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Remediation technologies for acid mine drainage: Recent trends and future perspectives

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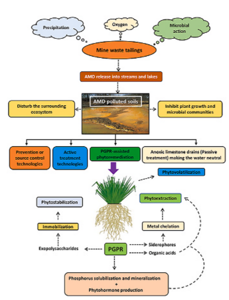
HIGHLIGHTS

- Acid mine drainage (AMD) severely inhibits plant growth and microbial communities.
- Active treatment technologies involve the use of different chemical compounds.
- Passive treatment technologies utilize natural and biological processes.
- Plant growth promoting rhizobacteria (PGPR) enhance plant biomass and phytoextraction.
- PGPR-assisted phytoremediation is an economical and eco-friendly approach.

GRAPHICAL ABSTRACT



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ABSTRACT

Acid mine drainage (AMD) is a highly acidic solution rich in heavy metals and produced by mining activities. It can severely inhibit the growth of plants, and microbial communities and disturb the surrounding ecosystem. In recent years, the use of different bioremediation technologies to treat AMD pollution has received widespread attention due to its environment-friendly and low-cost nature. Various active and passive remediation technologies have been developed for the treatment of AMD. The active treatment involves the use of different chemical compounds while passive treatments utilize natural and biological processes like constructed wetlands, anaerobic sulfate-reducing bioreactors, anoxic limestone drains, vertical flow wetlands, limestone leach beds, open limestone channels, and various organic materials. Moreover, different nanomaterials have also been successfully employed in AMD treatment. There are also reports on certain plant growth-promoting rhizobacteria (PGPR) which have the potential to enhance the growth and productivity of plants under AMD-contaminated soil conditions. PGPR applied to plants with phytoremediation potential called PGPR-assisted phytoremediation has emerged as an economical and environment-friendly approach. Nevertheless, various approaches have been tested and employed, all the approaches have certain limitations in terms of efficiency, secondary pollution of

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chemicals used for the remediation of AMD, and disposal of materials used as sorbents or as phytoextractants as in the case of PGPR-assisted phytoremediation. In the future, more research work is needed to enhance the efficiency of various approaches employed with special attention to alleviating secondary pollutants production and safe disposal of materials used or biomass produced during PGPR-assisted phytoremediation.

1. Introduction

Acid mine drainage (AMD) is a severe environmental problem associated with mining activities. AMD has been recently named the second most important global concern after global warming by the United Nations, highlighting the significance of this environmental challenge (Vasquez et al., 2022). AMD is produced upon the exposure of coal or pyrite minerals to atmospheric oxygen, water, and microorganisms (Rodríguez-Galán et al., 2019) and is generally characterized by low pH, high salinity, heavy metals (Fe, Cu, Pb, Cd, Al, Ca, Mn, Mg, Zn), metalloids (As), and sulfate contents. It negatively affects the water quality, which normally becomes unfit for the soil ecosystem as it destroys structure and functions occurring in the soil and becomes more vulnerable to erosion (RoyChowdhury et al., 2015). In addition, nutrients are often immobilized in the soil under acidic conditions, which hamper plant growth, microbial diversity, and their functions. Various growth, physiological and biochemical processes in the plants are negatively affected due to heavy metals added to the soil via AMD. In addition to the chronic pollution caused by AMD, major accidents, most often resulting from the breaching of an effluent retaining dike, can bring about major pollution incidents. For example, a dam breaking in Andalusia (South-Western Spain) resulted in the contamination of the Guadiamar river (Grimalt et al., 1999; Olias et al., 2006), a tributary of the Guadalquivir, which drains the Donana National Park (UNESCO world reserve).

In recent times, AMD has become a serious global concern owing to its harmful impact on the environment and living organisms. Major mining activities or operations are performed in Australia, Canada, the United States, China, and South Africa (Chen et al., 2015; Kefeni et al., 2017; Liu et al., 2018; Xu et al., 2019; Park et al., 2020; Tabelin et al., 2020). Approximately 20,000 to 50,000 mines are producing AMD worldwide (Rezaie and Anderson, 2020) which is severely affecting almost 6400 km of rivers and 8000 to 16,000 km of streams (Wang et al., 2021). Moreover, 19,300 km of freshwater, 72,000 ha of lakes and reservoirs, and about 15,000 to 23,000 km of streams have been severely impacted by AMD pollution bearing a high level of acidity (RoyChowdhury et al., 2019a; Xu et al., 2020). Therefore, AMD pollution harms nearby ecosystems such as soil and surface water, posing health risks to people and other biotic species.

There have been various methods or techniques used to remediate AMD-polluted soils. For example, active treatment technologies involve the use of different chemicals such as limestone, different nanomaterials, etc. (Masindi et al., 2015; Masindi et al., 2017; Lopez et al., 2018; Rambabu et al., 2020; Kim et al., 2022; Masindi et al., 2022). Passive treatments utilize natural and biological processes like constructed wetlands, anaerobic sulfate-reducing bioreactors, anoxic limestone drains, vertical flow wetlands, limestone leach beds, open limestone channels, and various organic materials to remediate AMD pollution (Martins et al., 2011; Villegas-Plazas et al., 2021; Carrillo-González et al., 2022; Gumede and Musonge, 2022; Ji et al., 2022; Vasquez et al., 2022). Certain bacteria found in the rhizosphere of plants, called rhizobacteria, have the potential to enhance plant growth with a subsequent role in the remediation of various pollutants found in AMD. These rhizobacteria are known as plant growth-promoting rhizobacteria (PGPR). PGPR-assisted phytoremediation is the use of PGPR through seed, root, soil, or even foliar inoculation of plants with phytoremediation potential to enhance the growth and biomass of plants, thereby improving the phytoremediation potential of plants (Liang et al., 2012; Hussain et al., 2020; Daraz et al., 2021). Recently, PGPR-assisted phytoremediation has received significant attention because it is not only low cost but also environment friendly. In the literature, various reviews have been available however, each one has focused on a specific area of AMD remediation (Du et al., 2022; Ighalo et al., 2022; Thomas et al., 2022; Tu et al., 2022). There is a lack of comprehensive understanding of AMD from its formation to remediation through various treatment methods with advantages and disadvantages. Based on this hypothesis, the present review was planned to elucidate the complete picture of emerging environmental concerns. This review comprehensively describes the formation of AMD, factors affecting AMD formation, the impact of AMD on soil, plants, and microbes, various treatment options along with emerging methods for AMD treatment. Finally, it gives future research directions for the treatment of AMD based on the gaps found in different treatment methods being employed.

2. Formation and composition of AMD

Complex sulfide ores such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS), produced during mining activities, are considered primary sources for AMD formation (Dold, 2014). Fig. 1 shows the formation of AMD and its impacts on the environment (Naidu et al., 2019). As clear from Fig. 1, AMD is formed by the combination of water in the form of precipitation, oxygen, and sulfate-reducing microbes. The detailed formation mechanism is described in section 3. The characteristics of AMD wastewater depend on various environmental factors such as the nature of the climate, soil structure, and the volume of waste materials (Pat-Espadas et al., 2018). The sulfide minerals cause elevated levels of heavy metals, sulfate, and H^+ ions in AMD and increase the bioaccumulation of metallic species in the environment (Park et al., 2019). AMD wastewater contains sulfates (1000–149,130,000 mg L^{-1}) with a high concentration of sulfuric acid and a solution of ferrous metals (200–1000 mg L^{-1}). Hence, the higher levels of acidity increase the solubilization process of metals such as Zn and Al (20–800 mg L^{-1}) and also other metals namely Cu, Mn, and Ni (trace concentrations to 250 mg L^{-1}) (Markovic et al., 2020). On the other hand, sulfur compounds and other metals solubilize easily, persist in the water, and ultimately contaminate the ecosystem (Fashola et al., 2016). Many scientists have reported the composition of AMD as shown in (Table 1).

3. Factors affecting AMD formation

The formation of AMD is driven by many factors including atmospheric oxygen, water, pH, mine type, surface area, particle size, and bacterial action (Fig. 2). The details about each factor are given below:

3.1. Oxygen and water

Water and oxygen are the main factors that assist in the formation of AMD. However, water is the source of pyrite oxidation, resulting in the generation of a highly rich acidic solution. Moreover, the chemical reaction of iron pyrite with oxygen and water begins through an oxidation reaction, resulting in the formation of ferrous iron and sulfate ions where hydrogen and soluble metal cations are precipitated:

$$2\ FeS_2\ (s) + 7\ O_2\ (g) + 2H_2O \rightarrow 2\ Fe^{2+}(aq) + 4\ SO_4^{2-}(aq) + 4\ H^+(aq) \quad (1)$$

On the other hand, oxygen plays a crucial role in maintaining the oxidation process, which is catalyzed by bacteria at a pH below 3.5. Along with oxygen (air) and water, mineral pyrite (FeS_2) breaks down to give Fe^{2+}, SO_4^{2-}, and H^+ ions.

$$FeS_2 + 3.5\ O_2 + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \quad (2)$$

The formation of ferrous ions (Fe^{2+}) is oxidized with O_2 to form Fe^{3+}. Furthermore, this chemical reaction is accelerated by sulfur-oxidizing bacteria (*Thiobacillus thiooxidans*, *Thiobacillus ferrooxidans*).

$$Fe^{2+} + 0.25\ O_2 + H \rightarrow Fe^{3+} + 0.5H_2O \quad (3)$$

However, ferric ion (Fe^{3+}) reacts with pyrite to make Fe^{2+}, SO_4^{2-}, and H^+ ions.

$$FeS_2 + 14\ Fe^{3+} + 8H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \quad (4)$$

With the formation of H^+ ions and low pH, the condensation process of Fe^{3+} occurs in the form of iron hydroxide [$Fe(OH)_3$], an orange-red precipitate also known as "Yellow Boy."

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3\ H^+ \quad (5)$$

Overall, the pyrite oxidation reaction can be presented as:

$$FeS_2 + 3.75\ O_2 + 3.5H_2O \rightarrow Fe(OH)_3 + 4\ H^+ + 2\ SO_4^{2-} \quad (6)$$

The overall process results in the formation of sulfuric acid and iron/ferric hydroxide [$Fe(OH)_3$]. The oxidation reaction of sulfur minerals (pyrites and other metal pyrites) in the presence of water and atmospheric oxygen is the main cause of AMD formation (Rambabu et al., 2020).

3.2. pH

Another important environmental factor that accelerates the formation of AMD is pH. In comparison to the rate of pyrite oxidation by dissolved oxygen, the low pH (below 3.5) causes a faster rate of pyrite oxidation by ferric iron (Fe^{3+}), resulting in the formation of AMD. Sulfide oxidation reactions release H^+ ions which result in low pH and increase the solubility of potentially toxic metals such as Pb, Zn, Cu, Cd, and As by making them more mobile (Rahman et al., 2021). Low pH-containing solutions induce discharging of more H^+ ions and accelerate the available metallic species for AMD formation. Meanwhile, the conversion of ferrous iron to ferric iron by the oxidation process is associated with low pH conditions as ferric iron is readily dissolved under low pH conditions (Skousen et al., 2017). Additionally, lower pH also accelerates the formation of precipitates of iron/ferric hydroxide. At higher pH, reduced metal ions such as Fe^{2+} and Mn^{2+} are considerably more soluble than their oxidized forms i.e. Fe^{3+} and Mn^{4+}.

Table 1
Composition of AMD samples from previous studies.

Element	Ayora et al. (2016)	Nieto et al. (2013)	Edraki et al. (2005)	Vital et al. (2018)	Ryu et al. (2019)
Al (mg L^{-1})	251	163	76–36073	293	150
Ca (mg L^{-1})	441	81.6	464–514	313	170
Fe (mg L^{-1})	744	153	13–1487	13.4	340
Mg (mg L^{-1})	1104	199	1280–1664	436	220
SO_4 (mg L^{-1})	11,700	2122	8390-22,700	8250	4300
Cu (mg L^{-1})	165	11.7	3–138	615	90
Mn (mg L^{-1})	467	21.9	22–230	203	–
Zn (mg L^{-1})	976	51.2	2–81	68.5	120

3.3. Mine type

Mine type plays a key role in the formation of AMD. Pope et al. (2010) found that open-pit mines contain a high amount of Al–Fe as compared to underground mines. The formation of Al precipitates in the mine causes a reaction between the sulfuric acid and alumino-silicate minerals. These reactions proceed faster in open-pit mines because sediments of coal are more unstable and have a higher reactive surface area in mine waste rock dumps as compared to underground mines (Wei et al., 2018). Meanwhile, underground mines have limited reaction between H_2SO_4 produced from pyrite oxidation and coal sediments and therefore have greater Fe than Al. There are various types of mines, such as Au–As, Au–W, Au–Cu, As, Cu–S, Cu–W, Cu–Zn, S, Pb–Zn, Hg, Sb, Co, Ni, Zn, Sn, U, W, coal, phosphorite, and kyanite. However, each mine

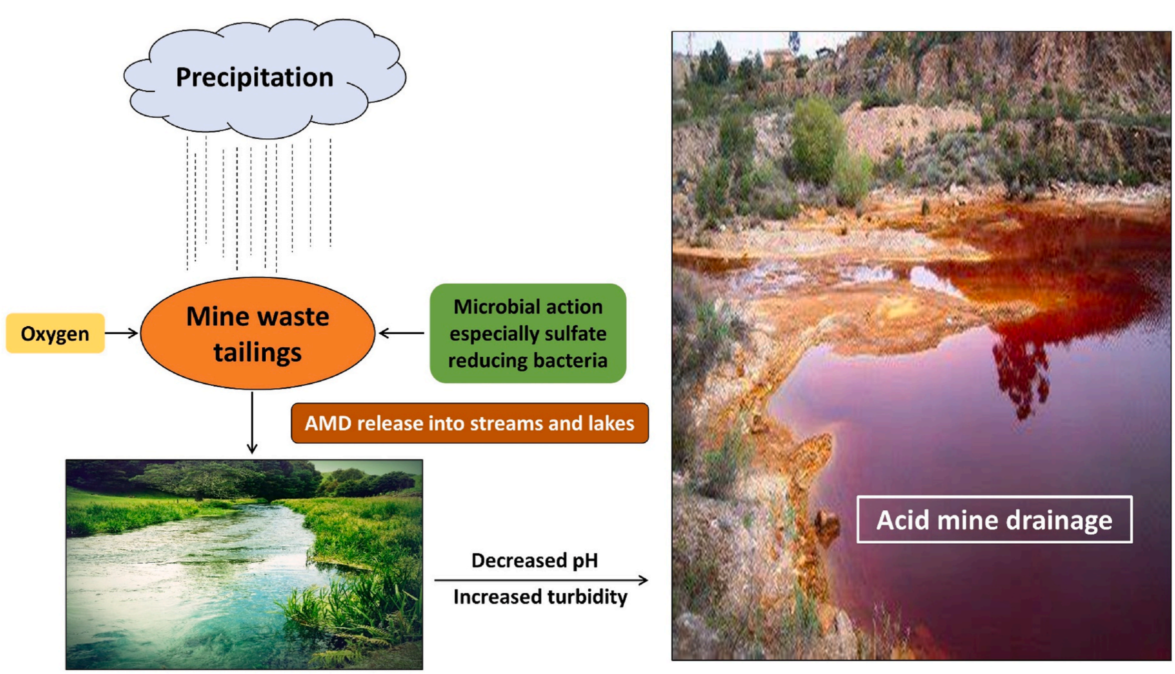

Fig. 1. Formation of AMD and related contamination pathway.

has a distinct soil texture, AMD formation process, and environment, that may be considered during the reclamation of mining wastes produced (Jabłońska, 2021).

3.4. Ore particle size/surface area

The quantity of AMD is directly proportional to the surface area of the pyrite mineral. Moreover, the surface area of minerals is linked with particle size, however, lower size does not always favor mineral solubilization (Yin et al., 2020). In addition, ore composition can stimulate or halt mineral dissolution regardless of particle size, for instance, Uranium (U) ore containing a higher concentration of gypsum can reduce U mineral solubilization even at lower particle size (<0.45 mm). The size of ore particles and permeability are key factors responsible for AMD formation due to their impact on the surface area (Masindi et al., 2018).

3.5. Microbial action

The microbes i.e. bacteria involved in the oxidation of pyrite increase the oxidation of sulfides of metals such as cadmium, copper, arsenic, and lead. Interactions between bacteria and sulfide metals play a fundamental role in AMD formation. This process is often catalyzed by microorganisms such as *T. thiooxidans* and *T. ferrooxidans* by using iron sulfide as a source of energy (Dave and Tipre, 2019). For bacteria to grow, environmental conditions must be favorable. For example, *T. ferrooxidans* is active in water with a pH below 3.2. If such conditions are not conducive, the bacterial impact on the formation of an acidic solution will be minimum.

3.6. Time

The mining sector as a whole has to acknowledge the importance of time-dependent aspects in the formation of AMD, which is not just limited to specific mine sites. The time it takes to develop acid conditions might range from less than one day to more than fifty years. Even in ore sources with 40% sulfur (S), acid drainage may not start to form for 10–20 years. However, materials with less than 1% S can start to generate acid right away and discharge significant amounts of acid (Miller and Murray, 1988). If the soil loses its ability to act as a neutralizer, the impact of AMD may worsen with time. This might happen if the neutralizing minerals have a propensity to precipitate salt or gypsum crusts that prevent further reaction or if the neutralizing minerals are depleted as a result of repeated reactions with AMD. If the rates of AMD development fluctuate as a result of changing site conditions, the effects of AMD may also change. Due to these factors, it frequently takes some time before AMD is discovered once mining activities start (Fig. 3). AMD might not be discovered until after surface reclamation has taken place; the times can range from 1 to 10 or more years. Once it starts, acid formation is difficult to stop, frequently accelerates, and can last for decades (Geidel and Camccio, 1977; Gaikwad and Gupta, 2007).

4. Impact of AMD on soil, plants, and microbes

AMD has a severe impact on food chains and ecosystems, resulting in the destruction of habitat and the death of organisms in both terrestrial and aquatic habitats. The AMD impact on humans and the environment generally depends on pH, metal contents, and their toxicity.

4.1. Soil biochemical properties

AMD-impacted soils are inimical for plant growth due to low pH, deficiency of nutrients, metal toxicity, and low water-holding capacity. Low pH increases the solubility and toxicity of various metals such as copper, cadmium, and zinc that compete with essential nutrients, causing the deficiency of nitrogen and phosphorous in plants with reduced microbial activity (Aguinaga et al., 2021). Dong et al. (2018) investigated that AMD (10 mL g^{-1} soil) decreased the available P and K up to 63 and 97%, respectively in soil. Humberto et al. (2020) found that a higher concentration of heavy metal significantly decreased the enzymatic activities in the following array: arylsulfatase > dehydrogenase > β-glucosidase > urease > acid phosphatase > alkaline phosphatase > catalase. Both enzyme Arylsulfatase (partly as exoenzyme) and dehydrogenase were significantly decreased by 72 and 64%, respectively. The enzymatic breakdown of organic compounds in AMD-impacted soils not only changes the proportion of carbon, nitrogen, phosphorous, and sulfur but also immobilizes them.

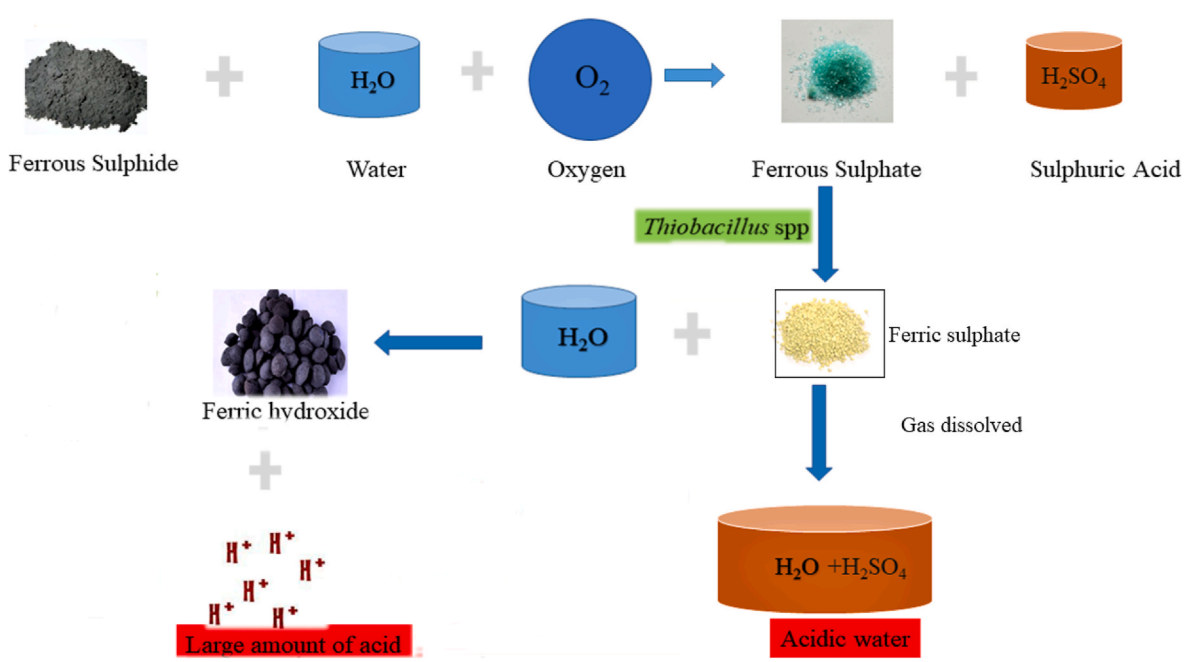

Fig. 2. Mechanisms of formation of AMD (Singh and Bhatnagar, 1985).

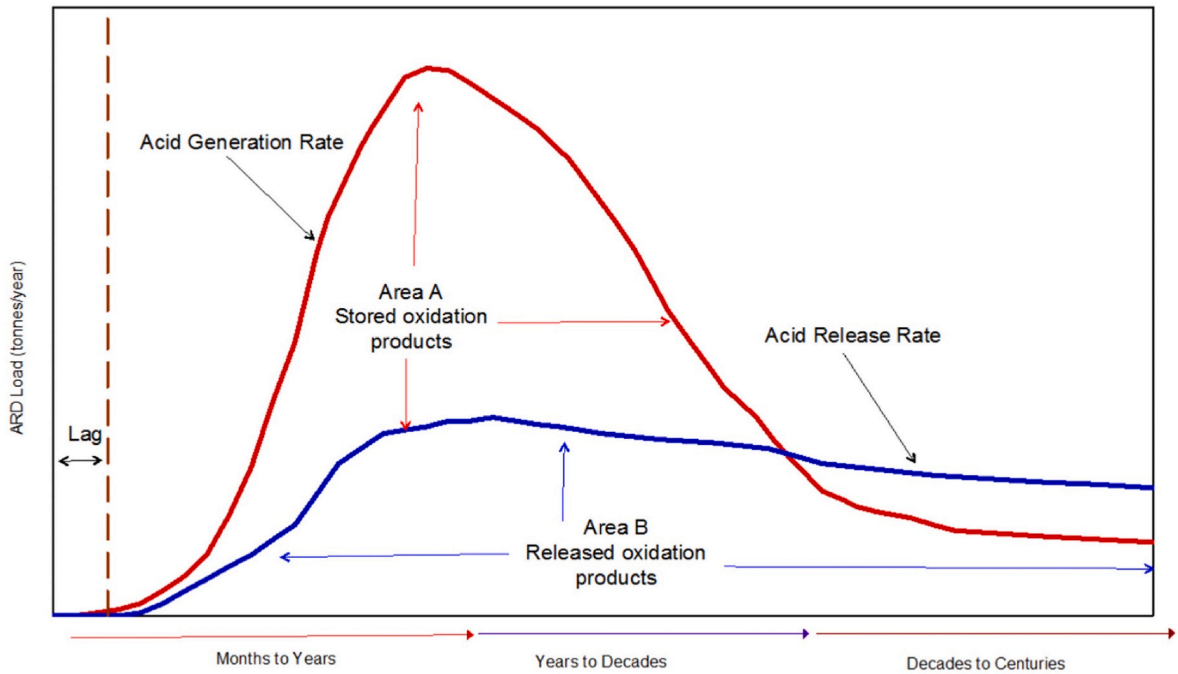

Fig. 3. Schematic representation of the time impact on AMD oxidation product generation and release from a waste storage facility. Source: Miller (2014).

4.2. Plant growth and productivity

AMD has severe consequences when drained into soil and water bodies. Once AMD contaminates the soil, a significant amount of hydrogen ions causes soil acidification, which affects plant growth and adaptability including respiration and absorption of nutrients via the root system (Goulding, 2016). Moreover, the high level of heavy metals in the soils due to mining operations are not easy to detoxify. Additionally, the toxicity of the heavy metal (Cd and Pb) and metalloid (As) produces substantial changes in the rhizosphere. In general, toxic heavy metals affect soil pH and reduce organic carbon and the microbial community in the soil thereby causing a severe impact on photosynthesis, plant growth, and biomass (Daraz et al., 2021). Previous research has highlighted the negative impacts of AMD on plants, for example, AMD toxicity induced oxidative stress that damaged the cell and disrupted morphological and physiological attributes of medicinal plants (Lajayer et al., 2017). Furthermore, a high level of heavy metals or in the form of a mixture negatively alters the growth and adaptability by causing harm to the plant cellular tissue and disturbance to the process of homeostasis.

4.3. Microbial communities

The microbial community structure is an important indicator to determine soil quality. In general, microorganisms are a fundamental part of the soil and play a key role in the transformation and cycling of different nutrients. However, soil microbial community structure and functions are impacted by higher concentrations of heavy metals in AMD (Pan et al., 2021). Moreover, AMD pollution in the soil can change the functions of the microbes. Soil AMD pollution is a severe environmental issue today for plant health and has a negative impact on microbial communities in soil. The toxicity of heavy metals significantly changed the structure and function of rhizospheric microorganisms (Thavamani et al., 2017). Moreover, metal pollution caused the deactivation of the enzyme or decreased the enzymatic activity of soil microbes with the essential metabolite to form a precipitate or chelate. Hence, AMD can inhibit bacterial proliferation, and affect the active pool of microbes. The increasing concentration of acidity decreased the microbial biomass carbon. In another study, Thavamani et al. (2017) also observed a significant reduction in cultivable heterotrophic bacteria in metal-polluted soil. The presence of metals in the rhizosphere also hampered the survival of the most beneficial bacteria and their functions (Daraz et al., 2021).

According to Baker and Banfield (2003), AMD enriched with heavy metals altered the bacterial community composition but had no impact on the fungal community structure. The extremely acidic solution and low pH in soils affected by AMD cause significant changes in structure rather than diversity. Species evenness can change the characteristics of soil microbial communities (Hou et al., 2019). Wu et al. (2018) reported that metal toxicity significantly decreased bacterial species richness as compared to species evenness. However, it was found that the increasing concentration of heavy metals badly affected the viable population of microorganisms in the soil (Daraz et al., 2021). Another study showed that metals significantly decreased the bacterial community and alpha diversity. In addition, the richness and community composition of denitrifying bacteria in soil was badly impacted by heavy metals. Similarly, several studies indicated that soil microbial community composition can change in response to heavy metal stress (Aguinaga et al., 2021). Yin et al. (2015) reported that the Cr pollution significantly changed the bacterial community structure from Proteobacteria to Firmicutes. It was also revealed that pristine soil had dominant phylum Actinobacteria and Acidobacteria, but turned into Proteobacteria due to metal (Cr, As) contamination. Overall, the rhizospheric microbial community structure showed determined environmental resilience under heavy metal stress.

Polluted soils have negative effects on soil pH, decomposition of organic matter, and activity of soil bacterial community. For example, the copper-polluted soils had a negative impact on microbial communities that participate in the nitrification and mineralization processes. A large number of metals may also affect the nitrification process in AMD-impacted soils. However, heavy metals, such as copper, zinc, lead, cadmium, and metal sulfides are associated with decreased nitrification rates in soils. Nevertheless, microbiota in soil are sensitive to more mercury (Hg), for instance, a concentration of $<$10 ppm Hg may have a negative impact on the nitrifier community in soil (Coral et al., 2018). Similarly, the higher concentration of Pb in soil negatively affects soil bacterial functions. Hence, processes of decomposition of organic matter are impacted because of decreased enzymatic activities of the soil bacterial community. Regarding the heavy metal-induced impact on the functional characteristics of soil bacteria, the elevated levels of Pb, Cd, and Cr reduced the available amount of nutrients and functional capabilities of the microbial community as compared to control soil (Hao et al., 2012). However, it was unclear whether or not the functionality of the rhizosphere bacterial community under-went specific changes after the introduction of bacterial strains in AMD-impacted soil. Pan et al. (2021) reported that Cu and Zn contamination in soil changed the structure and functional capabilities of bacterial communities and that different bacterial groups respond differently to heavy metals. However, previous studies have relied on a single functional approach and thus have not been able to determine the long-term impacts of heavy metals on the soil bacterial communities and their function.

5. Remediation of AMD wastewater

One of the major problems in mining areas is the treatment of wastewater in the form of AMD. If the production of AMD is not properly handled, environmental degradation can be accelerated. Various on-the-spot remediation methods have been conceived and are available in areas where mining activities are carried out. A summary of the advantages and disadvantages of different treatment technologies used for AMD remediation is presented in Table 2. AMD treatments can be divided into control at source and mitigation approaches.

5.1. Prevention or source control technologies

Prevention focuses on lowering the production of AMD at its source by reducing the reaction of sulfur with oxygen, water, and oxidizing bacteria. This approach is considered a permanent solution to preventing AMD formation and thus should not need any additional treatment for metal removal. RoyChowdhury et al. (2015) reported that prevention methods could be used to ameliorate AMD formation. The authors also suggested other techniques such as water covers, high water tables, and multi-layer covers can be used to prevent AMD formation. Prevention technologies include the use of limestone, oxygen barriers, organic coating, microcapsule method, etc. In covers, blending or layering of limestone at the rate of 25% was found satisfactory in controlling the formation of AMD at Freeport Indonesia and Grasberg mine in Papua province, Indonesia (Miller et al., 2006). Similarly, the flooding and sealing approach has also been employed for the prevention of AMD in abandoned underground mines (Johnson and Hallberg, 2005). The dissolved oxygen in the water will be consumed by the microbes and the subsequent mixing of oxygen is controlled by sealing the mine. The shallow water technique has also been utilized for mines with the potential to produce AMD (Li et al., 1997). In this technique, the contact between oxygen and minerals is reduced by a shallow water layer. This technique could be made more effective by adding a layer of organic materials or sediments, both of which would result in limited oxygen ingress. Both flooding and sealing and shallow water technique require a sufficient supply of water to prevent oxygen entrance during the dry season, which results in cracks formation. The AMD formation can also be controlled by soil compaction, dry cover, and cover using slag, clay minerals, and mine waste. To prevent microbial activity, some chemicals may also be employed (Pozo-Antonio et al., 2014). Another approach that has been utilized to prevent AMD formation is carrier microencapsulation which is based on the use of various materials such as organic in situ carriers, catechol, and titanium-containing minerals for the sulfide mineral surface coatings (Satur et al., 2007). Using the microencapsulation approach, various other chemicals such as H_4SiO_4, H_3PO_4, oxidants of H_2O_2 or hypochlorite, and limestone or sodium acetate (Evangelou, 2001), lime and blending of silicates (Zhou et al., 2017), iron oxyhydroxide coatings (Huminicki and Rimstidt, 2009), diacetylene-containing phospholipid (Kargbo et al., 2004), silicate coatings of Fe^{3+}-silica and/or Fe^{3+}-hydroxy-silica complexes (Kargbo and Chatterjee, 2005), silane-based coatings (Diao et al., 2013) have also been employed. In addition, the removal of solid wastes from AMD is the best option, which not only reduces the negative impacts but also does not require any financial investment. Despite all the above facts, several factors such as how to maintain the system at neutral pH, stabilization of the coating layer, and how to make this treatment economical need to be considered for such type of geochemical treatment. For such type of treatment, many silicate minerals keeping in view the type of AMD-producing source minerals could be considered as potential materials to be used.

5.2. Active treatment technologies

Recently, treatment technologies are considered the best method for remediation of AMD, involving the collection of AMD and its remediation either by active or passive means. Active treatment involves the use of different alkaline chemicals e.g. limestone ($CaCO_3$), hydrated lime ($Ca(OH)_2$), caustic soda (NaOH), soda ash (Na_2CO_3), calcium oxide (CaO), and magnesium oxide (MgO) to increase the pH and precipitate toxic metals from AMD (Masindi et al., 2017). In addition to chemical usage, some other strategies such as the use of activated carbon, clay minerals, different membranes, and other synthetic compounds or adsorbents (Masindi et al., 2015; Lopez et al., 2018).

Table 2
Summary of the advantages and disadvantages of different treatment technologies used for AMD remediation.

Treatment technologies	Materials or methods used	Advantages	Disadvantage
Prevention or source control technologies	Limestone, oxygen barriers, organic coating, microcapsule method, flooding and sealing approach, shallow water technique, and carrier microencapsulation	Permanent solution	–
Active treatment technologies	Use of different alkaline chemicals e.g. limestone ($CaCO_3$), hydrated lime ($Ca(OH)_2$), caustic soda (NaOH), soda ash (Na_2CO_3), calcium oxide (CaO), and magnesium oxide (MgO) to increase pH	Fast and more reliable	•Requires a continuous supply of chemicals with consumption of high energy for their production •Costly •In the case of different membranes usage, fouling is the main issue
Passive treatment technologies	Constructed wetlands, anaerobic sulfate-reducing bioreactors, anoxic limestone drains, vertical flow wetlands, limestone leach beds, open limestone channels, and organic materials	•Low cost •Does not need any maintenance once designed properly	•The main disadvantage is its long-term viability. •The presence of Al and ferric iron, both of which can precipitate hydroxide, reduces the efficacy of commonly employed methods. •Produce a substantial volume of the trash, which has a high removal and disposal cost.
Emerging technologies for AMD remediation	Nanomaterials	Cost-effective	Cause environmental contamination
PGPR-assisted phytoremediation	PGPR in combination with plants suitable for phytoremediation of different contaminants	•Cost-effective •Environment friendly	•Slow •Disposal of contaminated plant biomass produced

As clear from Table 3, the active remediation process is fast and more reliable in minimizing metal toxicity. The active remediation approach is linked to the handling and dumping of mine waste. The main disadvantage of this treatment is the requirement of a continuous supply of chemicals which require a lot of energy in their production (Kim et al., 2022; Masindi et al., 2022). The use of expensive chemicals and hiring more workforce considerably enhance the general cost of technology. These chemicals are very expensive and result in the formation of a large volume of mine waste that is difficult to handle. Moreover, there is the possibility to release unwanted chemicals such as NH_3 or NaOH that can cause environmental pollution. In the case of different membrane usage, fouling is the main issue that requires further research in the future (Rambabu et al., 2020).

5.3. *Passive treatment technologies*

Passive treatment comprises natural and biological processes to remediate AMD pollution (Jouini et al., 2020; Villegas-Plazas et al., 2021). This remediation technique can be divided into two approaches: conventional and emerging technologies.

5.3.1. *Conventional passive treatment technologies*

Conventional remediation process e.g., construction of wetlands and anaerobic sulfate-reducing bioreactors for long-term usage. Passive remediation is a more reliable, environment-friendly, and cost-effective technology than active methods (Martins et al., 2011; Vasquez et al., 2022). Passive remediation depends on physical, chemical, and biological processes. Biological passive treatment relies on bacterial growth and activity while oxidation of Mn and Fe catalyzed by bacteria and reduction of sulfate and other metals occur by the process of adsorption.

5.3.1.1. Constructed wetlands. Constructed wetlands are used as a passive AMD remediation approach. There are two types of wetlands i.e. aerobic and anaerobic. Aerobic wetlands are largely shallow-water bodies (<30 cm in depth) rich in limestone gravel, soil, and organic matter which support plant growth and precipitate and oxidize metal hydroxides (Nguegang et al., 2022). For instance, wetland plants including *Typha* sp., *Juncus* sp., and *Scirpus* sp. can modulate the flow of water, stabilization of metal precipitates that sustains microbial communities, and can improve the aesthetic value of the AMD-impacted soil (Wu et al., 2022). Wetland plants have two main mechanisms i.e. phytoextraction and rhizo-filtration to minimize the toxicity of metal from AMD wastewater. During phytoextraction, metal hyperaccumulators can extract heavy metals from the substrate while storing them in different plant parts. In rhizo-filtration, the plants can absorb, concentrate or precipitate metals in the plant rhizosphere.

Table 3
Different neutralization materials, their scope of application, advantages, and disadvantages.

Neutralization material	Scope of application		Advantages	Disadvantages
	Saturation pH	Solubility (mg/L) in cold water		
Limestone ($CaCO_3$)	8–9.4	14	•Fast •More reliable	•Require continuous supply of chemicals and energy to be effective •The use of expensive chemicals and hiring more workforce considerably enhances the general cost of technology •The chemicals may result in the formation of a large volume of mine waste that is difficult to handle •Possibility to release unwanted chemicals such as NH_3 or NaOH that can cause environmental pollution
Dolomite ($CaMg(CO_3)_2$)	8–9.5	10–300		
Magnesite ($MgCO_3$)	9.5–10	60–100		
Quicklime (CaO)	12.4	1300–1850		
Hydrated lime ($Ca(OH)_2$)	12.4	1300–1850		
Caustic magnesia (MgO)	9.5–10.8	1–50		
Mg Hydroxide ($Mg(OH)_2$)	9.5–10.8	1–50		
Soda Ash (Na_2CO_3)	11.6	75,000		
Caustic Soda (NaOH)	14	450,000		
Ammonia (NH_3)	9.2	900,000		

Moreover, wetland plants such as *Phragmites australis* and *Oryza latifolia* form a thin and flat plate (plaques) on the upper surface of the root by causing oxides of metal and hydroxide precipitation which can inhibit the movement of metals in plant cellular tissues (Pi et al., 2011). The effectiveness of wetlands in ameliorating AMD pollution relies on various factors such as acidity due to heavy metals and seasonal variations. The retaining capacity of aerobic wetlands becomes higher after the extraction of metals. Aerobic wetlands are not able to remove sulfates and are considered inefficient due to the high level of metals in the system.

Meanwhile, aerobic wetlands are mainly utilized to collect water, for the chemical reaction of iron (Fe), and to stimulate metal hydroxide flocs. If the wetland water is not alkaline, limestone is added to produce alkaline conditions; otherwise, the productivity and effectiveness of the aerobic wetland would be poor. The aerobic wetland is often a flimsy basin. The plants such as *Typha* (cattails) are mainly cultivated in a free substratum to improve flora and fauna as well as the slow movement of water, which connect sites for floc (Fitzpatrick, 2017). Wetland plants also assist to increase constant flow for more productive remediation. The oxidation of manganese (Mn) occurs more slowly than iron (Fe) oxidation, as the presence of Fe^{2+} stops Mn oxidation.

The main component of anaerobic wetlands is a mixture of soil containing decomposed remains of mosses, mushroom compost, waste byproducts, and other organic materials. These wetlands require only a small amount of neutralizing agents such as limestone. The organic-rich substrates are composed of environment-friendly materials such as manure with straw, peat, and sawdust. This soil mixture is generally considered a long-term food source for bacterial communities capable of reducing metal toxicity. The withholding ability of metal oxide, hydroxide, carbonate, and precipitate of sulfide also occurs in anaerobic wetlands. Anaerobic wetlands are a low-cost technology to remediate AMD wastewater. In addition, passive wetlands reduce the pattern of water, geochemical processes, ecosystem function, and diversity (Irshad et al., 2021). Anaerobic wetlands are more productive when used to treat a small quantity of AMD with limited acidity. These wetlands are also expensive to install, need regular maintenance and require a large land area.

5.3.1.2. Anaerobic sulfate-reducing bioreactors. Anaerobic sulfate-reducing bioreactors (ASRB) are the passive treatment that comprises sulfate-reducing bacteria to minimize AMD pollution. Active bioreactors need an industrialized setting and differ significantly from the passive remediation approach in that they do not work in harmony with the environment. The biological sulfate reduction process comprises several reactor designs e.g. mixed flow reactors, sequential batch reactors, airlift reactors, fluidized-bed reactors, anaerobic filters/packed bed reactors, anaerobic sludge blanket reactors, and membrane bioreactors (Burns et al., 2011). However, the reduction of sulfate by microorganisms is the technique to remediate AMD. These systems can handle highly acidic and elevated metal-rich water, such as mine drainage. Moreover, the rate of flow via these methods is unpredictable as these have poor flows. Microorganisms could be utilized in such bioreactors to make it a low-cost and efficient treatment. The introduction of specific microorganisms such as cellulolytic and fermentative can also help in the breakdown of the organic matter into elements used by sulfate-reducing microorganisms (Muyzer and Stams, 2008; Hiibel et al., 2011; Lefticariu et al., 2015).

Moreover, chemoorganotrophs are a group of sulfate-reducing bacteria, comprising several genera (Desulfovibrio, Desulfomicrobium, Desulfobacter, and Desulfotomaculum) and are known as anaerobic bacteria. Anaerobic sulfate-reducing bioreactors (ASRB) are formed by a layer of organic-rich compounds, surrounded by limestone. Another film of limestone is also utilized underneath the organic layer, which causes acidification and stimulates the drainage system. The AMD wastewater moves through the organic layer and limestone bed vertically and is released by the drainage system. The lowermost organic layer in sulfate-reducing bacteria can change sulfate (SO_4^{2-}) into hydrogen sulfide (H_2S) and decompose organic material (–CH_2O–) into bicarbonate ions (HCO_3^-) (Ayangbenro et al., 2018). Sulfate-reducing bioreactors or sulfidogenic bioreactors help to remove metal acidity, and elevated levels of sulfate in AMD and hence ameliorate water pollution (Deng et al., 2016). Various modifications in the use of sulfidogenic bioreactors have been proposed such as low pH sulfidogenic bioreactor using activated sludge as a carbon source (Xingyu et al., 2013), anaerobic membrane bioreactor (Sahinkaya et al., 2019), sulfidogenic fluidized-bed bioreactor (Makhathini et al., 2021), and sulfidogenic bioreactor inoculated with indigenous acidic communities (González et al., 2019).

Some of the major key factors such as the introduction of microorganisms, neutral pH, organic carbon, and potential of precipitated sulfur compounds are involved in the efficient sulfate-reducing bioreactor. However, lower pH (below 3.5) affects the efficiency of the sulfate-reducing bacteria. The lower temperature also affects the adjustment of the sulfur-reducing bacteria. In general, the sulfate-reducing bioreactors are let down for a long-time mainly owing to the use of the substratum needed for supporting the bacterial communities in biochemical reactors (Hiibel et al., 2011). In this regard, the enhanced populations of cellulolytic and fermentative microbial communities in addition to the sulfate-reducing bacteria also play an important role in the provision of easily metabolizable organic substrates e.g. acetate, formate, lactate, etc., especially during the initial phase of the AMD treatment (Muyzer and Stams, 2008). Both, sulfur-reducing bacteria and cellulolytic and fermentative microbes work synergistically, the latter provide organic substrates to the former, resulting in optimized treatment of AMD (Lefticariu et al., 2015).

The removal of sulfate and the increase in pH are some of the major advantages. Conventional AMD treatment technologies comprise several physicochemical approaches, which require a large number of chemicals and capital. These approaches also need precise control and maintenance.

5.3.1.3. Other commonly used passive treatment techniques. *Anoxic limestone drains (ALD)* are passive AMD remediation techniques (Neff et al., 2021; Merchichi et al., 2022). This system comprises 30 m long, 1.5 m deep, and 0.6–20 m below-ground limestone. Once anaerobic water is entered into ALD, it becomes impermeable to water and oxygen. In this process, limestone moves through AMD wastewater and produces carbon dioxide gas, which cannot be released further, promoting the process of acidification (Sibrell et al., 2007). Iron is oxidized under anaerobic conditions but iron hydroxide precipitates do not form. The ALD will form optimally if AMD wastewater contains no ferric or aluminum ions. Under high acidic conditions, pH needs to be 6.0 for the precipitates of metal hydroxide which form a layer on limestone in the ALD systems. Moreover, the formation of iron hydroxide precipitate negatively affects the effectiveness of the ALDs. The main disadvantage of ALD is its toughness. The appearance of ferric ions (Fe^{3+}) and aluminum (Al) in mine wastewater can form precipitates of hydroxide, which may inhibit the entrance and cost-effectiveness of the ALD system. Thereby, ALDs consist of a hybrid passive remediation method that can help both the aerobic and anaerobic wetlands.

Vertical flow wetlands (VFW) are a form of passive treatment, also known as permeable reactive barriers (Beauclair et al., 2021; Nguegang et al., 2022). AMD wastewater travels through a limestone bed before being released by a drainage system in a VFW procedure. The VFW method reduces the amount of dissolved oxygen by converting ferric to ferrous iron. In this system, sulfate and iron (Fe) precipitates are minimized. A huge number of drainage pipes are buried beneath the layer of limestone, directing the water into ponds where ferrous ions are oxidized and precipitated (Demchak et al., 2001).

Limestone leach beds (LSB) are a passive form of the treatment system, also called open limestone channels (Kim et al., 2022; Vasquez et al., 2022). LSB are ponds to store wastewater with low acidity and toxic metals. Thereafter, these ponds are filled with limestone and possess wastewater for 12-h. The layer of limestone can be replaced when required. This system shows alkalinity (75 mg L^{-1}). However, steel slag bed is manipulated to decontaminate the AMD pollution in these ponds. In LSB, the system can be easily restored up to 2000 mg L^{-1} alkalinity.

Open limestone channels (OLCs) are channels filled with limestone and are passive remediation approaches (Merchichi et al., 2022; Wang et al., 2022). In OLCs, limestone is covered with Fe and aluminum hydroxide [$Al(OH)_3$] is used to decrease the breakdown of limestone over time. This system relies on various factors e.g. pH, velocity, slopes, and thickness. This system can reduce the acidity of Fe (4–69%), Mn (72%), and Al (20%).

Organic materials such as wood waste and organic carbon are often used to remediate AMD (McCullough and Lund, 2011; Murtaza et al., 2021; Masindi et al., 2022). Moreover, the discarded waste with low air in mine tailings minimizes the oxidation process of sulfide. Organic materials are mostly applied in Canada for the restoration of the mine tailing area. Passive remediation methods, on the other hand, are costly and need time-based observation and improvement.

The main disadvantage is its long-term viability. The presence of Al and ferric iron, both of which can precipitate hydroxide, reduces the efficacy of commonly employed methods. The passive treatment method also produces a substantial volume of the trash, which has a high removal and disposal cost. The major advantage of some techniques like LSB is low-priced and does not need any maintenance once designed properly.

5.3.2. Emerging technologies for AMD remediation

The remediation of AMD and industrialized wastewater is being investigated in many research institutions through the utilization of nanomaterials. Treatment technologies can be improved by the use of newly designed nanomaterials for several technologies.

5.3.2.1. Nanotechnology for AMD treatment. Nanotechnology is a recent and emerging technology for the remediation of wastewater, and its importance could not be ignored. According to Mohapatra and Kirpalani (2017), positive as well as negative environmental impacts of different nanomaterials have been found. Although, nano-sized structures have greater remediation potential as size decreases, remediation potential increases. Nanomaterials are being used in the remediation of various environmental pollutants (Kefeni and Mamba, 2020). Moreover, with recent developments in nanotechnology, its application to control pollution caused by wastewater may prove better than other technologies. Nanotechnology is being used to remediate wastewater contaminated with sulfate and other metals (Vásquez et al., 2022). Moreover, the use of nanomaterials such as iron oxide and charcoal ash nanoparticles as coating materials, self-healing coatings based on PropS-SH and pH-responsive HNT-BTA nanoparticles, propS-SH/SiO_2 nanocomposite coatings for nanofiltration through adsorption to remediate mine wastewater has been reported by several researchers around the world (Cheng et al., 2011; Liu et al., 2017; Crane and Sapsford, 2018; Rodriguez and Leiva, 2019; Siew et al., 2020; Li et al., 2021;

Carrillo-González et al., 2022; Gumede and Musonge, 2022; Ji et al., 2022). The synthesized nano-coatings utilize various functional groups on their surface to adsorb various pollutants present in AMD (Siew et al., 2020; Li et al., 2021; Carrillo-González et al., 2022; Vásquez et al., 2022). Nanomaterials have strong adsorption abilities and reactivity due to their nano sizes and large surface area. One of the major advantages of several novel nanomaterials is their low cost, however, nanomaterials can cause environmental problems, thereby more research is needed to identify and predict future impacts.

5.4. Emerging passive treatment technology: phytoremediation

A new and more efficient approach such as phytoremediation is often used for the efficient remediation of mine wastewater. Phytoremediation combined with bacteria, on the other hand, is an efficient and cost-effective strategy for removing and destroying hazardous chemicals from contaminated environments. When AMD is drained into soil and water bodies, it can alter soil pH, diminish soil organic carbon, and disrupt soil microbial communities, all of which can have a negative influence on nutrient intake and plant growth. It also enhances the solubility and toxicity of several metals such as Cu, Cd, and Zn, which compete with vital nutrients in the soil, due to their low pH (Thomas et al., 2022).

A few studies have shown that AMD has harmful effects on plants, such as causing oxidative stress, which causes cellular damage, and disrupting the plants' morphological and physiological characteristics. It may also lower the pH of the soil, resulting in nutritional deficiencies in agricultural plants such as N and P. The degradation of organic matter is minimized because of a reduction in microbial functions. To overcome this problem, phytoremediation is one of the developing techniques to detoxify the impact of AMD and is pragmatic to both water and soil affected by AMD. It is referred to as "the use of green plants to eliminate environmental contaminants" (RoyChowdhury et al., 2019b). However, remediation of AMD-impacted soil is a serious global concern these days.

Phytoremediation approaches-including phytoextraction and phytostabilization are being used to remediate AMD-impacted soils. Moreover, phytoextraction extracts toxic metals with the help of plants and their storage in various parts of the plant such as stems, roots, and leaves. While phytostabilization introduces a vegetative cover to restore AMD-polluted soils. Revegetation of AMD-impacted soils can promote phytostabilization, which mainly depends on the addition of organic matter (amendments) and the revegetation process requires competent plant species (Rojas et al., 2014). Its focus is to stimulate the vegetation cover and in situ immobilization of trace elements by using metal-tolerant plant species. Meanwhile, the use of metal-tolerant plants in AMD-impacted soil can promote metal deactivation by altering the speciation of metals. Moreover, soil physicochemical properties and microbial community structure are improved by augmentation of PGPR, hence, soil functions can be restored in the long term (Daraz et al., 2021). Therefore, several plants are mainly used in the process of phytoremediation to tolerate AMD stress. Moreover, plants known as hyperaccumulators can tolerate metals 100 times more than a normal plant. Hyperaccumulators have a high potential to absorb and translocate heavy metals. The bioaccumulation factor is used to determine the ability to intake and store pollutants or contaminants in plants (Thomas et al., 2022). Meanwhile, the ratio of translocation of metals in shoots to roots of the plant is known as the translocation factor. Moreover, plants such as *Cyperus alternifolius* and *C. zizanioides* are indeed acid-tolerant species and have been found to grow under pH as low as 2.4. These plants not only help to reduce mine acidity but also extract a significant amount of sulfates. Several plant species like *Cyperus alternifolius*, *Chrysopogon zizanioides*, *Chrysopogon aciculatus*, *Sesbania rostrate*, *Cynodon dactylon*, and *Acacia auriculiformis*, etc. have been used for rehabilitation of AMD-affected soil (Ma et al., 2015). Some other plant species such as *A. auriculiformis*, *A. confusa*, *J. carcass,* and *M. armillaris* survive at pH 2.0 and are considered the best option for the remediation of AMD-affected soils. Many plants have the potential to remediate AMD stress via tolerance of acidic conditions (pH = 2.4, minimization of sulfate, reduction of metals such as Cu, Cr, Fe, Cd, etc., and various other mechanisms. *C. alternifolius* and *C. aciculatus* are well-known plants that tolerate low pH, former plants have the potential to tolerate acidic pH up to 2.4, whereas *C. dactylon* and *A. auriculiformis* are acid-tolerant as well as metal-tolerant plants, can handle metals such as Cu, Cr, Fe, and Cd (at pH 2.0–2.5). Vetiver (*C. zizanioides*) is a relatively new energy crop, cost-effective and environment-friendly that can be employed to clean up AMD-contaminated soils. *C. zizanioides* is a relatively new energy crop for the reclamation of AMD-affected soils that is both cost-effective and environmentally acceptable. C. zizanioides has a large and complex adventitious root system, and its morphological and physiological characteristics make it a good choice for the management of nutrient-deficient AMD-affected soil (Roongtanakiat et al., 2008). Dong et al. (2018) recently found that AMD (10 mL g^{-1} soil) reduced accessible soil P and K by up to 63 and 97%, respectively.

Moreover, vetiver grass not only grows in highly acidic soils but also sustains its health. Therefore, with vetiver physiological characteristics and a high ability to tolerate toxic metals such as Pb, As, Hg, and Cd, the vetiver system can be used effectively to reclaim AMD-contaminated soils. *C. zizanioides* can tolerate higher concentrations of Fe even at 63,920 mg kg^{-1}. It can lower contamination of mine tailings with a higher level of metals such as Fe, Zn, Mn, and Cu and can accumulate as high as 545–1197, 302–531, 415–648, and 13–66 mg kg^{-1} Fe, Zn, Mn, and Cu, respectively in its roots and shoot. Vetiver had higher translocation factors for various metals e.g. Mn (0.86), Fe (0.71), Zn (0.69) and Cu (0.55) (Datta et al., 2011). Vetiver contains an extensive root system, which can stabilize the metals and help to grow well in acid-sulfate soil. Hence, planting a vetiver plant on AMD-polluted soils can improve soil quality. Therefore, *C. zizanioides* can flourish in AMD-impacted soil with various mechanisms to tolerate the acidity of sulfidic minerals. It was also reported that vetiver systems could control soil erosion while planting on AMD acidic sulfate soil in Australia. It was also found that planting vetiver supports the end of the channel, contributing to minimizing weathering and stopping the breakdown of the AMD-impacted soils into the waterways. Vetiver can stabilize the contaminants in water, which can improve the overall water quality.

The impacts of AMD could be minimized via phytoremediation as clear from the hypothetical model (Fig. 4). In this model, hyperaccumulator plants are used to decrease the toxicity of heavy metals through certain mechanisms hence treated water could be obtained. Furthermore, phytoremediation of AMD-polluted soil showed positive results and encouraged comprehensive research in this field worldwide (Roongtanakiat et al., 2008; Datta et al., 2011; Ma et al., 2015; Dong et al., 2018; Daraz et al., 2021; Thomas et al., 2022). Consequently, phytoremediation is a low-cost and environment-friendly technology. Phytoremediation (biological treatment) has emerged as a major advantage since it is efficient, cost-effective, and eco-friendly. The majority of these treatments include the employment of microorganisms such as bacteria and fungi in a passive remediation procedure. On a small scale, several phytoremediation investigations were carried out in the greenhouse or outdoors. To support this developing technique, further field-based research is required.

5.5. PGPR-assisted phytoremediation of AMD-polluted soils

The rhizosphere is a narrow region of soil or substrate directly affected by the secretion of root exudates and associated microorganisms. In addition to providing mechanical support and absorption of water and nutrients, the roots of the plant also produce, obtain, and exude a variety of compounds (Jing et al., 2018). The rhizosphere is a specific environment with complex root-soil-bacteria interaction. To attract a large number of bacterial communities, roots emit chemical

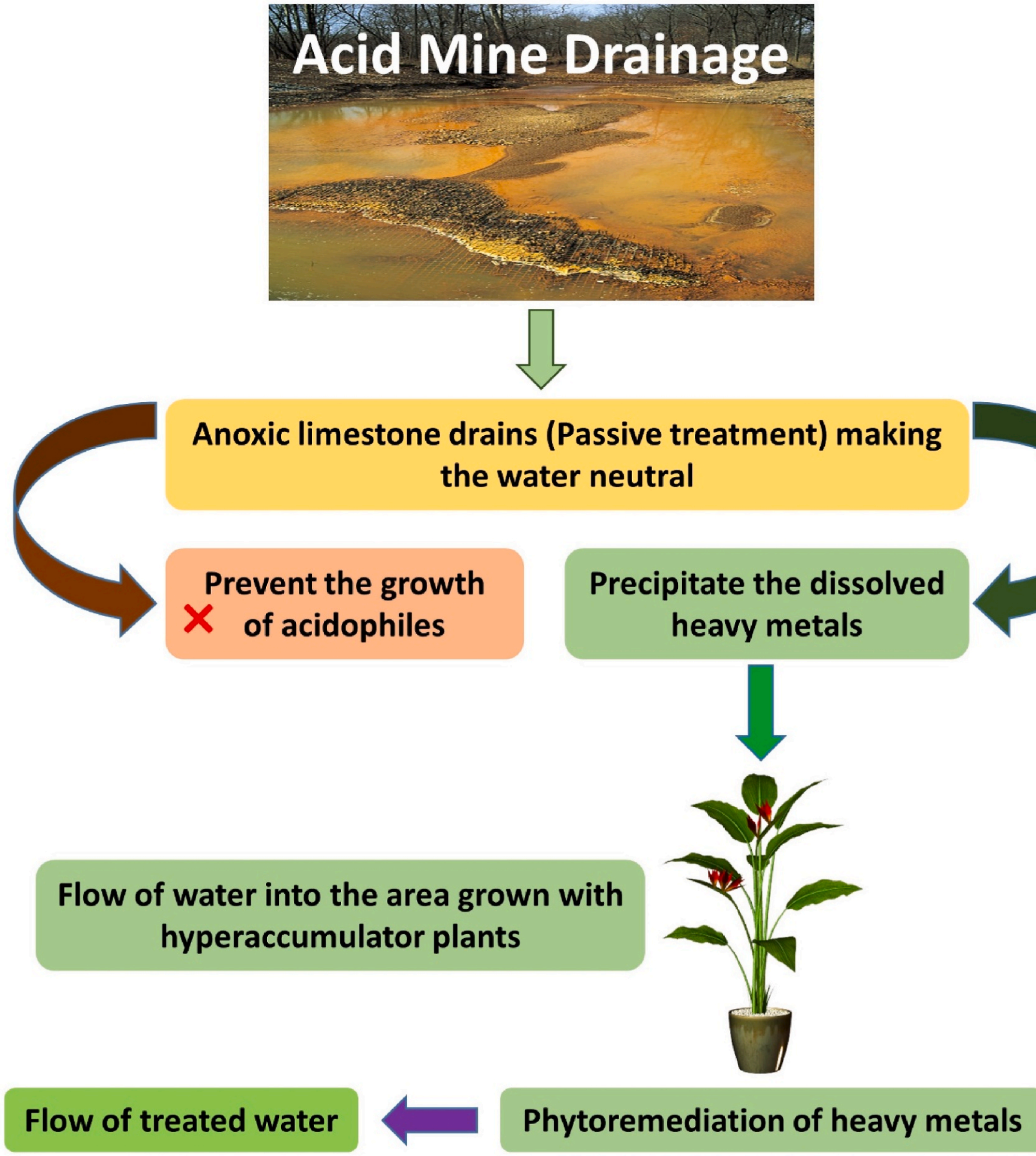

Fig. 4. Hypothetical model for the remediation of mine drainage water.

substances known as root exudates. This interaction aids in the attraction of beneficial soil bacteria to plant roots, and as a result, the rhizosphere stimulates the growth of many bacteria known as PGPR. Moreover, bacterial communities in the rhizosphere influence root structure and contribute to nutrient availability to plants, hence improving growth and adaptability under stress conditions (Ditta et al., 2015, 2018a,b; Hussain et al., 2020). It is investigated about 5–21% of carbon is transferred to the rhizosphere by soil organic carbon (exudates).

PGPR are capable to colonize the root, survive, divide, and competing with other microorganisms for plant promotion. Furthermore, PGPR can enhance plant development through various means, including biological nitrogen fixation, nutrient solubilization, indole acetic acid synthesis, and siderophore synthesis in plants. As a result, PGPR improves plant development by enhancing nutrient solubilization and nitrogen fixation (Ullah et al., 2021). It has been shown in previous research work that PGPR help in mobilizing nutrients more than non-rhizospheric PGPR. PGPR inhibit disease-causing agents and act as biocontrol agents. Although, PGPR help in the breakdown of organic contaminants and the minimization of metal toxicity in polluted soils. PGPR produce plant hormones such as IAA, and siderophores and act as phytostimulators. Some examples of PGPR are *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Bacillus*, *Burkholderia*, and *Acinetobacter* (Ullah et al., 2020; Sabir et al., 2020; Daraz et al., 2021).

Inoculation of bacterial strains can stimulate bacterial communities and root exudates, physicochemical properties of AMD-polluted soils. Indeed, grasses e.g. *M. giganteus* and *A. donax* substantially promoted and enhanced enzymatic activities in the soil surface (0–15 cm) and microbial community structure through their residues and root systems (Liang et al., 2012). Furthermore, another strategy for improving vetiver grass growth in AMD-affected soil is the exogenous administration of bacteria. PGPR dwell close to roots, play an important role in the metamorphosis of the plant and conversion of inaccessible nutrients into available forms for plant uptake. The combination of plants and microorganisms could be a sustaining, cost-effective option to minimize soil pollution (Fig. 5). Moreover, in AMD-polluted land, lower nutrient availability is a crucial factor hence, the application of specific PGPR can stimulate plant growth. Another approach is to introduce local plant

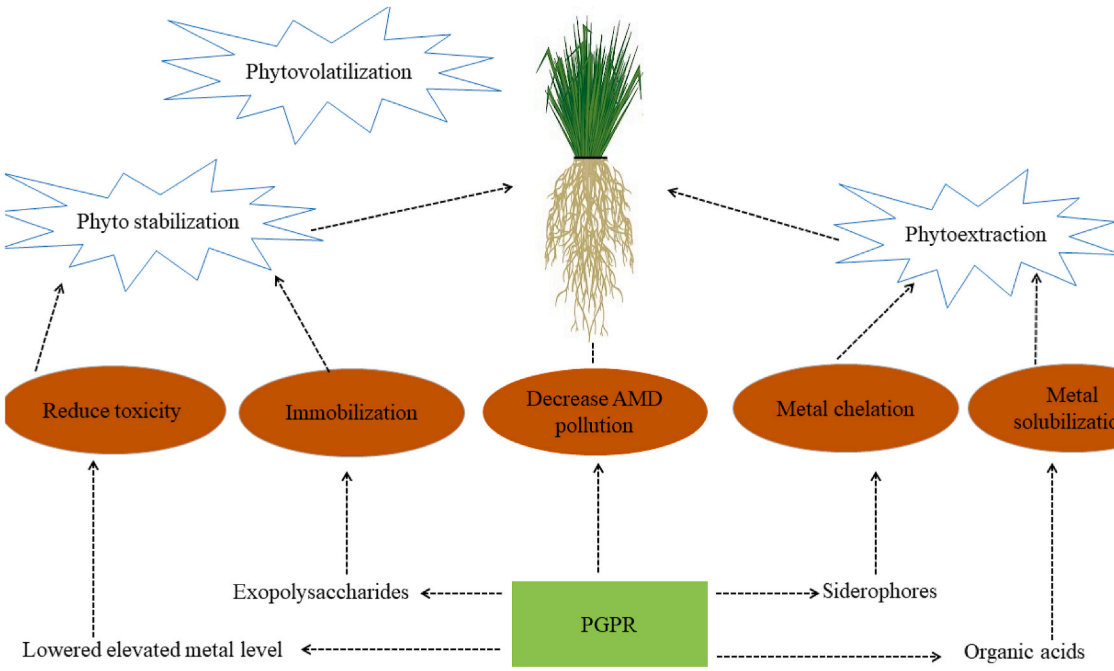

Fig. 5. Mechanisms of PGPR mediated phytoextraction, phytostabilization, and phytovolatilization.

species and associated nitrogen-fixing bacterial species. Rhizosphere bacterial community structures in the rhizosphere are higher as compared to bulk soil due to the presence of root exudates. Plant-microbe interactions also promote plant growth and development under adverse environmental circumstances (Sabir et al., 2020; Hamid et al., 2021; Naveed et al., 2021). The release of root exudates, called rhizodeposition, comprises carbon and nitrogen (10% fixation of carbon in photosynthesis and 15% total nitrogen) to attract microbes for plant growth enhancement. Moreover, PGPR positively increases root length and adaptability in mine-polluted soils. Some common PGPR belong to the following taxa e.g., *Agrobacterium*, *Bacillus*, *Burkholderia*, *Pseudomonas*, etc. Even though PGPR-assisted phytoremediation is a promising approach, certain limitations need attention. For example, the safe disposal of plant biomass produced at the contaminated site. Recently, certain approaches such as the conversion of contaminated plant biomass into carbon-rich pyrolytic material called biochar and phytomining which involves the extraction of metals from the contaminated biomass through chemical processes. The former approach could be employed in soils with low organic matter but it simultaneously results in the contamination of normal soil. More research is required on how long the biochar could retain contaminants in the soil and how prolonged release could be possible. The latter approach is promising as it results in complete removal but may not be suitable for plant biomass with a low concentration of contaminants.

6. Summary and future outlook

Acid mine drainage (AMD) is a serious environmental problem associated with mining that was recently named by the United Nations as the second most important global concern after global warming, highlighting the significance of this environmental challenge (Fig. 6). AMD occurs because of the exposure of coal and pyrite minerals to atmospheric oxygen, water, and microorganisms. Mining activities produce complex sulfur-containing minerals such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$), and sphalerite (ZnS), which are considered primary sources of AMD formation. The formation of AMD is driven by many factors including atmospheric oxygen, water, pH, mine type, surface area, particle size, and bacterial action. AMD is generally comprised of various metals such as Fe, Cu, Al, Ca, Mn, Mg, and Zn and is mainly characterized by low pH, high salinity, heavy metals, metalloids, and sulfate contents. It has a negative impact on water quality, which destroys the structure and functions of soil and makes it more vulnerable to erosion. In addition, nutrients are often immobilized in the soil under acidic conditions, impeding plant growth and microbial functions. AMD treatments are divided into control at source or prevention and mitigation approaches. Prevention focuses on reducing AMD production at its source whereas mitigation approaches include active and passive treatment technologies. Active treatment technologies involve the use of different chemical compounds to neutralize the acid effect by increasing the pH and removing toxic metals from AMD. The active remediation process is fast and more reliable in minimizing metal toxicity but may not be feasible due to the involvement of costly chemicals, the formation of a large volume of mine waste that is difficult to handle, and the release of unwanted chemicals such as NH_3 or NaOH that can cause environmental pollution. Passive treatment technologies comprise natural and biological processes to remediate AMD pollution and can be divided into two approaches: conventional and emerging technologies. The conventional technologies include the use of constructed wetlands, anaerobic sulfate-reducing bioreactors, anoxic limestone drains, vertical flow wetlands, limestone leach beds, open limestone channels, and organic materials. The emerging technologies for AMD remediation include the use of nanotechnology for AMD treatment and PGPR-assisted phytoremediation of AMD-polluted soils.

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Authors' contribution statement

Iftikhar Ahmad, Allah Ditta, and Umar Daraz: Conception and design of this study; Umar Daraz: material collected and wrote the original draft of the paper; Yang Li, Rashid Iqbal, and Allah Ditta: Reviewed the paper and gave valuable suggestions for improvement. Umar Daraz, Iftikhar Ahmad, and Allah Ditta: Reviewed and helped in drawing Figures; All

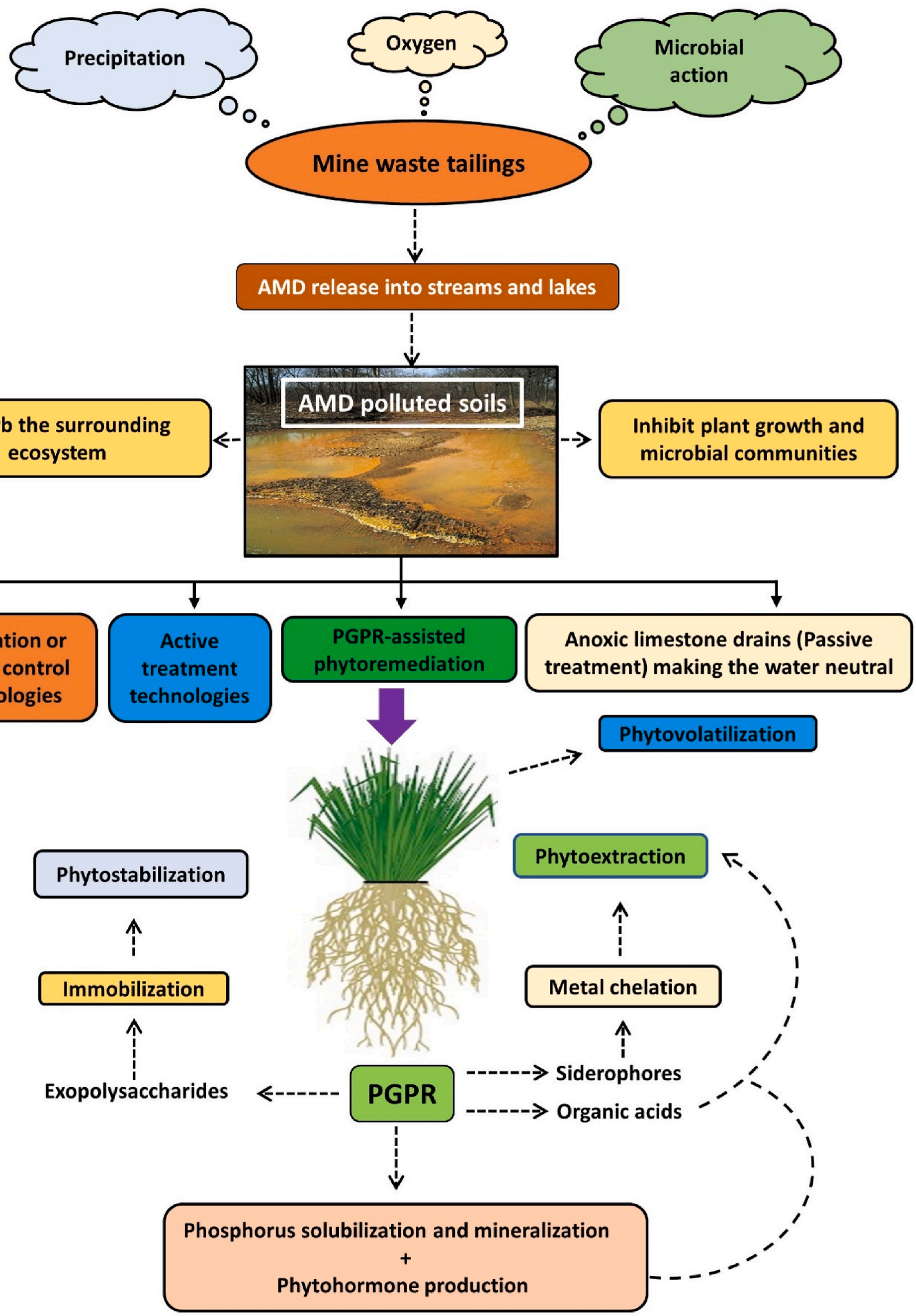

Fig. 6. Summary diagram regarding AMD formation, factors affecting and various approaches employed for the remediation of AMD wastewater.

authors have read and approved the final manuscript.

Compliance with ethical standards

Not applicable.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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