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Review Article

Advanced microbial technologies (AMTs) for the sustainable bioremediation of coal mining wastes

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ABSTRACT

Coal mining produces large volumes of waste, including spoil, tailings, and acid mine drainage, posing serious environmental risks. These wastes often release acidic compounds, toxic heavy metals such as arsenic, lead, and cadmium, and persistent organic pollutants like polycyclic aromatic hydrocarbons into surrounding soil and water, threatening ecosystems and human health. To address these challenges, microbial bioremediation has emerged as an effective and environmentally friendly on-site solution. This approach uses bacteria, fungi, or microbial consortia to naturally detoxify contaminated environments. Compared with conventional chemical treatments, microbial methods require less energy, generate minimal secondary pollution, and are largely self-sustaining. Microorganisms remove pollutants through mechanisms such as biosorption and bioaccumulation of metals, enzymatic degradation of complex organic compounds, and biomining that converts dissolved metals into stable solids. Although single-strain systems showed promise in laboratories, engineered microbial communities have proven more resilient under field conditions. Metagenomics and synthetic biology enable low-carbon waste management.

1. Introduction

Globally, coal mining is an important energy source, especially in developing/emerging economies. At the same time, this activity generates a vast quantity of waste materials collectively referred to as Coal Mining Waste (CMW). CMW includes overburden (rock) materials; coal gangue (the waste material from the mining process), mine tailings, fly ash, fine particulate matter, and acid mine drainage (AMD). The resultant environmental pollution threatens biodiversity disrupts aquatic/terrestrial ecosystems; and creates serious public health challenges for communities living near coal mining operations. Traditional remediation techniques, including chemical neutralization, physical containment, and thermal stabilization are effective to a degree but all have significant energy consumption and can create considerable secondary waste material and do not provide long-term sustainability [1]. In recent decades, microbial bioremediation has become increasingly well-recognized as an effective cost-efficient; environmentally acceptable, and self-sustainable method of remediating environmental contamination [2]. Microorganisms possess an extraordinary ability to tolerate and degrade toxic pollutants through numerous mechanisms including biosorption; bioaccumulation; biomining;

enzymatic biotransformation; bioleaching. The convergence of metagenomics, synthetic biology, nanobiotechnology and bio electrochemical engineering along with bioremediation science represents the confluence of Advanced Microbial Technologies (AMTs). The metabolic diversity of natural as well as genetically-enhanced microbial populations can be leveraged to provide targeted detoxification and recovery of resources from environments affected by CMW [3]. Field-scale demonstrations have validated the potential for using AMTs, and mathematical models can now be employed to provide a system-level assessment of performance and efficiency of AMT processes for CMW applications as well as their possible scalability into practical systems. This chapter provides a clear picture of:

- (i) CMW pollutant types; associated environmental concerns;
- (ii) bioremediation's microbial processes,
- (iii) existing AMTs that can be used to treat CMW,
- (iv) microbial diversity associated with mine sites,
- (v) existing mathematical models to assess performance,
- (vi) field applications and case studies, and
- (vii) future research needs and challenges associated with sustainable management of CMW [4].



2. Pollutants in coal mining waste: Types and environmental risks

Coal Mining Waste (CMW) is a heterogeneous mixture of both truly different materials that are categorized as inorganic contaminants, organic waste, and gas emissions to atmosphere. Therefore, CMW's composition will vary significantly from site to site therefore in order to understand how/where to treat them will be important in developing effective bioremediation strategies [5].

2.1 Metalloids and heavy metals

In CMW, heavy metals represent the largest class of hazardous inorganic pollutants, with arsenic, lead, cadmium, mercury, chromium, zinc, copper, and nickel typically present at elevated concentrations in mine waste rock and acid mine drainage (AMD). AMD is produced by the oxidation of iron sulphide minerals (e.g., pyrite) in the presence of water and oxygen, which releases metals into both groundwater and surface water systems, so that the extent of contamination may reach well beyond mining operations [6].

2.2 Polycyclic Aromatic Hydrocarbons (PAHs) and organic pollutants

PAHs are formed when carbon-containing materials do not burn completely and are commonly found in materials used for burning coal, such as coal gangue, fly ash from combustion, and burned materials from mining equipment. Some of these chemicals, such as naphthalene, anthracene, benzo(a)pyrene, and fluoranthene, are classified as priority pollutants because of their ability to cause genetic mutations (mutagenicity) or cancer (carcinogenicity). In addition to PAHs, diesel fuel, lubricants, and mineral oils that are emitted from mining equipment can also contribute to soil and groundwater pollutants located near mines [7].

2.3 Sulphate and acid mine drainage

Acid mine drainage (AMD) derived from the oxidation of sulphide-rich waste rock (note: Waste rock is the material that remains after valuable minerals have been extracted from the ore) and the production of sulphuric acid through chemical and microbial processes has caused a reduction in pH in aquatic systems, changing the chemistry of water and contributing to the transport of metal ions into natural waters. At elevated levels of sulphate, aquatic ecosystems can be adversely affected due to alterations in ionic neutralization, the accumulation of toxic sulphides in reducing environments, and inhibitory effects on sensitive aquatic life [8].

Table 1: Major pollutants and environmental hazards due to CMW [8].

Contaminant Group	Contaminants	Health Effects / Environmental Hazards
Heavy Metals	Arsenic, Lead, Cadmium, Mercury, Chromium, Zinc	Soil and water toxicity, bioaccumulation, long-term health effects
Polycyclic Aromatic Hydrocarbons	Benzo[a]pyrene, Naphthalene, Anthracene	Carcinogenic, mutagenic, aquatic toxicity
Acid Mine Drainage	Sulfuric acid, Iron (Fe ²⁺), Sulfate	Low pH, release of metals into environment, ecosystem damage
Aliphatic Hydrocarbons	Diesel, Lubricants, Mineral oil	Soil and groundwater contamination
Radioactive Trace Elements	Uranium, Thorium	Radioactivity over time, persistence in environment

3. Microbial mechanisms of bioremediation

Microorganisms utilize an extensive variety of biochemical and physiological methods to endure, convert, and eliminate contaminants in affected ecosystems. The biological basis for all AMT approaches is provided by these various mechanisms [9]. As shown in the Fig. 1 [10].

3.1 Biosorption

Biosorption is a method of binding (passive) metal ions or organic molecules to the surfaces of microbial biomass through physicochemical processes. Live or dead (nonviable) microorganisms are both good biosorbers because they contain many functional groups (e.g., sulfhydryl, and phosphate) their surfaces. Both bacterial and fungal cells have cell walls containing abundant peptidoglycans and polysaccharides, respectively [11]. In addition, the cell wall of fungal organisms also has chitin based on glucan. These functional groups provide sufficient interaction capabilities with metal cations that include ion exchange, formation of coordination complexes, and electrostatic attraction/repulsion. Biosorption is a reversible process that can be combined with desorption methods to recover metal values, and is therefore suitable for recovery applications in a circular economy [12].

3.2 Bioaccumulation

Bioaccumulation refers to the biological uptake of metals through chemical reactions that produce chemical compounds

from contaminated sources by using energy dependent transport of metals into the cytoplasm of cells and retaining them there. The accumulation of metals varies significantly between species and the type of metal being accumulated; however, several bacterial species e.g. *Bacillus*, *Pseudomonas*, *Cupriavidus* as well as several fungal species e.g., *Aspergillus niger*, *Trichoderma* have been reported to show very high rates of bioaccumulation of cadmium, lead, zinc and copper in numerous laboratory and pilot studies [13].

3.3 Biomineralization

Biomineralization is when dissolved toxic heavy metals are deposited by microorganisms as insoluble solid minerals, thereby removing them from the bioavailable pool of contaminated soil or water. This occurs when sulphate-reducing bacteria (SRB) such as *Desulfovibrio*, *Desulfotomaculum*, and *Desulfosporosinus* produce hydrogen sulphide (H₂S) as a product of anaerobic sulphate respiration, which then reacts with dissolved cations of heavy metals and forms very insoluble precipitates of metal sulphides (e.g., ZnS, PbS, CdS, and FeS) [14].

3.4 Enzymatic biotransformation

Microbial catalysis in biotransformation processes is a common way for biota to alter the chemical speciation, mobility and toxicity of numerous contaminants through microbially catalysed redox reactions [15]. In biological

treatment processes for organic pollutants, white rot fungi produce many types of extracellular oxidoreductases (e.g., laccases, lignin peroxidases, manganese peroxidases) that catalyse the mineralization of polycyclic aromatic hydrocarbons (PAHs) via the ring-opening and step-wise

degradation of the PAH ring structure. Furthermore, bacterial mono- dioxygenases catalyse the aerobic degradation of PAH intermediates via the formation of non-toxic aliphatic and carboxylic acid end products [16].

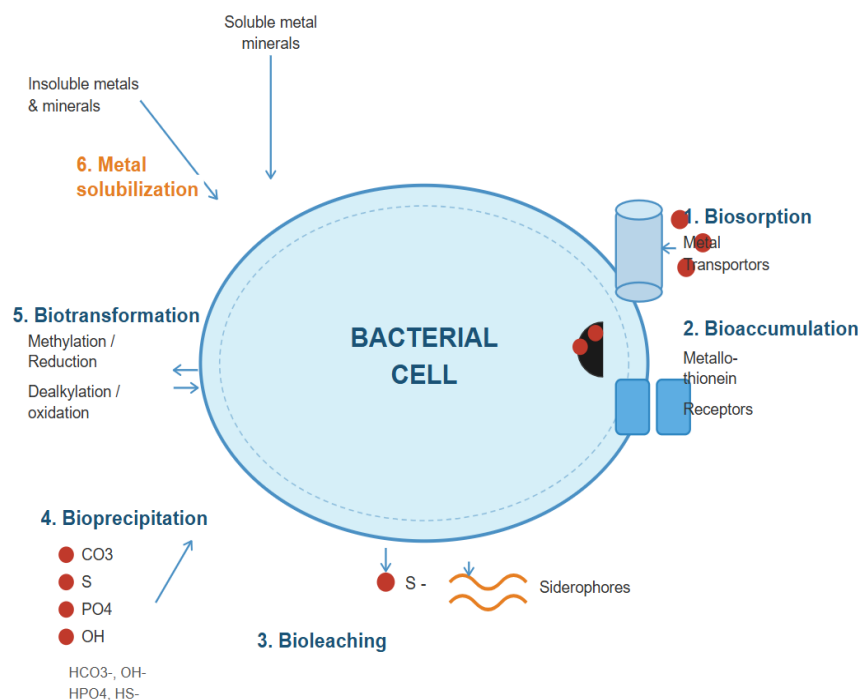


Figure 1: Microbial Mechanisms of Bioremediation [10].

3.5 Bioleaching

Microbes are employed in this process and their ability to oxidize various elements enables bioleaching. Microbial oxidation, along with geochemical factors such as the presence of acids, drives metal solubility and, as such, microbial catalysed oxidative dissolution mechanisms can operate in parallel to geochemical processes. In terms of microbial mechanism of action, microbial catalysis occurs when microbial cells are bound to a mineral surface and transfer electrons from their bodies to the mineral surface (i.e. oxidative dissolution) or when bacterially generated ferric (Fe³⁺) ions act as the oxidants that dissolve mineral sulfides [17]. Bioleaching has been shown to be successful for the selective extraction of a wide variety of metals including rare earth elements, copper, zinc, cobalt and gold from coal ash or mine tailings, making bioleaching a more environmentally friendly method of extracting metals in comparison to conventional acid-based methods of hydrometallurgy [18].

4. Advanced Microbial Technologies (AMTs) for coal mining waste bioremediation

4.1 Engineered microbial consortia

Single-strain pure cultures show potential for bioremediation in controlled laboratory settings. However, the heterogeneous and chemically complex nature of CMW requires resilient and versatile biological systems. Engineered microbial consortia consist of assemblages with multiple organisms that utilize metabolic complementarity by having one species provide substrates, intermediates, or products to other species' metabolic pathways [19]. For example, in AMD

bioremediation, syntrophic relationships where SRB obtain their electron donors from heterotrophic fermenters and iron-oxidizing autotrophs create self-sustainable treatment communities. In bioleaching systems, having *Acidithiobacillus* and *Leptospirillum* bacteria together in a consortium creates a greater range of available substrates and faster solubilization of metals than any of these organisms alone would do alone. Additionally, engineered consortia demonstrate a greater ability to adapt to environmental stressors as opposed to single-strain systems, resulting in a greater potential to function at the field scale [20].

4.2 Metagenomics and functional genomics

Metagenomic strategies allow for the overall and comprehensive characterization of the structure and genetic potential of microbial communities in CMW-impacted ecosystems, without the need for culture-based methods. Researchers can determine the locations of novel bioremediation-related genes within the total environmental DNA sequence from substrates such as mine soil, AMD biofilms, or tailings impoundments, and can reconstruct metabolic pathways of the microbial community, as well as monitor changes in the community structure over time in response to either contamination or bioremediation efforts [21]. Functional metagenomic techniques allow researchers to identify genes that encode for metal-reductases/oxidoreductases, metal efflux pumps, and PAH dioxygenases, as well as to assess gene expression from environmental DNA libraries. Meta transcriptomic and metaproteomic applications provide a dynamic view of microbial community function and allow for the determination

of true bioremediation rates as opposed to simply bioremediation potential [22].

4.3 Synthetic biology and genetic engineering

Powerful techniques of synthetic biology allow for the direct manipulation of microbes to achieve specific bioremediation goals beyond what would otherwise have been possible via natural selection methods. Genome editing using CRISPR-Cas9 has allowed targeted knockouts of competing metabolic pathways as well as precise upregulation of metal resistance regulons among *Cupriavidus metallidurans* and *Pseudomonas putida* strains. Regulatory oversight and appropriate biosafety evaluation are vital steps to be taken before genetically modified organisms can be deployed into open environments [23].

4.4 Nanobiotechnology

Nanobiotechnology is the application of nanotechnology to biological systems, leading to the creation of hybrid remediation products with enhanced performance characteristics. Nano-bio composites are made from combining the metal oxide or carbon nanoparticles of each of the above biogenically produced nanoparticles with the addition of microbial biomass, enzymes, or biosurfactants. Nano-bio composites have been shown to perform better than conventional methods in the removal of arsenic, chromium (VI), uranium, and complex PAH mixtures from mine-impacted water in both batch and continuous-flow conditions [14].

4.5 Phytoremediation and rhizosphere engineering

The rhizosphere microbiome optimises the performance of hyperaccumulator plants through soil acidification (which increases metal solubility), chelating metal ions via the production of siderophores, and transforming metals between oxidation states. The addition of plant growth-promoting rhizobacteria (PGPR) to soil can increase plant biomass, resilience to stress, and efficiency for removing metals from the environment. For passive and sustainable treatment of mine drainage from acid mine drainage, constructed wetland systems that combine phytoremediation with the use of sulphate-reducing bacteria (SRB) have been shown to work effectively [16].

4.6 Bio Electrochemical Systems (BES)

Medium of electricity generation in microbial fuel cells is provided by microorganisms that reduce oxidising compounds (e.g. oxygen or metals) in cathodes and oxidise organic carbon at their anodes. The types of microorganisms that are found in these systems include *Geobacter sulfurreducens* and *Shewanella oneidensis*. In microbial electrolysis cells, an external voltage is used to accelerate the reduction of certain heavy metals (e.g. Cr, U) and metalloids (e.g. Se) from one oxidation state to another. Overall, a BES coupled AMD treatment system offers an approach that provides an alternative means of treating organic material and recovering metal to generate energy (either as electric or hydrogen) as well as neutralise acid from AMD, and thus can be considered a true circular resource recovery process. [24].

5. Microbial diversity in coal mining waste environments

Microbial communities are well suited to colonize CMW environments which have extreme physicochemical characteristics (e.g., low pH often from 2-4 in AMD, high concentrations of dissolved metals, carbon sources which are limited to the amount of organic material there is to consume; high levels of dissolved sulphate). Despite these extreme conditions, metagenomic studies of AMD biofilms, coal gangue leachates and mine tailings indicate that a vast number of diverse microorganisms are thriving within each of these environmental niches [8]. The most prevalent genera of bacteria in acidic CMW environments include *Acidithiobacillus*, *Leptospirillum*, *Sulfobacillus*, *Ferrimicrobium*, *Thiomonas*, *Desulfovibrio*, *Bacillus* and *Pseudomonas*. Fungi such as *Aspergillus niger*, *Penicillium chrysogenum*, *Trichoderma harzianum* and *Cladosporium* have been recovered from the coal gangue and fly ash environments respectively, and generate organic acids that help to both mobilize and sorb metals in these systems. Overall, the characterization and discovery of extremophilic microorganisms have provided biocatalysts for the use of AMT especially in the geochemically challenging environmental conditions that characterize CMW remediation efforts [25]. One of the basic principles of in situ AMT bioremediation is to develop a bioremediation strategy by utilizing the existing native microbial community via bioaugmentation (adding in specific inoculum/specialized microbial inoculum) or bio stimulation (which adds in limiting nutrients or electron donors to stimulate existing microbial communities) [13].

Table 2: Microbial groups that play important roles in the bioremediation of mining wastes [13].

Microbial Group	Representative Species	Mechanism of Action	Pollutants Remedied
Iron Oxidizers	<i>Acidithiobacillus ferrooxidans</i>	Bioleaching / Biological metal extraction	Copper (Cu), Zinc (Zn), Iron (Fe), Rare Earth Elements
Sulphate Reducers	<i>Desulfovibrio</i> spp.	Bio-mineralization (sulfide precipitation)	Lead (Pb), Zinc (Zn), Cadmium (Cd), Arsenic (As), Acid Mine Drainage (AMD)
PAH Degraders	<i>Pseudomonas</i> , <i>Sphingomonas</i>	Enzyme-mediated biodegradation	Polycyclic Aromatic Hydrocarbons (PAHs), Aliphatic hydrocarbons
Metal Reducers	<i>Geobacter</i> , <i>Shewanella</i>	Reductive biotransformation (metal reduction)	Chromium [Cr(VI)], Uranium [U(VI)], Arsenic [As(V)]
White Rot Fungi	<i>Phanerochaete chrysosporium</i>	Laccase and peroxidase enzyme-mediated oxidation	Polycyclic Aromatic Hydrocarbons (PAHs), Phenolic compounds
Acidophilic Fungi	<i>Aspergillus niger</i> , <i>Trichoderma</i>	Biosorption and organic acid production	Heavy metals, Rare Earth Elements
Acidophilic Archaea	<i>Ferroplasma acidarmanus</i>	Iron and sulfur cycling under extreme acidic conditions	Iron (Fe) and Sulfur (S) transformations in Acid Mine Drainage (AMD)

6. Mathematical models for bioremediation performance assessment

Mathematical modeling is an important tool used to evaluate bioremediation performance, optimize operating parameters, and provide guidance for scaling laboratory-developed processes to applied field practices. The models discussed below are particularly relevant to the AMT-based CMW treatment systems [1].

6.1 Biosorption isotherm models

The Langmuir and Freundlich isotherm equations are standard tools for characterizing metal biosorption equilibria and estimating maximum biosorbent capacity [1]:

$$\text{Langmuir: } q_e = (q_{\max} \times \text{KL} \times C_e) / (1 + \text{KL} \times C_e) \quad (1)$$

$$\text{Freundlich: } q_e = \text{KF} \times C_e^{1/n} \quad (2)$$

where

q_e = amount of metal adsorbed per unit biosorbent mass (mg/g),

C_e = equilibrium metal concentration (mg/L);

q_{\max} = maximum monolayer adsorption capacity (mg/g),

KL = Langmuir affinity constant (L/mg),

KF = Freundlich capacity coefficient;

n = Freundlich heterogeneity factor.

Higher q_{\max} and KL values indicate higher biosorbent capacity and affinity, respectively.

6.2 First-order biodegradation kinetics

Generally, first-order kinetics have been used to characterize the concentration versus time profiles (C(t)) of PAH biodegradation and removal of organic pollutants are represented as follows [1]:

$$C(t) = C_0 \times e^{-kt} \quad (3)$$

where

$C(t)$ = concentration of the contaminant at time t ,

C_0 = concentration of the contaminant at time 0,

k = first-order rate constant for biodegradation (day^{-1}) and the contaminant half-life $t_{1/2} = \ln(2)/k$.

Higher k values indicate more microbial activity or greater AMT effectiveness.

6.3 Bioremediation Efficiency Index (BEI)

Expression of a composite BEI that integrates the efficiencies for removing metals, degrading organic pollutants and neutralizing acid mine drainage (AMD) can be expressed mathematically as [1]:

$$\text{BEI} = \eta_{\text{metal}} \times \eta_{\text{organic}} \times \eta_{\text{AMD}} \quad (4)$$

where

$$\eta_{\text{metal}} = (C_{0,\text{metal}} - C_{e,\text{metal}}) / C_{0,\text{metal}},$$

$$\eta_{\text{organic}} = (C_{0,\text{org}} - C_{e,\text{org}}) / C_{0,\text{org}} \text{ and}$$

$$\eta_{\text{AMD}} = \text{fractional AMD neutralization efficiency, based on pH and alkalinity.}$$

A BEI \rightarrow 1 indicates near complete remediation;

BEI \rightarrow 0 indicates little effect from treatment.

6.4 Integrated AMT Sustainability Index (IASI)

A holistic integrated AMT sustainability index will be determined to analyse the environmental performance of an integrated AMT process, the environmental effectiveness, based upon resource consumption and secondary waste production to the overall operation of a process, through the formula expressed as [23]:

$$\text{IASI} = \text{BEI} / (\text{Energy Consumption} + \text{Operational Cost} + \text{Secondary Waste Generated}) \quad (5)$$

Therefore, the higher the Integrated AMT Sustainability Index, the more effective the AMT process in providing superior remediation results using less resource consumption and producing less secondary environmental impact. This index will provide a tool for comparing and selecting technology using all alternative AMT approaches available to administer a specific contaminated media sub-scenario.

7. Field applications and case studies

AMTs have been shown to work effectively in real-life situations around the world with different types of contaminated mines (CMW). Passive bioremediation systems that utilize sulphate-reducing bacterial communities in anaerobic constructed wetlands have been successfully operated as a means of AMD treatment in abandoned coal mine drainage in both the U.S. and Europe. These systems have been able to continuously reduce dissolved metal concentrations and normalize pH levels for greater than 10-15 years of operation. In India, there have been multiple-scale pilot-bioremediation trials using various acidophilic mixed cultures of Acidithiobacillus ferrooxidase and Leptospirillum ferriphilum to recover copper, zinc, and nickel from coal gangue originating from coal fields located in Jharkhand and Chhattisgarh at near-ambient temperatures [20]. Many of these projects recorded measurable reductions in bioavailable metal fractions in soil over a period of 3 - 5 years. Bioaugmentation field trials were conducted using commercially produced PAH degrading microbial inoculum on coalmine-impacted soils in Germany and Australia resulted in reductions of total PAH concentration (40 - 65%) after 12 - 18 months, with greatest reductions occurring with lower molecular weight 2 and 3 ring PAH's. Although bio electrochemical systems are primarily at the pilot scale, these systems have demonstrated potential ability to simultaneously reduce Cr (VI) and generate electricity from treatment of mine drainage water in South Africa and China [18].

Table 3: Summary of AMT Applications in the Field for Bioremediation of Coal Mining Waste [18].

Location (Where AMT was Applied)	Types of AMT Used	Target Pollutants	What was Accomplished
USA - Iron Mountain, CA	Passive SRB Bioreactor	AMD metals, H ₂ SO ₄	90% removal of metals and pH normalization over 15 years
India - Jharkhand	Bioleaching Consortium	Copper (Cu), Zinc (Zn), Nickel (Ni) from gangue	Pilot-scale recovery of metals demonstrated at ambient temperature
China - Shanxi Province	Phytoremediation with PGPR	Lead (Pb), Cadmium (Cd), Zinc (Zn) in mine soil	40% reduction in bioavailable metals over 4 years
Australia - Hunter Valley	PAH-degrading microbial consortium	Polycyclic Aromatic Hydrocarbons (PAHs) in mine spoil soil	60% reduction in PAHs within 18 months after bioaugmentation
Germany - Lusatia	Constructed wetland with SRB	Sulfate (SO ₄ ²⁻), Iron (Fe), Manganese (Mn) in drainage water	Long-term passive AMD treatment (>15 years)
South Africa	Microbial Fuel Cell (BES)	Chromium [Cr(VI)] in mine drainage	Reduction of Cr(VI) to Cr(III) with simultaneous electricity generation

8. Challenges, limitations, and future directions

8.1 Challenges in field deployment

Variability in the composition of CMW among different mines and between different waste streams from one site to another makes it difficult to standardize AMT protocols. This necessitates characterizing sites and optimizing processes for AMT before they can be adopted on a large scale. Very high concentrations of dissolved metal ions or extreme pH can inhibit microbial growth and activity, which means that some pre-treatment of the CMW (for example, diluting, adjusting its pH or partially neutralizing the metal content) is needed before applying an AMT technology to the CMW [19]. Temperature restrictions will likely affect the efficiencies of mesophilic organisms at mines that are situated at high altitudes or in Canada or other northern latitudes. When moving from the laboratory to the field, substantial engineering optimizations will be required regarding the configuration of bioreactors, delivery systems for inoculum, mixing regimes and control systems for monitoring and controlling the AMT process [2].

8.2 Regulatory and safety considerations

In addition, prior to releasing GM microorganisms, you must conduct field trials under contained conditions to assess the safety of the organism and obtain permission/guidance from local authorities (biosafety regulators). Therefore, concerns relating to gene transfer to local organisms (horizontal gene transfer), unintentional persistence or ecological harm caused by introduced organisms, and the public's acceptance of environmentally based GMOs are major barriers for deploying AMTs based upon synthetic biology. Using native microbial consortia (microbial communities found in nature) and applying bio stimulation or bioaugmentation using naturally occurring microorganisms may result in significantly lower regulatory barriers and may provide similar final outcomes relative to remediation by enhancing functional output of the community [21].

8.3 Future directions

The primary focus points regarding the remediation of coal mining waste (CMW) with amine modified alloys (AMTs) will be: developing real-time monitoring and machine learning models that utilize multiple 'omics', developing encapsulated microbial inoculum for protection and controlled release under challenging environmental conditions; and designing hybrid treatment systems that use biological, physical, and chemical methods. In addition to the above mentioned priorities, there needs to be more research on how

to leverage extremophilic microorganisms to achieve effective CMW remediation in extreme conditions, given that this technology exists today; develop techno-economic frameworks linking bioremediation with resource recovery such as rare earth elements and bioenergy, and develop supportive policies and financial incentives that will enable the large scale implementation of bioremediation technologies particularly in developing countries that currently rely heavily on coal [26].

9. Conclusions

Advanced Microbial Technologies are an ecologically sound, economically feasible, and scientifically proven approach to solving the complexities of remediating coal mining waste. Microorganisms can detoxify, immobilize, and recover many inorganic and organic contaminants in coal mining waste impacted environments through various biological mechanisms. These include biosorption (the absorption of a substance onto a biological material), bioaccumulation (the accumulation of a substance in an organism), biomineralization (the process by which living organisms produce minerals), enzymatic biotransformation (the process by which enzymes change or transform a compound), bioleaching (the extraction of metals from ores using microorganisms), and phytoremediation and bio electrochemical engineering (the use of electrochemical principles to recover energy from microorganisms), the functional scope and operational capabilities of Advanced Microbial Technology have expanded greatly, allowing for types of applications that were not previously possible with traditional bioremediation methods. Field scale demonstrations of AMTs (throughout multiple continents) have verified the practicality of AMT systems for numerous applications of remediating coal mining waste, including: using passive constructed wetlands for acid mine drainage remediation; utilizing bioaugmentation to remove polycyclic aromatic hydrocarbons (PAHs); and using plants to remediate metal contaminated coal mine soils. When evaluating AMT performance, the use of mathematical modeling frameworks, such as biosorption isotherms, biodegradation kinetics, and the Integrated AMT Sustainability Index, provides vital quantitative data to compare technologies and to ensure proper scale up design. The global mining industry is experiencing increasing pressure to move toward sustainable practices and to embrace the principles of the circular economy. Advanced Microbial Technologies present viable opportunities for transforming coal mining waste from an environmental liability to a valuable recoverable resource. Microbial

Technologies application has great potential; however, major challenges lie in the areas of (a) manufacturing (timely scale up to production), (b) regulatory restrictions on their use (i.e. government use of Organisms), and (c) economic competition with existing technologies. These challenges require collaborative efforts among researchers (microbiologists, environmental engineers), policy makers, and companies developing and using these Technologies. Financing will be critical to developing Pilot Demonstrations; Standardization of Bioremediation Protocols; and Established Regulatory Frameworks for all Microbial Technologies in order to develop Sustainable Green Mining and Long-Term Environmental Stewardship of Coal Mine Waste Globally.

Authors' contributions

All authors contributed equally to the conception, design, experimental work, data analysis, interpretation of results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript for publication.

Conflicts of interest

The author declares no conflict of interest.

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Data availability

No new data were created.

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