore, Australia and Brazil collectively contributed to a significant portion of the world's iron production. The United States likewise relied largely on mineral fuels, though not solely (Hodge et al., 2022).

1.3 ENVIRONMENTAL IMPACTS OF MINING

Mining practices, both direct and indirect, can have an impact on the environment at the local, regional, and global levels. The chemicals produced by mining activities can cause erosion, sinkholes, biodiversity loss, and contamination of soil, groundwater, and surface water. These processes also affect the climate through emissions of carbon, which influences human wellness and the environment (Sonter, 1892).

- **Erosion:**—Water available for plant growth can be reduced due to soil erosion, resulting in a decrease in plant population (Moreno-de las Heras, 2009). Excessive rainfall, lack of soil management, and chemical exposure from mining are the primary causes of soil erosion (Wantzen and Mol, 2013). Mining in wilderness areas has the potential to devastate ecosystems and habitats (Zhang et al., 2015).
- **Sinkholes:**—Sinkholes are mainly caused by the collapse of the mine roof as a result of resource extraction, unstable overburden, or geological discontinuities at mine sites. Cracks in the subsoil or rock can be caused by overburden at mine sites, which can be filled with sand and soil from the layers above. The overburden voids have the potential to collapse and generate a sinkhole at the surface, which can be dangerous to life and property (Singh and Dhar, 1997).
- **Water pollution:**— Mining can cause various detrimental effect on surface water and groundwater. The enormous amounts of water used during mine drainage, mine cooling, aqueous extraction, and other mining processes increase the likelihood of these chemicals contaminating ground- and surface water.
- **Air pollution:**—Surface mines may generate dust as a result of blasting operations and transport routes. Methane, a greenhouse gas, is emitted by many coal mines. Heavy metals, sulfur dioxide, and other pollutants may be released into the atmosphere by smelter operations that do not have adequate safeguards in place.

- **Impacts on biodiversity:**—The primary cause of biodiversity loss is habitat destruction, although direct poisoning from mine-extracted material, as well as indirect poisoning through food and water, can also damage animals, flora, and microbes.
- **Impacts on aquatic organisms:**—Rainwater or surface drainage transports acid from the mine site and deposits it in surrounding streams, rivers, and lakes. AMD decreases water quality significantly, can destroy aquatic life, and renders water essentially useless.
- **Impacts on humans:**—Mining has an impact on humans as well. When contaminants released during the mining process come in contact with water bodies and soil, they can cause several diseases. Approximately 30% of the world's populace has access to fresh water that is renewable, which is used by businesses that discharge massive amounts of chemical effluents into freshwater (Schwarzenbach et al., 2010). The Dabaoshan mine, an abandoned mine in China, was the subject of research because the impact of metals collecting on organisms, water bodies, and soil was a significant problem for nearby villages (Zhuang et al., 2009).

Some research has pointed out the effects of mining on the soil. To begin, the contaminants and quantity of components in various soil levels must be inspected, and sediment must be established to define the margins of safety (Salomons et al. 1995). The concentration of these trace elements in the mine, as well as their likelihood of creating acid mine drainage, the principal and secondary minerals in the waste, and the mobility of the hazardous elements must next be evaluated (Pérez-Santana et al., 2007; Zhang et al., 2015).

1.4 LITERATURE SURVEY

We are going to outline a number of findings and patterns about the writing of articles about waste management, specifically with regard to mining and metallurgical wastes. Let's break down and discuss the key points we've mentioned:

i. Publication Trends: The field of waste management, particularly in the context of mining and metallurgical wastes, has seen irregular patterns of article publication since its inception in 1992 (Aznar-Sanchez et al., 2018). The number of articles published each year has varied.
ii. Key Journals: Several prominent journals have been focal points for publishing articles in this field. Notable journals include *Ecological Engineering, Minerals, Environmental Earth Science and Pollution Research, The Journal of Environmental Management, The Journal of Geochemical Exploration,* and *The Journal of Hazardous Materials* (Aznar-Sanchez et al., 2018). These journals serve as platforms for sharing research and insights related to waste management and its environmental implications.
iii. Environmental Laws and Social Awareness: Over the years, environmental laws and social awareness programs have played a role in raising awareness about the potential environmental threats posed by mining and

metallurgical wastes (Matinde et al., 2018). These laws and programs have been established to promote responsible mining practices, address contamination concerns, and emphasize the importance of rehabilitating affected environments.

iv. Circular Economy Model: The circular economy model, which focuses on reducing, recycling, and reusing materials, has gained prominence in addressing waste management challenges associated with mining and metallurgical activities. This model aims to minimize waste generation and promote the sustainable use of resources.

v. Sustainability Concept: The concept of sustainability encompasses economic, environmental, and social dimensions. Sustainable development requires balancing economic viability, ecological integrity, and social well-being for present and future generations (Popovic et al., 2015). However, mining activities, including waste management, often create tensions and conflicts among these three dimensions (Velasco-Munoz et al., 2018).

vi. Focus on Waste Reuse: A significant number of publications—70.6% of the total analyzed articles—emphasize the reuse of waste materials (Aznar-Sanchez et al., 2018). This highlights the importance of exploring ways to repurpose waste products to minimize their impact on the environment and potentially create economic value.

vii. Profitable Processes and Environmental Impact: A subset of articles (17.6%) specifically addresses profitable processes for recovering polluted soils (Aznar-Sanchez et al., 2018). This indicates a recognition of the economic potential associated with remediating contaminated sites and reusing waste materials.

viii. Institutional Cooperation for Profitability and Environmental Impact: Some studies aim to examine how institutional cooperation can contribute to the development of waste management projects that enhance profitability while reducing environmental impact. This highlights the importance of collaboration between various stakeholders to achieve both economic and environmental goals.

In conclusion, our observations shed light on the dynamic and multidimensional nature of waste management in the context of mining and metallurgical activities. The evolution of publication trends; the emphasis on waste reuse; and the challenges of reconciling economic, environmental, and social sustainability underscore the complexity of addressing waste management issues in this field. Continued research, collaboration, and innovation will be essential for developing effective strategies that align with sustainable development principles.

1.5 NOVEL METHODS AND TECHNIQUES

Every method and technique of bioremediation discovered has always brought with it some pros and cons. Some have been a blessing for mankind while others have caused catastrophes, and each discovery is followed by a flood of questions and possibilities: questions regarding the method's suitability, adaptability, efficiency, accessibility, remuneration, prospects, short- and long-term effects on our surroundings (ecosystems and organisms from microscopic and macroscopic levels), and so on. How is it going to affect our economy, through investments in scientific research and development, and later manpower and technological inputs for implementation? These techniques provide opportunities for the use of fossil fuels, renewable energy, and energy conservation that are sufficiently adaptable and flexible to be used in other domains. These ruminations can be scientific, philosophical, or ethical. But, as members of the science community, let's dive deeper into the scientific approaches and discuss methods and techniques for the remediation of mining waste residues (Reichl et al., 2016).

Biodegradation technologies have shown promise in the field of newly occurring adulterants (Bakken, 2007). Emerging contaminants (EC) refer to a diverse group of synthetic or naturally occurring compounds that have been recently detected in the environment but are not yet regulated. These compounds include pharmaceuticals, personal care products, endocrine disruptors, and other chemicals that can have potential adverse effects on ecosystems and human health. Various techniques have been embraced for the management of debris and contaminants resulting from industrial projects, including physical, chemical, and biological techniques, as well as, more recently, advanced techniques such as membrane technologies, enhanced oxidation processes, and nanotechnology. Oxidation processes involve the introduction of oxidizing agents to transform contaminants into less harmful substances. Advanced Oxidation Processes (AOPs) utilize powerful oxidants like ozone, hydrogen peroxide, and ultraviolet (UV) light to generate reactive species that can degrade pollutants. Membrane technologies, such as reverse osmosis and nanofiltration, use semi-permeable membranes to separate contaminants from water. They are particularly useful for removing dissolved pollutants, including emerging contaminants. Figure 1.1 lists four major methods for the treatment of emerging contaminants in our ecosystems.

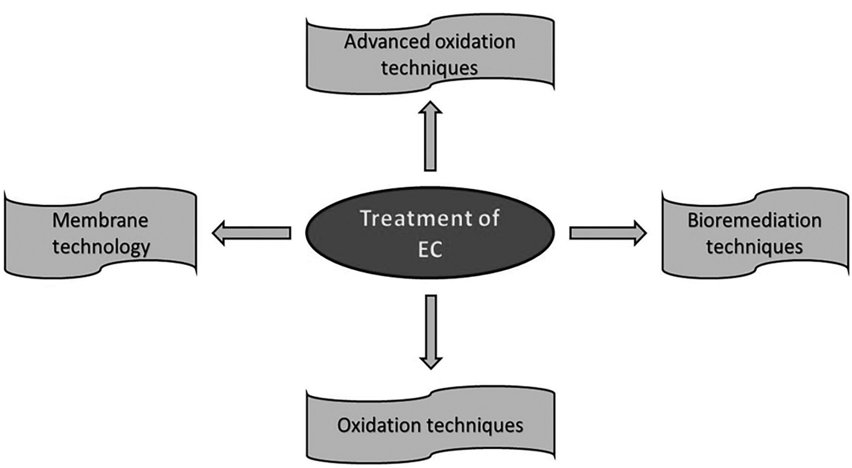

FIGURE 1.1 Treatment methods for emerging contaminants.

1.6 BIOREMEDIATION

Bioremediation uses naturally occurring microorganisms, plants as well as fungi, to break down hazardous pollutants into safe inorganic components. Living creatures are used to remove, neutralize, or immobilize toxins from the polluted site (Gidarakos and Aivalioti, 2007; Das et al., 2006; Johnson, 2014). Bioremediation attracted public scrutiny in the 1960s, after many experiments were conducted. Bioremediation advocate Robinson George catalogued numerous applications of the technique during the 1970s (Adams et al., 2015). It is cost-effective, environmentally friendly, and safe. Agrochemicals, pesticides, xenobiotics, radioactive waste, heavy metals, chlorinated compounds, agrochemicals, dyes, greenhouse gases, and hydrogen gas are among the pollutants that can be removed using bioremediation. Here the microorganisms used depend on environmental adulterants and bring about a decline in the composition of the adulterant. The population of microorganisms declines as they consume the adulterants, because less food (i.e. adulterants) is available.

Bioremediation can use indigenous or non-indigenous microorganism. Indigenous or "native" microorganisms are those that pre-exist in the contaminated area. However, suitable oxygen levels, a stable soil temperature, and the nutrients necessary for the microorganisms' growth must all be present to promote the growth of this category of microbes (Fantroussi and Agathos, 2005; Naik and Duraphe, 2012; Boopathy, 2002). Exogenous microorganisms are added to the contaminated soil to compensate for the absence of biological processes necessary for the breakdown of pollutants. To guarantee the microorganisms' survival in the new environment, managers must provide the external oxygen and nutrients the microorganisms need to survive, and might also need to change the site circumstances such as the deficiency of certain elements that the microbes may require to work more efficiently. However, it is important for microbes to perform bioremediation changes according to different longitudes, latitudes, regions, temperature, environmental conditions, soil pH, humidity, etc. For the best possible results from bioremediation, it is necessary to properly analyze and test each site that needs to be remediated. The type of microorganisms present, the site's environment, the volume and toxic effect of the contaminants, and other elements all play a part in determining the specific bioremediation technique. Different kinds of microbes interact with particular kinds of pollutants and can survive in various environments (Fantroussi and Agathos, 2005; Naik and Duraphe, 2012; Boopathy, 2002).

Bioremediation technologies have many applications, including the following:

i. Clean-up of oil spills, which often kill aquatic organisms and are one of the most common forms of pollution in areas with significant oil reserves: Bioremediation involves introducing bacteria that devour the spilled oil. Dispersants are typically used to help the process.
ii. Treatment of rivers, estuaries, and streams: Bioremediation is used to remove pollutants such as pesticides and fertilizers.
iii. Sewage treatment: Wastes and chemicals combine to create sewage that can be handled throughout the recycling procedure. The mentioned procedure delivers the best value in terms of effectiveness and cost (Velasco-Munoz et al., 2018).
iv. Compost bioremediation: By combining the composts, the bacteria present in the compost remove contaminants from polluted soil areas. This form of bioremediation is highly effective.

v. Bioremediation sometimes involves using genetic engineering to transform natural decomposers into extremely powerful "super-decomposers," which accelerates the elimination of environmental pollutants (Popovic et al., 2015).

There are many benefits to bioremediation. These include its cost-effectiveness compared to more conventional methods, which require extensive clean-up of the dangerous material before and after the operation. The method is simple to use and may be completed on-site without interfering with the microbes' regular activities, thereby avoiding the expense of moving the garbage off-site and any potential risks to the environment and public health. Additionally, this method takes less time than most conventional methods. Since it is a non-intrusive strategy, the site may be used continuously. Additionally, bioremediation enables a high level of contamination clearance. Despite all of its benefits, there are a few drawbacks to bioremediation. Only biodegradable pollutants can be remedied by microbes. In other instances, the pollutants are changed into intermediary substances that might be more harmful than the original substances. In addition, bioremediation is thought to take longer than alternative techniques such as complete excavation of the toxic soil. It is also challenging to scale up bioremediation procedures from different batches and small scales to higher-scale applications (Desai et al., 2010).

1.6.1 In-Situ vs. Ex-Situ Bioremediation

Bioremediation can be accomplished in two ways: in-situ and ex-situ. In the former, toxic metals are removed and remediated at the point of origin, whereas ex-situ procedures involve transporting the excavated polluted medium from the site of origin to another location for remediation. Figure 1.2 presents different types of ex-situ and in-situ bioremediation, with examples.

In the in-situ approach, the polluted soil is cleaned on-site, using a carefully selected bioremediation technique. Since it does not call for the removal of

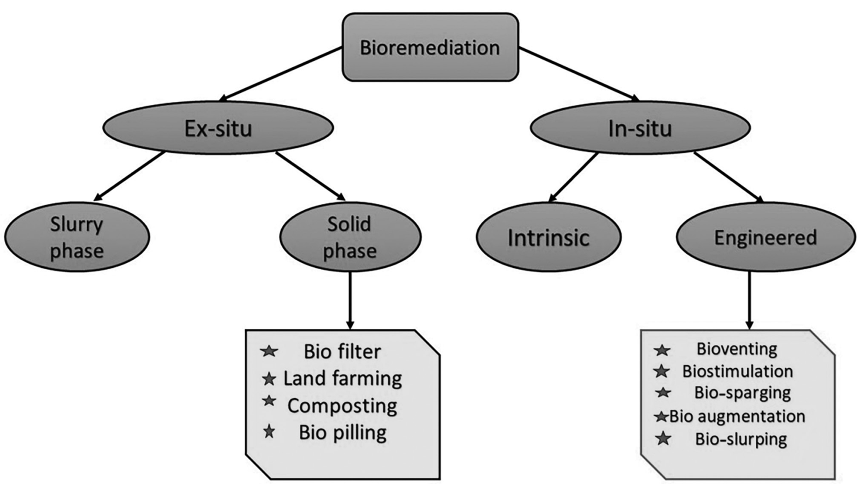

FIGURE 1.2 Ex-situ and in-situ bioremediation.

contaminated soils, it is less expensive and produces far less dust than the ex-situ approach, but it can also be slower and more difficult to control. It is most effective when used on permeable soils. In the aerobic in-situ approach, the organisms participating in the bioremediation are supplied with oxygen and nutrients, often by means of hydrogen peroxide injection or venting (Folch et al., 2013; Frascari et al., 2015; Roy et al., 2015). The ex-situ method, which entails either the removal of contaminated dirt or the pumping of contaminated groundwater before treatment, has been effectively used for many different categories of contaminants since it is simpler, less expensive, and easier. Ex-situ methodology comprises both slurry and solid-phase bioremediation, when promotion of remediation is crucial. Slurry phase bioremediation is a batch treatment approach in which excavated soil or sediments are combined with water and treated in bioreactor vessels or ponds. When contrasted with the slurry phase method, bioremediation of the solid phase is substantially simpler in application, requires more room, and takes longer to complete (Frutos et al., 2012; Smith et al., 2015).

In-situ bioremediation comprises two major types of technique: intrinsic and engineered.

Commonly referred to as the "natural reduction process," the intrinsic method involves passively cleaning up contaminated areas without the help of outside forces or human involvement, by stimulating the neighbourhood or natural population of microorganisms. The breakdown of the contaminated ingredients that consists of the recalcitrant sections is dependent on aerobic and anaerobic processes. Because external inputs are not used, this method is less expensive than other in-situ procedures. In the engineered method, genetically modified microbes are added to the polluted area, accelerating the clean-up process by improving the physicochemical conditions that encourage microbial development.

1.6.2 Bioremediation Techniques

There are many different bioremediation techniques, technologies, and strategies, but the most widely used ones are windrows, bioreactors, bioventing, bio-slurping, bio-sparging, phytoremediation, and permeable reactive barriers. Figure 1.2 shows the different types of bioremediation technique for mine waste management.

1.6.2.1 Microbial Bioremediation

This method uses bacteria to convert dangerous pollutants into harmless forms. The division of labour, immobilization, and concentration of contamination levels caused by the interactions between the pollutants and the bacteria enable this (Perez-Santana et al., 2007; Zhang et al., 2015).

1.6.2.2 Phytoremediation

This inexpensive, solar-powered cleaning system uses vegetation for in-situ pollutant deterioration, removal, or restriction in soil, sludge, sediments, or groundwater. If the levels of toxins are high, the plants used for clean-up may perish. If the contaminated region is very large, a bigger surface area of the plantation is necessary for effective bioremediation (Meagher, 2000; Kuiper et al., 2004).

1.6.2.3 Mycoremediation

Fungi, and primarily mushrooms, are used in this bioremediation process. The strategy relies on the performance of the enzymes the fungi create when breaking down various substrates. Fungi can be used in addition to the enzymatic process of biosorption, in which pollutants are ingested by the mushrooms and stored in their mycelium, rendering the mushrooms inedible. In the maritime environment, Aspergillus, Pleurotus, and Trichoderma have been proven to be beneficial in removing lead, nickel, cadmium, arsenic, iron, and mercury.

1.6.2.4 Bio-Pile

In this method, hazardous soil is dug up and stacked aboveground, aerated, and replenished with nutrients to increase the microbial metabolic rate. The method uses oxygenation, soaking, fertilizers, and techniques for gathering leachate and processing bed systems. Due to its cost-effective qualities, which enable excellent command of operational biotransformation components such as pH, nutrients, temperature, and oxygenation, this ex-situ technology is being assessed with increasing frequency. The bio-pile is used to deal with unstable low-molecular-weight adulterants, and it can also be used to clean up heavily contaminated, extremely cold, and harsh environments (Gomez et al., 2014; Dias et al., 2015). A warm-up arrangement may be incorporated into the design of the bio-pile to encourage pollutant availability and microbial activity, which promote biodegradation, thereby allowing the bio-pile to be adapted for a shorter remediation duration. Warm air can be included in the bio-pile to provide air and heat concurrently, improving biotransformation. To accelerate the remediation process, bulking agents including wood chips, bark, sawdust, and other organic matters have been added to a bio-pile construction. The bio-pile arrangement is related to other ex-situ biotransformation methods such as cropland, bioventing, and bio-sparging, but its implementation faces unique hurdles including strong engineering, high cost of operation and maintenance, and lack of electrical power for air circulation at remote locations. Furthermore, significant air warming can result in topsoil drying, which reduces important microbial activities and hence encourages volatilization instead of biodegradation of pollutants (Whelan et al., 2015).

1.6.2.5 Cropland Farming

Cropland farming involves excavation and tilting of polluted soil. Although it is used most frequently in ex-situ bioremediation, it can be used in-situ as well, depending on the site location. Adulterant deepness is crucial in cropland farming. In ex-situ bioremediation, the noxious soil is removed and treated on-site. To aid aerobic digestion by native microorganisms, excavated dirty soils are typically deposited on a stable supporting layer above the ground surface. Cropland farming is generally an easy-to-execute technology with low capital costs, which can be used to remediate massive amounts of contaminated soil with minimal energy consumption or ecological impacts (Silva-Castro et al., 2012; Lee, 2013).

1.6.2.6 Windrows

Windrows are a set of bioremediation procedures in which mounds of contaminated soil are regularly turned over to increase the microbial breakdown of native and transfers hydro-carbon plastic. The rate of bioremediation, which can be carried out via acclimatization, biotransformation, or mineralization, is accelerated by the repeated turning of polluted soil, which increases oxygenation and ensures equitable dispensation of nourishments, pollutants, and microbial deterioration activities. Windrow treatment has shown a much faster rate of hydrocarbon removal than has the bio-pile treatment, although the overall effectiveness at removing hydrocarbons from the soil is lower for the former. Moreover, regular turning combined with windrow treatment is not the best approach for the bioremediation of soil contaminated with dangerously unstable compounds. Due to the anaerobic zone that forms inside heaped dirty soil after windrow treatment, the technique has been linked to the production of greenhouse gases (CH_4) (Coulon et al., 2010; Hobson et al., 2005).

1.6.2.7 Bio-Slurping

This system brings together vacuum-assisted pumping, soil vapor extraction, and venting to deliver oxygen indirectly and promote biodegradation of adulterants, including volatile and semi-volatile chemicals, in organic soils and groundwater. This strategy was developed for product recuperation. It is appropriate for the remediation of semi-volatile and volatile organic compound-polluted soils. Products from saturated and unsaturated areas will be recovered via the use of the bio-slurping technology, light non-aqueous phase fluids, and capillary remediation. In this method, liquids are drawn up with the use of a free product layer known as a "slurp" that unfurls into it. Light non-aqueous phase liquids are transported upward by the pumping machine and separated from air and water at the surface. The moisture content of the soil lowers microbial activity by decreasing air permeability and oxygen transfer rate. Although this technique is not ideal for rehabilitating low-permeability soils, it is an economical method that consumes little groundwater, thereby lowering costs for storage, treatment, and disposal (Gidarakos and Aivalioti, 2007; Rawat and Rangarajan, 2019).

1.6.2.8 Bioreactor

In this approach, polluted soil samples are placed in a bioreactor, a device that utilizes a sequence of biological reactions to transform raw substances into particular commodities. Different operational modes are used in batch, fed-batch, sequencing batch, continuous, and multistage bioreactors. Conditions regarding the growth of bioremediation are perfect in bioreactors. Bioreactors have several advantages over ex-situ bioremediation techniques. By providing greater control over temperature, substrate, inoculum concentration, pH, agitation, and aeration, they allow for faster bioremediation. This ability to control and modify procedure parameters in a bioreactor suggests that biological reactions can be altered and controlled. The flexibility of bioreactor designs allows for optimum biological deterioration while minimizing abiotic losses (Mohan et al., 2004).

1.6.2.9 Bio-Sparging

Biosparging involves introducing air into the subsurface of polluted soil to promote microbial activity. It is similar to bioventing, which entails the introduction of air into the unsaturated zones, which may aid in the volatile organic molecules' upward migration to the unsaturated zone and hence speed up the process of biodegradation. In in-situ air sparging (IAS), which is closely connected to venting and soil vapor extraction (SVE), contaminant volatilization depends on high air-flow rates. The effectiveness of biosparging is primarily determined by soil permeability and pollutant biodegradability. It has been most commonly used to clean up kerosene- and diesel-fuel-contaminated aquifers (Rawat and Rangarajan, 2019).

1.6.2.10 Permeable Reactive Barrier (PRB)

PRB is an in-situ method for removing heavy metals and chlorinated chemicals from contaminated groundwater by means of biological mechanisms such as precipitation, degradation, and sorption (Obiri-Nyarko et al., 2014). Alternative names for the methodology have been suggested, including biological PRB, bio-enhanced PRB, and submissive bio-reactive barricade, to accommodate its various bioremediation and biotechnological features.

1.6.2.11 Bioventing

In this method, the flow of air is deliberately stimulated by supplying oxygen to the area that isn't saturated, increasing the activity of the localized microorganisms responsible for bioremediation. Amendment here is in context of the modifications created with the addition of moisture is largely utilized to speed up the bioremediation procedure. Among the different in-situ approaches, this method has attracted particularly significant attention. The contaminants are rendered safe through transformation at the microbial level. The modifications created with the addition of moisture are largely used to speed up the bioremediation procedure. Among the different in-situ approaches, this method has attracted particularly significant attention (Kulshreshtha et al., 2014; Kour et al., 2021).

1.6.3 Factors Influencing Bioremediation

Microorganisms' enzymatic metabolic pathways advance chemical reactions that aid in the breakdown of pollutants. The microbes act on the pollutants only when in contact with substances that help produce energy and nutrients for nutrient multiplication. The effectiveness of the bioremediation process is influenced by the contaminants' concentration and chemical makeup, and by the ease with which they can be accessed by the original microbes. The main determinants include the number of microorganisms present, the environment's makeup, soil pH, temperature, nutrients, and oxygen content (Cases et al., 2005).

The effectiveness of bioremediation is determined by biotic and abiotic factors. Biological factors such as biomass production, gene horizontal transfer, enzyme activity, mutation, and population size and composition help promote antagonistic associations between protozoa or microorganisms and bacteriophages, as well as the disintegration of various organic pollutants by bacteria with insufficient sources of carbon (Adams et al., 2015). The rate of degradation is mostly affected by the catalyst used in the biochemical reaction as well as the nature of the contaminants present. Abiotic factors such as soil structure, temperature, oxygen content, redox potential, toxicity, solubility, moisture, nutrients, pH, kinds, and concentration all affect how

TABLE 1.1
Factors Affecting Bioremediation And Their Roles

Factors	Role
Bioavailability of pollutants	• Irreversible sorption • Incorporation into humic matters • Equilibrium sorption
Surface factors	• Availability of electron acceptors • Chemical structure of contaminants • Solubility of contaminants • Concentration of contaminants • Toxicity of contaminants • Microbial population at the site • Biological aerobic versus anaerobic process • Oxidation/reduction potential
Mass transfer limitations	• Diffusion of nutrients • Oxygen diffusion and solubility • Miscibility/Solubility with/in water
Environmental factors	• Lack of nutrients • Depletion of preferential substrates • Inhibitory environmental conditions
Microbial factors	• Enrichment of the capable microbial populations • Enzyme induction • Mutation and horizontal gene transfer • Production of toxic metabolites • Growth of microorganisms takes place till the biomass has reached its critical production
Growth of microbes, and co-metabolism	• Alternate carbon source present • Type of contaminants • Microbial interaction • Concentration

successfully pollutants and bacteria interact, as do the physicochemical characteristics of the microorganisms used in the restoration process. In most earthbound environments, pH levels in the 6.5–8.5 range are ideal for the biodegradation of contaminants. Since it depends on the kind and amount of readily accessible soluble components, as well as osmotic pressure and pH, moisture affects the breakdown of contaminants (Lee and Lee, 2004).

Table 1.1 lists the factors affecting bioremediation and the roles played by each factor.

1.6.4 Bioremediation: Some Recent Approaches

Bioremediation offers a wide range of unexplored and alluring options for research in bioinformatics, an interdisciplinary field that combines biology and computer science (Hussain et al., 2009). In bioinformatics, information about DNA, RNA, and proteins is stored, manipulated, recovered, and distributed using computer technologies. Bioremediation can be advanced using "omics"-based techniques, such as genomics, transcriptomics, interactomics, proteomics, and metabolomics. These approaches require a substantial amount of data from various sources, such as protein sequence, biology and physiology, comparative genomics, chemical structure, reactivity of organic compounds, and environmental biology. Bioinformatics helps to correlate DNA sequences with the amount of mRNA, proteins, and metabolites, providing a more accurate and comprehensive picture of in-situ bioremediation.

i. Proteomics and metabolomics: While metabolomics is concerned with the quantification and characterization of all total metabolites produced by an organism at a certain time or under specific conditions, proteomics is concerned with the total number of proteins expressed in a cell at a specific location and time (Khardenavis et al., 2007). The quantity of proteins and changes in their composition can be detected using proteomics-based research, and key proteins involved in the physiological reactions of microbes to anthropogenic contaminants can also be found (Qureshi et al., 2007). Functional study of microbial communities is more insightful and holds greater promise than genomics.

   Two primary approaches are used in metabolomics research to assess biological systems. The first is a broad, unfocused research approach for which prior knowledge of the metabolic pathways of the biological system is not required. This method assists in the identification and recovery of a wide variety of metabolites present in the sample, producing a vast amount of data that can be compared between samples to ascertain the interconnection of metabolic pathways. The second method involves designing a study specifically to identify particular metabolic pathways or metabolites using information already available (Gupta et al., 2020). The microbial metabolomics toolbox includes numerous methods, such as target analysis, metabolic fingerprinting, and metabolite profiling, for the detection and measurement of a wide variety of cellular metabolites. Identification of the active chemicals required for cell-free bioremediation will be aided by the integration of proteome and metabolome data.

ii. Genomics: A variety of microorganisms can be used in bioremediation (Singh et al., 2006; Pandey et al., 2019). Genomic research is a burgeoning field in the study of microbial strains involved in bioremediation (Dey et al., 2023). This approach examines every piece of genetic data present in a microbe's cell. PCR, micro assay analysis, DNA hybridization, isotope distribution analysis, molecular connectivity, metabolic engineering, and metabolic foot printing are used to explain biodegradation pathways and improve the biodegradation process. Numerous genotypic fingerprinting methods based on PCR are available for microbial communities that have been mixed up, including amplified fragment length polymorphisms (AFLP), automated ribosomal intergenic spacer analysis (ARISA), amplified ribosomal DNA restriction analysis (ARDRA), terminal-restriction fragment length polymorphism (T-RFLP), single strand conformation polymorphism (SSCP), randomly generated polymorphism (RGP). DNA analysis can be employed in examining fundamentally connected bacterial species, genetic fingerprinting, and structural and functional interpretation of soil microbial communities (McGrath et al., 2008). LH-PCR can be used to identify the natural length variations of different SSU rRNA genes within microbial communities. T-RFLP can be used to simultaneously profile microorganisms from various taxonomic groups in an environment (Ishii et al., 2015).

iii. Transcriptomics: An essential connection between the cellular phenotype, genome, interactomics, and proteome is the transcriptome, which is a collection of genes that are transcribed under specified circumstances and at specific times. Gene expression regulation is a crucial process for adapting to environmental changes and, ultimately, for survival. Transcriptomics investigates this process across all of the genome. A particularly effective tool in transcriptomics for assessing the level of mRNA expression is DNA micro assay analysis. Transcriptomics research includes the extraction and enrichment of total mRNA, cDNA synthesis, whole cDNA transcriptome sequencing, and microarray hybridization of cDNA. The valuable transcriptomics technology known as the DNA microarray can be used to analyse and investigate virtually every gene's expression in an organism's mRNA (Pandey et al., 2019). By analysing transcriptional mRNA patterns, transcriptomics and metatranscriptomics are valuable for learning about the functions of environmental microbial communities (McGrath et al., 2008). It has been demonstrated that metagenomics, along with genome binning, metagenomics, and transcriptomics, can provide information on microbial relationships, syntrophism, and complementary metabolic pathways during the biodegradation process (Ishii et al., 2015).

iv. Metatranscriptomics: This is a potent approach for gathering qualitative along with quantitative gene expression data (Giovanella et al., 2020).

1.7 REMEDIAL STEPS IN MINING AND METALLURGICAL WASTE MANAGEMENT

The mining and metallurgical industries continue to produce a lot of garbage, despite long-term efforts to reduce this quantity. This waste stream is one of the biggest in the world. Environmental laws and social awareness campaigns have been implemented over time to reduce the potential risks to humans and the environment posed by mining and metallurgical wastes.

Waste is produced in a variety of ways, and the volume and composition of this waste are heavily influenced by consumption patterns as well as the industrial and economic systems that are in place. Standard waste management practices have until now concentrated on managing how the waste is produced and disposed of. Industrial, mining, and metallurgical wastes are typically abandoned and/or landfilled since they are thought to have little to no obvious economic purpose.

The mining and metal extraction sectors can be combined to create a circular economy model that supports zero waste through the recycling and re-use of waste products. To put it another way, many waste streams can be thought of as secondary sources of valuable minerals and metals (Pradip et al., 2019). The recycling of mine wastes, according to Lotter Moser, involves extracting new valuable resource elements from the waste, using the waste as feedstock, or turning the entire waste stream into a new valuable product (Lebre et al., 2017). Recyclability is the ability of waste products to be collected, transformed into new material, or repurposed. The ability to recycle a material depends on the availability of technology, processes, and markets for recovered goods. The World Steel Association (2015) defines re-use broadly as using an item or substance more than once for the same or a related purpose without significantly changing the item's physical shape. Creating financial assets, improving resource efficiency by reducing linear resource consumption, reducing waste production and accumulation, and encouraging innovation and growth of new technologies are just a few of the short- and long-term benefits of recycling and reusing mining and metal extraction wastes (Hegab et al., 2023). Increasing recycling and re-use of mining wastes can provide sustainable and cost-effective alternatives to traditional disposal methods, thereby reducing the environmental impact of disposal and conserving resources. While challenges exist, advances in technology and innovative approaches are continually being explored to address these issues and maximize the value and sustainability of mining waste re-use. Balancing economic, environmental, and social considerations is key to achieving successful and responsible waste management practices in the mining industry (Lebre et al., 2017).

The sections that follow provide an overview of recycling and re-use possibilities for specific kinds of mining and metal extraction wastes, based on the new paradigm for turning wastes into useful resources. Table 1.2 lists and describes the types of waste.

1.7.1 Waste Rock, Overburden, Beneficiation Waste, and Sludge

Waste rock and overburden are typically considered low-grade minerals that are not economically viable for extraction. They can find new life as construction materials (e.g., aggregates, backfill, landscaping), waste repository capping, mine revegetation substrates, and other applications. Reusing waste rock and overburden reduces the need for virgin resources and minimizes environmental disruption from disposal. Beneficiation waste consists of tailings and residual materials from mineral processing. Tailings can be reprocessed to recover metals and compounds, offering a second chance for resource extraction. Different types of tailings have specific reuse potentials, such as sand-rich tailings for backfill and clay-rich tailings for soil improvement or manufacturing purposes. Mine drainage sludges can be treated to extract valuable metals or used for water treatment applications. Phlogopite-rich tailings and ultramafic tailings can be utilized in sewage treatment, glass manufacturing, and rock wool production. Sandy soils can be improved using clay-rich tailings, and various tailings types can be used for ceramics, cement, tiles, and bricks.

While there are significant opportunities for reusing these wastes, there are also challenges. The complex mineralogy and heterogeneous composition of these waste

TABLE 1.2
Overview of Wastes Produced in the Mining and Metals Extraction Industry (Kalisz et al., 2022; Whitworth et al., 2022)

Types of waste	Comment
Overburden	Soil and rock that has been dug up and heaped up to gain access to mineral resources. Overburden typically has a low risk of contaminating the environment, although acid rock discharge can occur.
Waste rock	Mineral concentrations in waste rock are thought to be too low for profitable extraction. Due to the deposition of wastes from various mine sources, waste rock has a heterogeneous mineralogical composition and a variety of chemical and physical properties. Waste rock can be a concern because acid rock (mine) drainage can arise depending on the material being extracted.
Mineral beneficiation tailings	Fine, lifeless rock that is left behind after the precious components have been removed through processing. Tailings are typically deposited into tailings ponds as water-based slurry and may also contain leftover chemicals.
Metallurgical slags	Materials that resemble glass or are amorphous and are created as by-products of smelting and refining metals. The presence of entrained and/or dissolved heavy metals makes it difficult to reuse some slags, even though they have found broad use in the building and agricultural industries and can be environmentally safe.
Wastewater	Emanates from a variety of processes, with varied levels of purity and the potential to pollute the environment. Mine water, process (mill) water, leachate (containing dissolved minerals, chemicals, and/or metals), effluent (process water discharged into surface water, often after treatment), and mine drainage water are typical examples.
Water treatment sludge	Slurry or residue that is still semi-solid after mine and industrial wastewater and water have been treated locally. Heavy metals and other leftover compounds may be present in sludge. There is a lot of research being done on the recycling and recovery of precious metals from industrial and mining sludges. Waste treatment sludges are categorized as hazardous materials depending on the methods.
Acid mine drainage (AMD)	Acid mine drainage (AMD) is produced by tailings, waste materials, and/or mining infrastructure like underground workings and closed active or abandoned pits.
Gaseous and particulate emissions	Atmospheric emissions from the high-temperature chemical processing of metals include particle dust and poisonous gases including SOx, NOx, CO, CO_2, organometallic compounds, polychlorinated-p-dibenzodioxins, and dibenzofurans (PCCD/Fs). In most jurisdictions, these emissions are categorized as hazardous materials due to the entrained poisonous heavy metals, toxic organometallic compounds, and PCCD/Fs.
Post-consumer waste	Produced by consumers in homes, businesses, industries, and institutions when products are no longer useful. One example is e-waste.

materials can impact their suitability for reuse in specific applications. High concentrations of transition metals, hazardous elements, and reactive minerals in mining and beneficiation wastes need to be carefully managed to prevent environmental damage. Careful assessment and management of potential environmental impacts, such as acid rock drainage and contamination, are crucial when considering recycling and re-use options.

1.7.2 Acid Mine Drainage

Acid mine drainage (AMD) is the result of acidic, sulphate- and metal-containing wastewater being discharged into the environment. Sulphide-containing minerals, when exposed to oxygen, water, and acidophilic chemolithotrophic bacteria, generate AMD. AMD can originate from various sources, including tailings, waste rock, and mine structures, leading to environmental degradation and negative impacts on ecosystems. Untreated AMD can harm human health, animals, plants, and aquatic life due to its acidic and metal-laden nature. Remediation methods aim to treat or recover AMD before its release into water bodies, with approaches falling into active and passive categories. Traditional remediation methods may generate new waste streams and residual materials requiring further treatment and disposal.

AMD is being explored for metal recovery as part of a comprehensive remediation strategy to meet environmental regulations and recover valuable materials. Metal recovery can reduce waste handling and disposal, create revenue streams, and enhance the sustainability of mine water treatment projects. The most commonly used method for metal recovery involves precipitating hydroxide compounds from AMD using alkaline reagents such as NaOH. Challenges of this method include concentrated sludge generation and the difficulty of selectively extracting metals.

Various techniques exist for treating AMD and recovering metals, such as wetland treatments, electrodialysis, ion exchange/adsorption, ultrafiltration, solvent extraction, and reverse osmosis. These methods offer the potential for recovering other beneficial materials, such as electricity, alkaline earth substances, building materials, agricultural products, adsorbents, and pigments. Recovery of saleable products like sulfur, sulfuric acid, pigments, and metal sulfates can contribute to revenue generation and offset treatment costs. AMD treatment techniques can promote sustainable mine water management while producing valuable materials for various industries (Dhir, 2018; Bergerson and Lave, 2004). As technological advancements continue, innovative approaches to AMD remediation and metal recovery hold the promise of minimizing environmental harm and contributing to sustainable resource management (Kefeni et al., 2017; Akcil and Koldas, 2006).

1.7.3 Metallurgical Dust

In the off-gas from smelting and refining furnaces, complex oxides from feed and process materials are mixed heterogeneously to form metallic dust. Blast furnace ironmaking, raw material agglomeration (such as coke, sinter, and pellet plants), electric arc furnaces (EAFs), basic oxygen furnaces (BOFs), stainless steel refining, base metal smelting and converting, and submerged arc furnaces (SAFs) for ferrochrome and ferromanganese production are just a few processes that produce significant amounts of these waste materials (Krishnan et al., 2021).

Metallurgical dust's physicochemical characteristics vary significantly depending on the process design, parameters, operational practices, and type of raw materials employed. For instance, for each tonne of hot metal (tHM), approximately 7–45 kg of blast furnace particle dust containing 100–150 g of Zn is produced. Because they include harmful metals such as Pb, Cr, Zn, and Cd, these materials are typically categorized as hazardous waste and cannot be dumped in landfills without first undergoing pretreatment and/or stabilization. Direct in-process recycling is typically restricted due to the possibility of a build-up of hazardous and volatile metal compounds (Kumari and Samadder, 2022). For instance, the metallurgical dust generated during the production of iron and steel mostly consists of heterogeneous mixes of complicated feed material oxides entrained in the off-gas. These materials frequently have high concentrations of iron, reductants, and alloying elements.

Numerous methods have been developed or are being investigated to recover the significant metallic components present in metallurgical dust while guaranteeing a non-destructive barren outcome. Pyrometallurgical and hydrometallurgical techniques are the two main alternatives for recovering valuable metals from ferrous metallurgical dust. In the former, the necessary metals are separated from other materials using thermal energy based on variations in the oxidation potentials, melting temperatures, vapor pressures, densities, and/or miscibility of the dust components when melted. In hydrometallurgical technologies, the necessary metals are separated while in an aqueous solution, utilizing methods that take advantage of variations in constituent solubilities and/or electrochemical characteristics.

The existence of volatile hazardous metal compounds such as Zn, Cd, As, and Pb restricts the direct recycling of ferrous dust (Turner et. al., 2021). Due to the strong reliance on the use of scrap galvanized steel as feed to these operations, Zn-bearing compounds like zincite (ZnO) and franklinite ($ZnFe_2O_4$) are particularly problematic in the steelmaking process. The carbothermic reduction sequence $ZnFe_2O_4$(s) ZnO(s) + Fe_2O_3(s) Zn(v) + Fe(s) of $ZnFe_2O_4$ in dust, and the subsequent volatilization of the zinc before recovery in the downstream condensers, are the key components of the pyrometallurgical processing of ferrous dust. To recycle ferrous metallurgical dust economically, several pyrometallurgical techniques have been widely used throughout the world to date. The capacity to handle metallurgical dust with high levels of Zn present as $ZnFe_2O_4$ cheaply is one of the main benefits of the pyrometallurgical techniques discovered to date. Although these procedures involve complex dust collection systems, extra steps must be taken to recover volatile metals from the flue gas, and they are sensitive to economies of scale.

In comparison, hydrometallurgical processes have lower startup costs and few or no environmental issues related to flue gases, dust, and noise, but they also require careful management of water, wastewater, and process solutions to be technically and economically feasible. The complex physical, chemical, and mineralogical features of the dust components have significantly limited the broad use of hydrometallurgical processes. Poor selectivity and dissolution are additional issues with hydrometallurgical processes using traditional leaching and chelating media, which add to the complexity of subsequent solution purification procedures. Consequently, several substitute leaching and pretreatment procedures have been developed to improve the kinetics and economics of traditional methods.

Table 1.3 summarizes some of the distinguishing properties of several groups of metallurgical dust and options for their recycling.

1.7.4 Metallurgical Slags

Metallurgical slags are created in enormous quantities during pyrometallurgical smelting and refining operations and are essential for the effective extraction of metals. Slag separates from the metal or alloy during the smelting and refining operations and is removed from the furnace before being ground or slowly cooled. Solidified metallurgical slags contain considerable levels of entrained and/or dissolved metals, which, depending on the process design and conditions, can seriously impact the environment in the long run (Kaniki et al., 2019). Process slags are currently disposed of in landfills, which poses environmental problems. As a result, extensive efforts to improve these materials' potential for recycling and reusing must be made (Gaskell, 2007). Numerous studies have concentrated on the uses of metallurgical slags in different areas of the economy, including as building materials, in the production of ceramics and other functional materials, and as polymeric materials. However, one of the main obstacles to the recycling and reuse of these materials continues to be the presence of entrained and/or dissolved hazardous metal components as well as the build-up of deleterious elements in the slag.

1.7.5 Post-Consumer Waste

Post-consumer trash is any garbage produced by households, businesses, industries, or institutions after a product has been used to its full potential and is no longer useful for that purpose. The amount of these anthropogenic materials has dramatically grown as a result of the growing global population, technological advancements, and increased use of natural resources. Unused and/or outdated goods are typically disposed of in landfills, posing environmental issues. Reducing environmental harm while promoting sustainable development objectives through the effective use of resources can be accomplished by viewing these materials as anthropogenic sources of secondary resources that can be recycled and reused (Singh and Ordoñez, 2016). Numerous studies have been done to recover valuable metals from used auto catalysts and electronic trash utilizing both established aqueous leaching and chelating medium and newly developed non-aqueous leaching and chelating media. To date, several methods for recovering metals have been developed, including biohydrometallurgy and complexing agents including cyanide, halides, thiosulphate, thiourea, and acidic media. Recently, the focus has been on employing ionic liquids to recover precious elements from used auto catalysts and e-waste.

Due to their desired qualities, such as non-volatility, low toxicity, good ionic conductivity, and a broad electrochemical potential window, ionic liquids, low-temperature molten salts containing cations and organic/inorganic anions are increasingly being researched for the extraction of metals. Ionic liquids can recover valuable metals from used auto catalysts and electronic waste in their pure form with

TABLE 1.3
Typical Properties of and Recycling and Mitigation Processes for Metallurgical Dust (Tian et al., 2021; Makhathini et al., 2023)

Category	Characteristics	Recycling and mitigation	Challenges to recyclability
Blast furnace dust	7-45 kg of dust/tHM; 100-150 g Zn/tHM	Briquetting and in-process recycling as additional sources of iron and carbon.	The accumulation of volatile metal compounds, organometallic compounds, and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) during processing limits the amount of material that may be recycled. Complex off-gas cleaning systems are necessary, although fugitive emissions may still be an issue.
Coke plant dust	Varies (approx. > 1 kg coke breeze/ton coke	Additives in the sinter plant as auxiliary fuels and reductants.	
Ferrous raw material agglomeration	Varies	Briquetting and in-process recycling as well as auxiliary additives in the blast furnace and EAFs.	
Basic oxygen furnace (BOF) dust	14-143 kg dust/t liquid steel 0.75-24 kg/t liquid steel	Briquetting and in-process recycling. Metal recovery using pyrometallurgical, hydrometallurgical, and plasma processes. Solidification and/or stabilization.	Controlled material is necessary since it is unclear how harmful metal components would behave over an extended period in stabilized/solidified dust. The accumulation of volatile metal compounds during processing, the changing value-metal thresholds, and the complicated chemical and mineralogical properties of the dust all limit recycling potential. Costly additional metal recovery procedures.
Electric arc furnace dust (EAFD)	15-20 kg dust/t steel. Over 8.5 Mt are produced per year		

Stainless steel-making dust	10-70 kg dust/t HCFe Cr		
Submerged arc furnace (HCFeCr)	18-25 kg dust/t HCFe Cr	Process-integrated dust recycling systems. Emissions reduction by mandatory adoption of closed furnaces, agglomeration of feed, use of intricate wet scrubbing systems, and control of raw material quality and process parameters.	Variable value-metal thresholds and in-process accumulation of volatile metal compounds limit the ability to recycle. The issue of fugitive emissions persists. Complex wet scrubbing systems can be expensive and occasionally unavailable.
Submerged arc furnace (HCFeMn)	Up to 25 wt% Mn and varying amounts of volatile metals.		
Base metals (copper) smelter dust	Up to 30 wt.% Cu and high amounts of Fe, S, Zn, and metalloids (As, Sb, Pb, Cd, Bi)	In-process recycling of smelter dust. Metal recovery using conventional pyrometallurgical and hydrometallurgical processes, or a combination of both.	The accumulation of harmful, volatile toxic metals (such as As, Sb, Pb, Cd, and Bi), low value-metal thresholds, and the complicated chemical and mineralogical features of the dust all hinder the recyclability of smelting dust.
PMG smelter and converter dust	Varying amounts of entrained PGMs, Fe, S, Zn, and metalloids (As, Sb, Pb, Cd, Bi)		

great selectivity, while detoxifying and creating residues that are safe for the environment (Islam et al., 2020).

1.8 CONCLUSION AND FUTURE TRENDS

We have provided a comprehensive overview of the concept of emerging contaminants, the challenges they pose, and the various approaches used for their treatment and remediation. Bioremediation, which involves the use of living organisms (usually microorganisms) to degrade, transform, or remove contaminants from soil, water, or air, stands out as a promising and efficient method for restoring contaminated areas, leveraging the natural capabilities of microorganisms. However, its success depends on factors such as microbial degradation potential (the ability of microorganisms to enzymatically degrade specific contaminants); the availability of nutrients such as carbon, nitrogen, and phosphorus, which microorganisms require for their growth and metabolism; and the abundance and diversity of microbial populations at a contaminated site. In some cases, adding nutrients to a contaminated site (a process called biostimulation) can enhance microbial activity and accelerate bioremediation. Introducing specific microbial strains or consortia can help enhance degradation capabilities. Different contaminated sites present unique challenges, including variations in soil composition, hydrology, and contaminant types. Tailoring bioremediation strategies to the specific conditions of each site is essential for optimal results.

Bioremediation is effective primarily for contaminants that can be broken down by microorganisms. Some compounds may be recalcitrant (resistant to degradation) or require extended treatment times. In such cases, alternative technologies such as oxidation processes, advanced oxidation processes, and membrane technologies are employed. Given the complex and evolving nature of emerging contaminants, ongoing research is crucial for developing innovative and efficient treatment strategies. This includes exploring new microbial strains, optimizing bioremediation conditions, and integrating various technologies for enhanced remediation outcomes.

In conclusion, the field of emerging contaminants and their remediation is multidisciplinary and rapidly evolving. Bioremediation is a powerful tool, but its application needs to be carefully tailored to specific contamination scenarios. Combining bioremediation with other advanced technologies can provide comprehensive solutions for tackling the challenges posed by emerging contaminants in our environment.

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