

Nature-Based Solutions to Treat Mining-Impacted Waters: A Narrative Review

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Abstract

Mining-impacted waters, in particular acid mine drainage (AMD), is a concerning global environmental problem since it is very acidic and it has high concentration of dissolved metals and sulfates. Whereas conventional systems of treatment are effective, they are, in most cases, not economically and ecologically viable, particularly in long-term remediation. This review synthesizes the literature (2000-2024) on the effectiveness, mechanisms and the limitations of NbS including constructed wetlands, passive bioreactors, phytoremediation and algal systems. Microbial sulfate reduction, metal sulfide precipitation, adsorption, and plant uptake are major processes that provide control over performance in treatment. One of the proposed ideas is a conceptual framework that is used to explain the relationships existing between environmental conditions, the biological processes, and system design to determine the remediation outcomes. The results show that NbS is both cost-efficient and less harmful to the environment than regular treatments and can reach high removal rates of metals and sulfate. However, problems that adversely impact on large scale applications are performance variability, climatic sensitivity, land requirements, and stability in the long term. The following research should be conducted on the standardized design criteria, hybrid treatment system, and long-term monitoring to improve reliability and scalability.

Keywords: Mining wastewater, nature-based solutions, acid mine drainage, constructed wetlands, phytoremediation

1. Introduction

Mining is very important in the development of the world economy as it provides the necessary raw materials to power, infrastructure, and technological development. Mining activities, however, have major environmental consequences, especially in the shape of mining-impacted waters, such as acid mine drainage (AMD) (Younger et al., 2002; Nordstrom, 2011). The waters are usually low PH and rich in dissolved metals and sulfates that are formed by oxidation of sulfide minerals like pyrite in the presence of oxygen and water (Johnson & Hallberg, 2005).

The environmental impact of AMD is also detrimental and persistent, such as the deterioration of aquatic ecosystems, biodiversity loss, and water pollution, which can have an impact on human health (Akcil et al., 2006; Skousen et al., 2017). It is worth noting that the effects of the mine can continue over decades or centuries after mine closing, requiring long-term and long-lasting treatment plans (Nordstrom, 2011). The traditional treatment techniques, including lime neutralization, ion exchange, and membrane filtration, are good in eliminating contaminants; however, they are linked with high operational costs, energy, and

sludge. These restrictions render them inappropriate in distant or deserted mines (Matlock et al., 2002; Fu and Wang, 2011).

This has been countered by the introduction of nature-based solutions (NbS) as alternatives that are sustainable and which use natural processes to eliminate contaminants. NbS include biological, chemical, and physical methods of treating the mining-affected waters passively and energy-efficiently, which include microbial sulfate reduction, metal precipitation, adsorption, and plant uptake (Neculita et al., 2007; Vymazal, 2014).

Despite the development of different NbS technologies, their functionality is extremely site-dependent and environment-dependent, as well as contaminant-dependent (Younger et al., 2002; Neculita et al., 2007). Moreover, the literature tends to concentrate on the performance of individual technologies and not to present a holistic view of system performance.

This narrative review will fill these gaps by integrating existing information on NbS to treat mining-impacted waters. In particular, it is aimed at: (i) studying the nature and effects of the mining-impacted waters; (ii) testing the functioning and efficiency of main NbS technologies; (iii) creating a conceptual framework that will combine environmental, biological, and design considerations; and (iv) determining the most important challenges and the prospects of future research.

2. Methodology

This study adopts a **narrative review methodology** to synthesize and critically evaluate existing literature on nature-based solutions (NbS) for treating mining-impacted waters. (Baumeister and Leary, 1997; Snyder, 2019).

2.1 Literature Search Strategy

A comprehensive literature search was performed in significant scientific databases as Scopus, Web of Science, ScienceDirect, and Google Scholar to provide a wide coverage of peer-reviewed articles. The search was based on the studies published in 2000 to 2024, which represent the increased interest in NbS after 20 years.

The keywords and Boolean combinations, which were used, included the following:

1. "acid mine drainage" OR "AMD"
2. mining wastewater" OR mine water.
3. nature-based solutions OR NbS
4. built wetlands OR passive treatment.
5. bioreactors OR sulfate reduction.
6. phytoremediation OR algal remediation

Citations were tracked backward and forward as well in order to find more relevant studies (Tranfield et al., 2003).

2.2 Inclusion and Exclusion Criteria

To achieve rigor and relevance, the selection of the studies was determined with the following criteria:

Inclusion criteria:

1. The peer-reviewed journal articles.
2. Investigations on NbS in mining-affected waters.
3. Empirical, experimental, or review research that has either quantitative or qualitative results.
4. English-language publications.

Exclusion criteria:

1. Research based on traditional chemical interventions.
2. Not peer-reviewed (e.g. non-scientifically validated report)
3. Investigations not characterized by clear methodology.

Table 1. Study Selection Criteria

Criterion Type	Description
Inclusion	NbS-focused, peer-reviewed, 2000–2024
Exclusion	Non-NbS, grey literature, unclear methods

2.3 Study Selection Process

The initial sample of about 120 articles was found. 70 studies were kept for full-text review after duplicates were eliminated and titles and abstracts were screened. Finally, 45 high-quality studies were selected due to relevance, the rigor of the methodology, and the influence on citation.

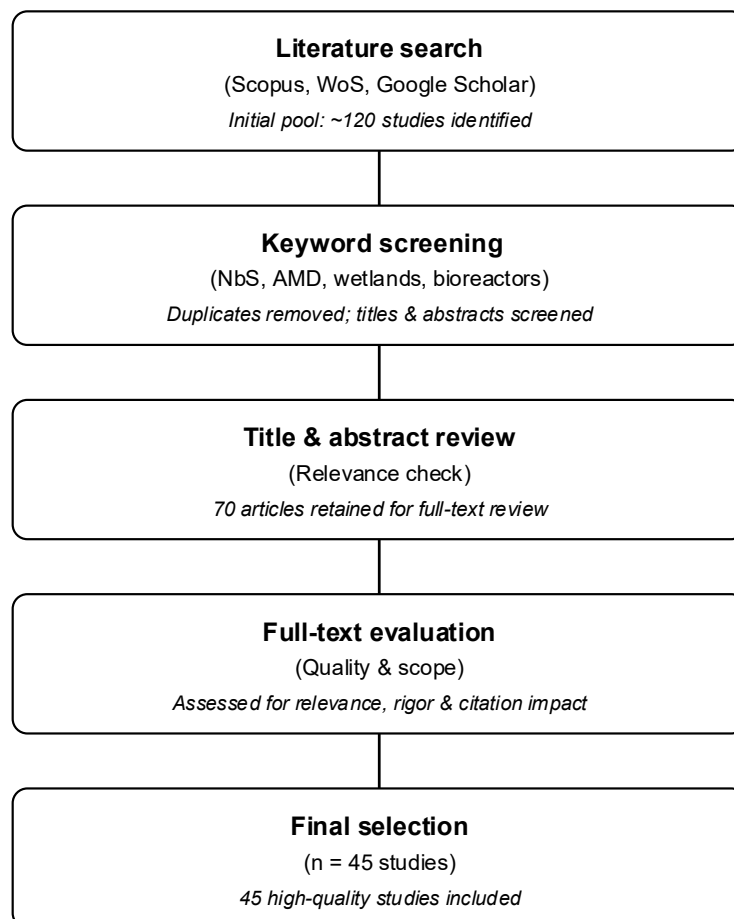


Figure 1. Literature Selection Process (PRISMA-inspired Flow)

2.4 Data Extraction and Synthesis

Data were extracted and categorized systematically according to:

1. NbS technology nature (e.g., wetlands, bioreactors)

2. Contaminants treated with Fe, Cu, Zn, sulfates.
3. Removal efficiencies
4. The environmental parameters (pH, temperature)
5. System design parameters (hydraulic retention time, type of substrate)

A thematic analysis strategy was utilized to establish the similar patterns and associations among the research (Thomas and Harden, 2008). The findings were tabulated in accordance with the key themes, including treatment mechanisms, performance drivers, and limitations of the system.

Table 2. Data Extraction Framework

Category	Variables
Technology	Wetlands, bioreactors, algae
Contaminants	Metals, sulfate, acidity
Performance	Removal efficiency (%)
Design	HRT, substrate, flow rate

2.5 Conceptual Framework Development

The conceptual framework was developed to demonstrate the interrelations of the determinants of the NbS performance that are of significant importance. The framework incorporates:

1. Environmental conditions
2. Biological processes
3. Parameters in the system design.

These factors are interconnected to determine the effectiveness of therapy and viability of a system.

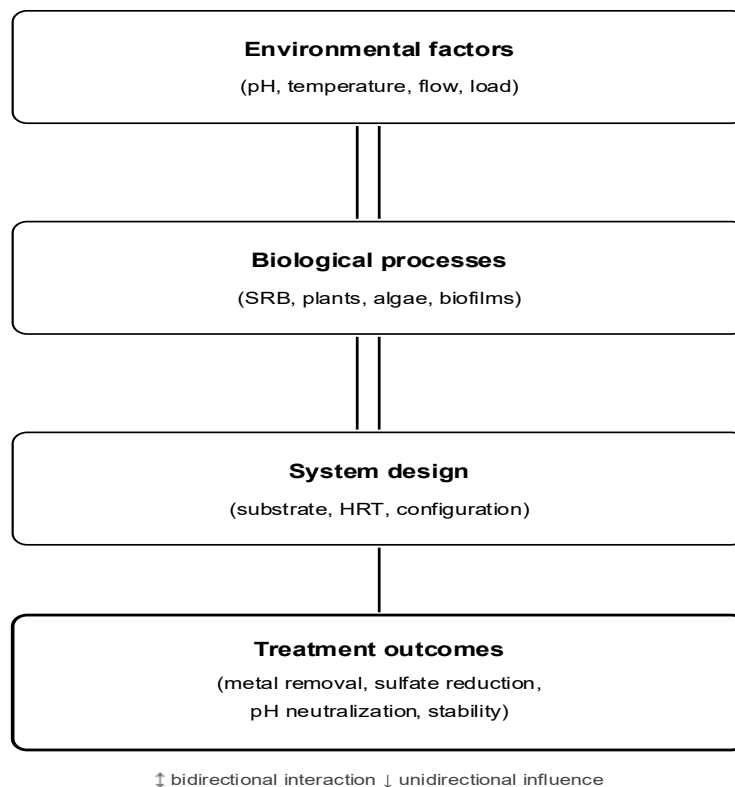


Figure 2. Conceptual Framework of NbS Performance Drivers

2.6 Limitations of the Methodology

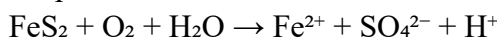
Narrative reviews are more flexible and detailed in nature, but by definition, they can be exposed to possible bias in the selection and interpretation of the study (Snyder, 2019). In contrast to systematic reviews, the method does not use formal meta-analysis methods. Nevertheless, the transparency and rigor were attempted by having well-defined selection criteria and full coverage of databases.

3. Overview of Mining-Impacted Waters

Mining-impacted waters include a spectrum of contaminated effluents produced during and after mining processes which includes acid mine drainage (AMD), neutral mine drainage (NMD) and metalliferous effluents. These waters are also one of the gravest environmental legacies of mining since they are persistent, toxic and have complex geochemical (Younger et al., 2002; Nordstrom, 2011).

3.1 Formation and Geochemical Processes

The oxidation of sulfide minerals, especially the pyrite (FeS₂) in the presence of oxygen and water is the main factor in the formation of AMD. Through this process sulfuric acid is produced and dissolved metals are emitted into the surrounding water systems (Johnson & Hallberg, 2005). The overall reaction can be simplified as:



These reactions are catalyzed by microbial activity, in particular iron-oxidizing bacteria, including *Acidithiobacillus ferrooxidans*, which enhance acidity and metal mobilization (Nordstrom, 2011).

3.2 Types of Mining-Impacted Waters

The composition of the mining effluents differs based on the composition of the mineral and the environmental conditions. The significant groups are:

1. Acid Mine Drainage (AMD): low PH (<4), high levels of metal.
2. Neutral Mine Drainage (NMD): Neutral pH, high metals.
3. Alkaline Drainage: High PH which has lower solubility of metals but may have scaling problems.

Each type requires different treatment strategies, highlighting the need for adaptable and site-specific solutions (Skousen et al., 2017).

3.3 Chemical Characteristics and Environmental Impacts

Mining-impacted waters are characterized by acidity, a high level of sulfates, and dissolved metals like iron (Fe), aluminum (Al), manganese (Mn), copper (Cu), zinc (Zn) and lead (Pb) (Akcil & Koldas, 2006). The composition is diverse and it depends on the type of ore, climate and hydrological conditions.

Those conditions cause severe environmental problems, such as toxicity of aquatic organisms, interference in the ecological processes, and contamination of the surface and groundwater systems. Metal deposition may also lead to deposition of sediments, which deteriorate aquatic environments even more (Younger et al., 2002).

Table 3. Typical Characteristics of Mining-Impacted Waters

Parameter	Typical Range	Environmental Impact
pH	2–6	Toxic to aquatic life
Sulfate	500–5000 mg/L	Alters water chemistry
Iron (Fe)	10–1000 mg/L	Precipitation, sedimentation
Heavy metals (Zn, Cu, Pb)	1–500 mg/L	Bioaccumulation, toxicity

3.4 Challenges in Treatment

Various factors complicate the treatment of the waters affected by the mining activity:

1. Extreme water chemistry variability.
2. Constant production of pollutants.
3. Mining sites that are located far away.
4. Extensive therapy needs.

These issues explain why the traditional treatment systems are limited and why long-term solutions like NbS are required (Skousen et al., 2017).

4. Nature-Based Treatment Technologies

The nature-based solutions (NbS) of addressing mining-impacted waters include various passive and semi-passive systems that apply nature-based processes to eliminate contaminants. The technologies are being marked by an increased level of sustainability, cost-efficiency, and long-term performance with minimal external requirements (Cohen-Shacham et al., 2016; Skousen et al., 2017).

4.1 Constructed Wetlands

One of the most prevalent NbS types is constructed wetlands that are used to replicate natural wetland systems. They help to eliminate contaminants by relying on sedimentation, microorganisms, and uptake by plants (Vymazal, 2014).

Wetlands are normally categorized as aerobic (surface flow) and anaerobic (subsurface flow). The Aerobic wetlands are useful in the oxidation and precipitation of iron and the anaerobic wetlands in the sulfate reduction and the formation of metal sulfide (Kadlec and Wallace, 2009; Skousen et al., 2017). Although constructed wetlands are cheap and environmentally friendly, they require some factors in their performance, which include temperature, hydraulic retention time and availability of organic matter.

4.2 Passive Bioreactors

Passive bioreactors, especially sulfate-reducing bioreactors (SRBRs), employ organic substances like wood chips or compost in order to sustain microorganisms. The systems are known to be useful in treating acidic waters that contain high levels of sulfates and can be used to attain high levels of removal efficiencies of dissolved metals (Neculita et al., 2007).

The bioreactors also produce alkalinity that helps in neutralizing pH. But the long-term performance may be challenged by problems like substrate depletion, blockage, and hydraulic inefficiencies.

4.3 Phytoremediation Systems

Phytoremediation is the practice, which uses plants to absorb, stabilize or accumulate or transform contaminants. *Phragmites australis* and *Typha latifolia* are the plants that can be frequently adapted to metal stress because of their application in the mining settings (Ali et al., 2013).

Although phytoremediation is socially acceptable and aesthetically advantageous, it is more likely to be slower compared to other NbS and can also necessitate the biomass harvesting in order to avoid the re-release of contaminants (Ali et al., 2013).

4.4 Algal and Microbial Systems

There has been interest in algal systems due to their capacity to eliminate metals via biosorption, bioaccumulation and precipitation. Precipitation of metals can also be enhanced by microalgae by means of photosynthetic activity, which can raise the pH (Gonzaes et al., 2019).

Further, microbial consortia are highly important in the biogeochemical recycling especially in the sulfur and iron cycling. A combination of bacteria and algae in hybrid systems has demonstrated good prospects towards better results in treatment effectiveness.

4.5 Permeable Reactive Barriers (PRBs)

Permeable reactive barriers are underground structures that contain reactive substances including organic matter, limestone, or zero-valent iron. The water passes through the barrier and the pollutants are eliminated by chemical and biological reactions (Blowes et al., 2000).

PRBs are effective for in situ treatment, and they need less maintenance. However, their performance will deteriorate in the long term because of clogging or exhaustion of reactive materials.

Table 4. Comparative Performance of NbS Technologies

Technology	Key Mechanism	Removal Efficiency	Advantages	Limitations
Constructed Wetlands	Sedimentation, microbial activity	70–95%	Low cost, passive	Climate sensitivity
Bioreactors	Sulfate reduction	80–99%	High efficiency	Maintenance, clogging
Phytoremediation	Plant uptake	40–80%	Eco-friendly	Slow process
Algal Systems	Biosorption, pH increase	60–90%	Renewable biomass	Operational control
PRBs	Chemical/biological reactions	70–95%	In situ treatment	Material depletion

4.6 Hybrid and Integrated Systems

The recent studies highlight the combination of various NbS technologies to address the shortcomings of each one. Wetlands with bioreactors or PRBs have shown a better treatment and resilience in changing conditions (Skousen et al., 2017; Vöro smarty et al., 2018).

5. Mechanisms of Contaminant Removal

Nature-based solutions (NbS) to address the impact of mining in waters requires a complex interplay of biogeochemical, physical and ecological processes to determine the efficacy. These processes are combined and closely dependent on the environmental factors, system design and the interaction of microbes (Neculita et al., 2007; Vymazal, 2014).

5.1 Microbial Sulfate Reduction

Microbial sulfate reduction, which is facilitated by sulfate-reducing bacteria (SRB), is also one of the most important processes in NbS. These sulfate-reducing anaerobic microorganisms can use organic carbon as an electron donor to reduce sulfate (SO_4^{2-}) to sulfide (S^{2-}), which reacts with dissolved metals to produce insoluble metal sulfides (Johnson and Hallberg, 2005; Neculita et al., 2007). The effect of temperature, availability of organic substances, and redox conditions determine the efficiency of sulfate reduction.

5.2 Metal Precipitation and Co-precipitation

In NbS, metal removal is frequent, and is commonly done by way of precipitation reactions, in which the dissolved metals are precipitated as insoluble compounds like hydroxides, sulfides and carbonates. As an

example, in the aerobic condition, iron is usually precipitated as ferric hydroxide whereas in the anaerobic condition, such metals as Zn and Cu are precipitated as sulfide (Nordstrom, 2011).

The co-precipitation processes also maximize the efficiency of removal because trace metals become part of mineral structures and thus lower their mobility and bioavailability.

5.3 Adsorption and Ion Exchange

Adsorption has been very useful in the removal of contaminants especially in systems that have organic substrates, sediments and biofilms. Electrostatic interactions, complexation, and ion exchange are the processes through which metals attach to surfaces (Fu & Wang, 2011).

Organic materials e.g. compost and peat are rich in binding sites and microbial biofilms are effective in increasing the sorption capacity. Adsorption can however be reversible, so it can be affected by the pH and ionic strength.

5.4 Plant Uptake and Rhizosphere Interactions

Plant-mediated processes help in the removal of contaminants in systems that have vegetation in terms of uptake, accumulation and stabilization. The metals are absorbed by the plants via their roots and can be stored in the tissues or they can be transformed with the help of the rhizosphere (Ali et al., 2013).

Root-associated microbes have the ability to modify the PH and redox states, which further affect metal mobility.

5.5 Biosorption and Bioaccumulation

Microorganisms and algae help in the elimination of contaminants by biosorption (passive absorption of metals onto cell walls) and bioaccumulation (active absorption into the cells). These reactions are especially essential in the algal systems and microbial biofilms (González et al., 2019).

Biosorption is fast and reversible, whereas bioaccumulation is slower, but more permanent. The combination of them is important in removing the dissolved metal in water.

5.6 Redox Transformations

NbS systems rely on redox reactions. Alteration of oxidation-reduction conditions affect solubility, specifications of contaminants and contaminant mobility. In general, reduction processes allow the formation of sulfides and the oxidation process of Fe 2 to Fe 3 results into precipitation (Nordstrom, 2011). To maximize the treatment systems, proper redox gradients must be maintained in the treatment systems.

Table 5. Key Mechanisms of Contaminant Removal in NbS

Mechanism	Process Description	Key Outcomes
Sulfate Reduction	Microbial conversion of sulfate to sulfide	Metal sulfide precipitation, alkalinity generation
Precipitation	Formation of insoluble metal compounds	Reduced metal mobility
Adsorption	Binding to organic/inorganic surfaces	Temporary immobilization
Plant Uptake	Absorption by vegetation	Bioaccumulation
Biosorption	Metal binding to biomass	Rapid removal
Redox Reactions	Oxidation-reduction transformations	Control of metal speciation

5.7 Interaction of Mechanisms

Importantly, these mechanisms do not work independently but they synergize together in NbS systems. An example is the fact that microbial activity has an effect on the redox conditions, which subsequently

have an impact on the precipitation and adsorption processes. On the same note, plant roots improve microbial communities and promote uptake and transformation processes (Vymazal, 2014; Skousen et al., 2017).

This knowledge of interactions is needed in order to maximize system design and to enhance the efficiency of treatment.

6. Conceptual Framework

A conceptual framework is suggested to connect environmental conditions, biological processes and system design parameters, to output of the treatment in order to incorporate the complex interactions that govern nature-based solutions (NbS) performance.

6.1 Theoretical Foundations

It is based on the ecosystem services and the biogeochemical cycling systems, in which the natural systems balance the quality of water by microbial activity, chemical reactions, and ecological processes (Cohen-Shacham et al., 2016; Nordstrom, 2011). It is also an indicator of sustainability-related strategies that focus on low-energy, adaptive treatment systems (Vörösmarty et al., 2018).

6.2 Core Components of the Framework

The framework comprises three domains that are related to each other:

Environmental factors:

pH, temperature, hydrology, and load control reaction rates, metal solubility, and performance of the system.

Biological processes:

Vital changes in the removal of contaminants are facilitated by microbial activity (e.g., sulfate reduction) and vegetation and algal systems.

System design parameters:

Contact time, redox condition and treatment efficiency are controlled by substrate composition, hydraulic retention time (HRT) and system configuration.

6.3 Interactions and Feedback Mechanisms

These are dynamically interplaying factors. Environmental conditions alter biological activity whereas microbial processes alter pH and redox conditions. Such interactions are controlled by system design that controls flow patterns and environments of reaction. It is worth noting that there exist feedback mechanisms in which over time the conditions of the treatment processes vary in order to affect the performance and long-run stability.

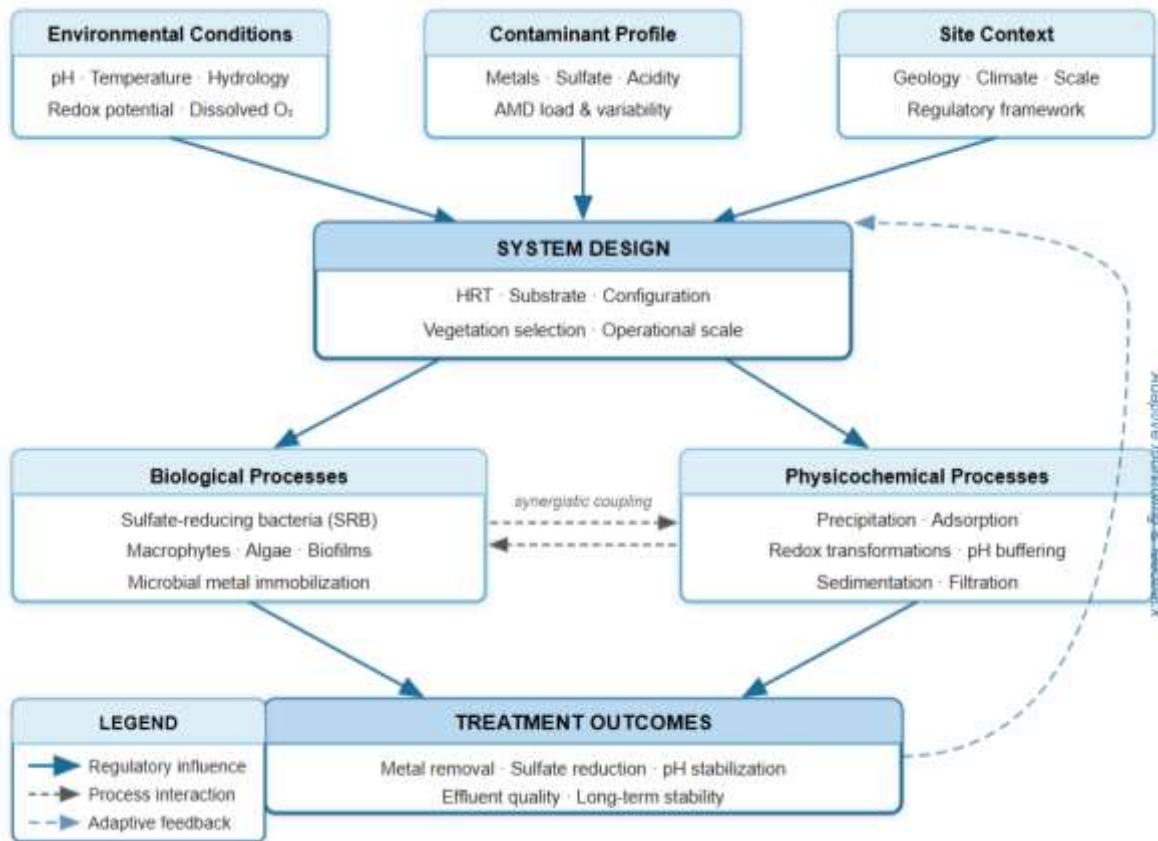


Figure 3: Theoretical paradigm of the nature-based treatment of the mining-impacted waters.

The figure shows the connections between the environmental conditions, the properties of the contaminants, and the site context, which affect the design of the system. These factors control biological and physicochemical processes that promote the removal of contaminants, which results in the following outcomes of treatment, metal removal, sulfate reduction, and stabilization of pH.

6.4 Implications of the Framework

The provided framework contains a number of insights:

- **Holistic Design:** NbS should be effective, and this necessitates a combination of ecological and engineering considerations.
- **Site-Specific Adaptation:** The systems should be optimized to the local environmental conditions.
- **Performance Optimization:** With the understanding of interactions, one can better design and operate.
- **Scalability:** Framework facilitates building of hybrid systems and large-scale systems.

6.5 Contribution to Literature

This framework is systems level as opposed to the previous research that used separate technologies to provide a definition of the problem of NbS performance since it includes numerous diverse dimensions that give a broad a priori perspective of the problem. It may serve as the foundation of the future empirical research, as well as a method of creation of the standardized design principles.

7. Comparative Analysis of Technologies

The nature-based solutions (NbS) comparison is the matter of essence to compare the relative effectiveness, operational feasibility, and applicability to the various environmental circumstances.

Despite the strong potentials of each single technology, they do not work equally with the disparities depending on the system design, the nature of contaminants, and peculiarities of the location (Skousen et al., 2017; Vymazal, 2014).

7.1 Performance Efficiency Across Technologies

NbS technologies display varying removal efficiencies of the important contaminants which include the heavy metals and sulfate. Compared to phytoremediation systems, constructed wetlands and bioreactors are more likely to exhibit higher removal efficiencies because of combined physical, chemical, and biological mechanisms, although they tend to be slow (Neculita et al., 2007; Ali et al., 2013).

Table 6. Comparative Performance of NbS Technologies

Technology	Target Contaminants	Removal Efficiency (%)	Key Strengths	Limitations
Constructed Wetlands	Fe, Mn, Zn, acidity	70–95	Passive, low cost	Climate sensitivity, land area
Bioreactors (SRBR)	Sulfate, Zn, Cu, Pb	80–99	High efficiency, alkalinity generation	Substrate depletion, clogging
Phytoremediation	Metals (Zn, Cu, Pb)	40–80	Sustainable, low cost	Slow kinetics, biomass disposal
Algal Systems	Metals, nutrients	60–90	Renewable, pH control	Operational variability
PRBs	Metals, acidity	70–95	In situ treatment	Material exhaustion

7.2 Influence of Environmental Conditions

The temperature, pH and hydrology are some of the aspects of the environment that have great impacts on the performance of NbS. An example of this is the fact that microbial processes such as sulfate reduction are very sensitive to temperature and thus lead to low efficacy in low temperatures (Neculita et al., 2007). On the same note, changing flow rates may influence hydraulic retention time (HRT) and hence contaminant removal.

7.3 Limitations and Scalability

Although NbS have some benefits, they are limited in terms of land needs, variable performance and reliability over time. These constraints are more eminent as systems are scaled to treat large amounts of mining wastewater. Specifically, biological processes can have a high start-up time and be vulnerable to environmental changes (Vörösmarty et al., 2018).

7.4 Synthesis of Comparative Insights

There is no optimal NbS technology. Rather, site-specific conditions, contaminant profiles, and treatment goals should be used in the selection of the system. Compounds are more promising when combining various technologies to enhance the efficiency of treatment and high reliability (Skousen et al., 2017).

8. Discussion

The findings of this review show that the success of nature-based solutions (NbS) is not predetermined

with the mechanism of action of one or another treatment process, but with the interplay of environmental factors, biological activity, and system design. This systems level view as embodied in the conceptual framework offers a more detailed view of NbS performance in comparison to technology specific analyses. One of the primary lessons is that NbS work according to the mechanisms of coupled biogeochemical processes in which microbial activity, redox conditions, and hydrological processes are complementary to each other in the removal of contaminants. However, this interdependence is variable and it is not also predictable that the system will perform as compared to traditional treatment technologies.

Site-specific performance is also very high despite the fact that NbS have advantages in terms of sustainability and low costs of operation. The temperature, hydraulic retention time, and load of the contaminant might have a significant influence on the success of the treatment particularly in field scale processes. This indicates the limitation of generalizing the results of controlled research to the actual world.

The other trade off that should be considered is the efficiency and scalability trade off. Although bio-reactors and constructed wetlands may be effective in achieving high removal efficiencies, they may not work on large scale application due to hydraulic constraints, substrate constraints, and environmental variations. The above problems indicate the need to have a hybrid system of implementing passive and active treatment strategies to enhance reliability.

There is still a pressing concern of performance doubt in the long-term. Biological systems are dynamic systems and the stability of the system can be affected by the factors such as the depletion of the substrates, clogging of the system and alteration of the microbial communities over time. This implies that the sustainable operation could not be sustained without the long-term monitoring and adaptive management. NbS, in larger sense, constitute a shift towards a more sustainable and ecosystem-based approach to water management. Their wider implementation is however not only restricted to the technical performance, but also development of the standardized design requirements, improved predictive models and the improved policy frameworks.

On the whole, the results indicate that the NbS is not to be treated as a set of isolated interventions, but rather as the elements of comprehensive treatment systems that are to be developed based on the situation-related factors.

9. Research Gaps and Future Directions

Although there has been considerable progress in creating and implementing nature-based solutions (NbS) to manage waters that were affected by mining activities, there are a number of research gaps that are critical. These gaps need to be addressed in order to create a more reliable, scalable and long-term sustainable system.

9.1 Lack of Long-Term Performance Data

The absence of long-term monitoring studies is one of the greatest limitations that exist in the current body of literature. In most studies, the research is concentrated on short-term performance, usually in conditions of controlled/pilot-scale (Skousen et al., 2017). Nevertheless, the waters that are affected by mining cannot be treated in the short run, and the stability of NbS systems in the long term is unclear. Substrate degradation, clogging and changes in microbial communities are some of the issues that may greatly influence performance with time (Younger et al., 2002).

The next research direction should focus on longitudinal research that would evaluate the work of the system in the real world, seasonality, and extreme weather conditions.

9.2 Standardization of Design and Operation

Existing NbS systems do not have standardized design requirements as well as rules of operation. Parameters of design, which include hydraulic retention time (HRT), substrate composition and system set up differ widely among studies and it is hard to compare and repeat successful systems (Neculita et al., 2007). Empirical evidence should be used to develop design frameworks and best practice guidelines that can be utilized to facilitate greater adoption.

9.3 Insufficient Understanding of Microbial Dynamics

Microbial activity, especially sulfate reduction, is the focus of performance in NbS. Nonetheless, the structure, heterogeneity, and dynamic processes of microbial communities in most systems are poorly understood (Johnson & Hallberg, 2005). The development of methods in molecular biology, including metagenomics and transcriptomics, is also an opportunity to comprehend the interactions of microbes and to optimize the functioning of the systems.

9.4 Climate Sensitivity and Geographic Variability

The environmental factors that are very sensitive to NbS system are temperature and hydrology. A majority of the research is focused in temperate areas, and very little has been done in tropical and dry conditions (Vymazal, 2014). Future studies are needed to examine the use of NbS in various climatic conditions to enhance their application in the world.

9.5 Scalability and Industrial Application

Although NbS have proved useful on a small scale, their applicability to an industrial scale has been a significant issue. Their negative impact is the high land demand, inconsistent performance and performance, and a failure to integrate with an established infrastructure (Vörösmarty et al., 2018). The studies need to be conducted on modular designs, hybrid systems and optimization techniques to improve the scalability and operational efficiency.

9.6 Socio-Economic and Policy Dimensions

Technical feasibility does not suffice to be used widely. There are barriers to implementation due to economic limitations, regulatory, and low awareness of stakeholders (Cohen-Shacham et al., 2016). In further research, the socio-economic examination and policy frameworks should be incorporated in order to assist with the practical implementation of NbS.

Table 7. Key Research Gaps and Future Directions

Research Gap	Future Direction
Lack of long-term data	Longitudinal field studies
Design variability	Standardized guidelines
Microbial uncertainty	Advanced molecular studies
Climate sensitivity	Cross-regional research
Scalability issues	Modular and hybrid systems
Limited policy research	Socio-economic integration

10. Conclusion

This review has shown that nature-based solutions (NbS) offer an economical and sustainable treatment of water affected by mining, especially through integrated biogeochemical treatment of such waters by reduction of sulfate and metal, and biological uptake. Their functionality relates to the interplay among

environmental conditions, biological activity, and system design, as mentioned in the suggested conceptual framework.

Although NbS would provide evident benefits in comparison to traditional therapy, the issues regarding performance inconsistency, sensitivity to climate conditions, and scalability are still present. The wider implementation will require the provision of solutions to these issues by designing better systems, having hybrids, and long-term monitoring. Generally, NbS is a good direction for sustainable management of mine water, although further investigation is needed to increase its accuracy and scale of application.

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