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Uncovering microbial community structures and their roles in abandoned tin-mined pits in Bangka Island

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ABSTRACT

The formation of abandoned tin-mine pits (locally known as *kolong*) is a clear manifestation of ecological destruction caused by tin mining on Bangka Island, Indonesia. In the early stages of their formation, many of these abandoned tin-mined water bodies exhibit poor water quality, characterized by low pH (acidity), high oxidation levels, low nutrient and organic matter content, and potential heavy metal contamination. Similar characteristics are observed in various other mine waters – some of which exhibit extreme acidity resulting from the oxidation of sulfide minerals and metals contamination – a phenomenon known as acid mine drainage (AMD). Over time, the physicochemical properties of these water bodies can undergo significant changes. Although numerous studies have highlighted the presence and role of microbes in post-mining waters and AMD, few have comprehensively explored their existence and contribution in abandoned tin-mined pits. This narrative review aimed to outline the presence of microbes and uncover their potential ecological roles in abandoned tin-mined pits by comparing them with other mine-impacted waters. The review synthesized critical insights regarding bacteria and archaea as the primary microbial groups likely to act as pioneers in abandoned tin-mined pits. Through their biogeochemical activities, these pioneer microbes can drive environmental transformations, gradually rendering the aquatic environment habitable for other organisms during ecological succession. Bacterial phyla – including Pseudomonadota (Proteobacteria), Actinomycetota (Actinobacteria), Chloroflexota (Chloroflexi), Acidobacteriota (Acidobacteria), Bacillota (Firmicutes), Planctomycetota (Planctomycetes), Bacteroidota (Bacteroidetes), and Cyanobacteriota (Cyanobacteria)—alongside archaeal phyla such as Methanobacteriota (Euryarchaeota) and Thermoproteota (Crenarchaeota), play crucial roles in these processes. Currently, specific research exploring the exact biogeochemical functions of these microbial groups in Bangka Island's abandoned tin-mined pits remains scarce. This gap presents a valuable research opportunity to further unveil the ecological roles of these microbes. Furthermore, existing studies highlight the practical implications of microbial presence in post-mining aquatic environments, particularly their potential applications in bioremediation and ecological rehabilitation through microbial ecological engineering. The research can be adopted for implementation in abandoned post-tin-mined pits to accelerate succession and improve environmental quality.

Keywords: abandoned tin-mined pits, ecological role, microbes, succession.

INTRODUCTION

Indonesia has been one of the world's leading tin-producing countries over the past decade, ranking second after China. The country also possesses substantial tin reserves and contributes approximately 24% of global tin production. Bangka and Belitung are the two major tin-producing islands in Bangka Belitung Province, which accounts for the largest share of

Indonesia's tin production. These islands are also located within one of the world's most prominent tin-producing regions (Irzon, 2021a).

The mineralization of tin (Sn) is an important subject of geological research because, although tin resources occur in various parts of the world, major tin deposits are concentrated along a metallogenic province known as the Southeast Asian Tin Belt. This belt extends from Myanmar to Indonesia and is associated with Tertiary granitic rocks that are widely distributed across the region, including the islands of Bangka and Belitung (Figure 1) (Sainsbury, 1969; Asmarhansyah, 2017; Irzon, 2021b). Bangka is the largest island in the Bangka–Belitung region and is part of the Southeast Asian Tin Belt within the Sunda Shelf (Sundaland Craton) (Ng et al., 2017). Ironically, tin mining activities alter the landscape, modify habitats and ecosystems, and cause negative ecological impacts in the surrounding areas. They also significantly affect the socioeconomic conditions of communities living near mining zones.

Open-cast mining, surface mining, open-cut mining, or open-pit mining refers to a tin extraction method that involves excavating mineral-bearing soil and rock to a certain depth. Mining activities cause land degradation and the loss of substantial amounts of vegetation, biodiversity, topsoil, and organic matter. They also reduce soil fertility, as indicated by the high proportion of sand in former tin-mining areas (Asmarhansyah, 2017). Furthermore, mining activities disrupt ecosystems by causing physical, chemical, and biological alterations at various levels. Specifically, open-pit tin mining causes deforestation and transforms the landscape by generating mine tailings. These tailings are characterized by a coarse texture, a high sand content, very low organic matter and nutrient levels, low clay mineral content, low cation exchange capacity, and quartz dominance, all of which contribute to extremely low soil fertility (Nurcholis et al., 2013).

Furthermore, open-pit mining leads to the formation of water-filled voids, which can serve as reservoirs for water used in tin ore washing. These voids vary in length and width, ranging from just a few meters to 300–400 meters, and can reach depths of up to 50 meters (Asmarhansyah, 2017; Sukarman and Gani, 2017). These voids tend to form stagnant or lentic water bodies after tin mining activities are abandoned. They resemble ponds, lakes, or pits and are locally referred to as *kolong* in Bangka (Kurniawan, 2020; Kurniawan et al., 2023a).

The trophic status of abandoned tin-mined waters, based on the trophic status index (TSI), is

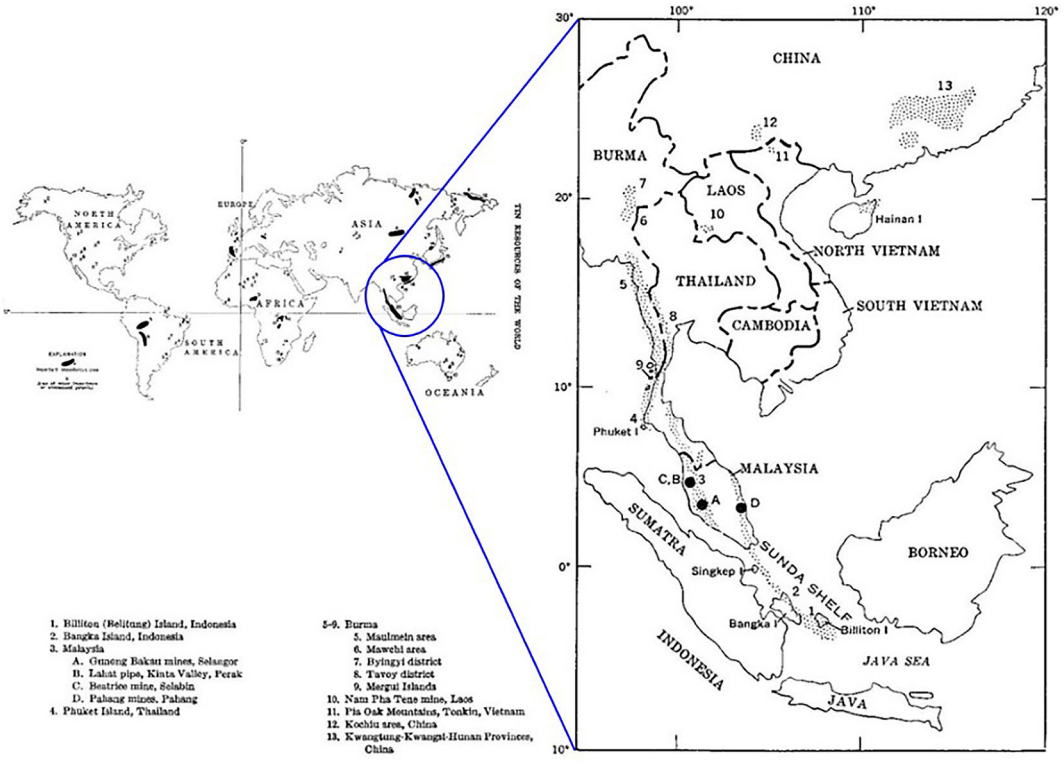

Figure 1. Tin bearing area in the Southeast Asea (Modification of Sainsbury, 1969)

classified as oligotrophic, indicating low nutrient availability and productivity (Juliana et al., 2019). During the early stages of their formation, these waters are characterized by a low pH (acidic conditions), low dissolved oxygen (DO) concentrations, and low chemical oxygen demand (COD) and total suspended solids (TSS) levels. Over time, these water quality characteristics may change, particularly the pH, which may increase toward more favorable conditions (Kurniawan et al., 2020). These waters also contain various metals and heavy metals, including Cr, Cu, Fe, Pb, Mn, Sn, and Zn. However, changes over time, as observed through a chronosequence, do not necessarily lead to reductions in heavy metal concentrations (Ashraf et al., 2012a; Kurniawan et al., 2019).

Mineral–microbe interactions play important roles in biogeochemical cycles and environmental change. Xu et al. (2020) demonstrate that geochemical factors drive changes in microbial communities, which, in turn, influence microbial responses to environmental conditions. These changes in microbial responses can subsequently contribute to environmental changes. Therefore, investigating the correlations and interactions between habitat conditions and microbial responses is important, particularly in abandoned tin-mined waters across different stages of ecological succession.

Recent studies highlight the presence of microorganisms exhibiting unusual activities in mining environments. Over the past few decades, scientists have sought to engineer microbial species for the remediation of contaminated environments, including those characterized by unfavorable pH conditions, nutrient deficiencies, and toxic metal pollution (Hudu et al., 2026). Microorganisms employ various physical and physiological mechanisms to survive in such contaminated environments, including biosorption, enzymatic processes, ion exchange, complexation, precipitation, transportation, sequestering, to detoxification (Sharma et al., 2026).

Acidophilic bacteria and archaea generally play important roles in remediating contaminated environments. These microorganisms act as chemolithotrophs and chemoheterotrophs that thrive under acidic conditions and utilize inorganic compounds as energy sources and contribute to biogeochemical cycling (Esposito et al., 2026). Unfortunately, limited information is available on the complex survival mechanisms of indigenous microbiota in mining environments, particularly in abandoned tin-mined pits. Therefore, this review aims to elucidate changes in the community structure of microorganisms, particularly bacteria, in abandoned tin-mined waters and to analyze their roles in the dynamics of water quality changes.

ABANDONED TIN-MINED PITS AND THE ORGANISMS WITHIN THEM

Locally known as *kolong* in Bangka, Indonesia, these water bodies refer to abandoned mining pits or lake-like depressions formed on land as a result of tin-mining activities (Figure 2). One of the key parameters measured in post-tin-mined water bodies is pH. Several studies report that the pH of abandoned tin-mined waters ranges from 3 to 7 in Bangka, Indonesia (Kurniawan, 2020), 6.89 to 8.16 in Ipoh City, Malaysia (Hashim et al., 2018), and 6.38 to 6.8 in Plateau State, central Nigeria (Mafuyai et al., 2020). Based on pH values, Kurniawan et al. (2023a) classify acidic waters affected by tin-mining activities as a form of acid mine drainage (AMD). This classification



Figure 2. Abandoned tin-mined waters (personal documentations)

is consistent with Ashraf et al. (2012b), who explain that tin-mining activities can expose pyrite (FeS_2) and other sulfide minerals to oxygen and water. This exposure triggers oxidation processes that occur through chemical reactions and can be accelerated by microbial activity, resulting in the formation of acidic water known as AMD.

Nevertheless, Gomes and Favas (2006) emphasize that water bodies in abandoned tin-mined pits are not necessarily classified as AMD. Depending on local geological and environmental conditions, such waters may exhibit acidic characteristics or contain dissolved metals, whereas other post-tin-mined water bodies may remain circumneutral or become neutralized. Several references also indicate that not all abandoned mines generate acidic mine water, as its characteristics depend on the geological conditions of the mining basin, the FeS_2 content of the ore, and water–rock interactions (Cheng et al., 2026). In addition to oxygen-driven chemical oxidation, studies investigate several mechanisms associated with mineral oxidation, electrochemical reactions, microbial activity, and sulfur transformations.

Mustikasari et al. (2020) describe the characteristics of abandoned tin-mined waters in Bangka across a chronosequence. Waters aged 1–5 years have a pH of 3.81–3.84, DO concentrations of 5.33–5.63 mg L^{-1}, Eh values of 0.190–0.198 V, TDS concentrations of 93.98–102.23 mg L^{-1}, and electrical conductivity values of 141.78–153.78 µS cm^{-1}. Waters aged 5–15 years exhibit a pH of 3.86–3.91, DO concentrations of 5.63–5.97 mg L^{-1}, Eh values of 0.160–0.188 V, TDS concentrations of 12.40–21.63 mg L^{-1}, and electrical conductivity values of 19.03–32.83 µS cm^{-1}. Waters aged 15–25 years display a pH of 7.25–7.46, DO concentrations of 6.30–7.07 mg L^{-1}, Eh values of 0.025–0.030 V, TDS concentrations of 91.40–132.00 mg L^{-1}, and electrical conductivity values of 137.10–198.67 µS cm^{-1}. Waters aged 25–50 years have a pH of 7.79, a DO concentration of 7.07 mg L^{-1}, an Eh value of 0.011 V, a TDS concentration of 81.63 mg L^{-1}, and an electrical conductivity value of 122.45 µS cm^{-1}. Waters aged 50–100 years exhibit a pH of 6.88, a DO concentration of 7.20 mg L^{-1}, an Eh value of 0.049 V, a TDS concentration of 38.93 mg L^{-1}, and an electrical conductivity value of 58.40 µS cm^{-1}. Finally, waters aged more than 100 years show a pH of 5.45–5.67, DO concentrations of 6.33–6.43 mg L^{-1}, Eh values of 0.056–0.062 V, TDS concentrations of 18.07–23.67 mg L^{-1}, and electrical conductivity values of 27.50–34.17 µS cm^{-1}.

Recent research shows that abandoned tin-mined waters support a diverse range of organisms, including bacteria, archaea, phytoplankton, and fish. According to Kurniawan (2020), these waters, which exhibit acidic to neutral pH conditions, harbor diverse bacterial phyla, including Pseudomonadota (formerly Proteobacteria; Oren and Garrity, 2021; Kurniawan et al., 2023b), Actinomycetota (formerly Actinobacteria; Mbusi and Lyimo, 2025), Acidobacteriota (formerly Acidobacteria; Dedysh and Yilmaz, 2018), Bacteroidota (formerly Bacteroidetes) and Bacillota (formerly Firmicutes; Oren, 2024), Chloroflexota (formerly Chloroflexi; Wiegand et al., 2023), Cyanobacteriophyta (formerly Cyanobacteria; Aleksovski et al., 2025), Planctomycetota (formerly Planctomycetes; Lage et al., 2025), and Nitrospirae, among others. In addition to bacteria, these waters also harbor diverse archaeal groups, including Methanobacteriota (formerly Euryarchaeota) and Thermoproteota (formerly Crenarchaeota) (Oren, 2024).

Kurniawan et al. (2023c) also identify phytoplankton in abandoned tin-mined waters with pH values ranging from 3.71 to 7.09. These phytoplankton include Chlorophyta (green algae), represented by the class Chlorophyceae (Chlorella, Closterium, and Coelastrum), and Bacillariophyta (diatoms), represented by the class Bacillariophyceae (Synedra). Kurniawan et al. (2020) also report several fish genera in abandoned tin-mined waters, including *Channa*, *Trichogaster*, *Puntius*, *Oreochromis*, *Betta*, *Gambusia*, *Rasbora*, *Anabas*, *Belontia*, *Brevibora*, *Oryzias*, and *Aplocheilus*.

THE ACIDOPHILE MICROORGANISMS IN TIN-MINED PITS

The environmental parameters determine the structure, diversity, and composition of microbial communities in acid mine drainage (AMD), including those in abandoned tin-mined waters. In this study, the microbial community in acid mine drainage is classified as acidophilic. Acidophiles are predominantly prokaryotes, including eubacteria and archaea. However, eukaryotic microorganisms, such as algae, protozoa, fungi, and fungi-like protists, are also found in these environments. These microorganisms thrive under acidic conditions, with optimal growth

generally occurring at pH values below 7.0 (Lund et al., 2020).

Although any organism that thrives at low pH can technically be considered an acidophile, many neutrophiles, which typically prefer pH values near 7.0, can also grow at pH 6.0 or below. For practical classification, acidophiles are generally defined as microorganisms with optimal growth at pH values below 5.0. They can be further classified into moderate acidophiles, which exhibit optimal growth at pH 3.0–5.0 (Benison et al., 2021); extreme acidophiles, which thrive at pH values below 3.0; and hyperacidophiles, which exhibit optimal growth at pH values below 1.0 (Johnson and Quatrini, 2020).

Kurniawan et al. (2019) reported that abandoned tin-mined ponds aged less than one year to 5–10 years had pH values ranging from 2.72 to 3.07. According to Ianutsevich et al. (2023), extremely acidic habitats are characterized by pH values below 3.0. These findings suggest that abandoned tin-mined waters can provide suitable habitats for moderate and extreme acidophiles. However, Kurniawan et al. (2023c) also reported that pH values in abandoned tin-mined waters range from 3.71 to 7.09, indicating that these waters may also support acid-tolerant neutrophiles. In addition to prokaryotes, including bacteria and archaea, these habitats also support eukaryotic organisms.

The presence of an acidophilic microbial community in abandoned tin-mined pits contributes to ecological changes. The productivity of this environment is driven by chemolithotrophic prokaryotes. These chemolithotrophic prokaryotes, primarily bacteria and archaea, oxidize inorganic compounds, such as iron, sulfur, and ammonia, to obtain energy for growth and maintenance (Kazemi et al., 2021). Their activities may be supported by phototrophic prokaryotes, which act as primary producers. Microorganisms in metal mine waste contribute to energy production through two pathways: phototrophy and chemotrophy.

Phototrophic microorganisms, or phototrophs, use light as an energy source to support their metabolism. They are broadly classified into oxygenic and anoxygenic phototrophs. Although microalgae and some bacteria inhabit pollutant-contaminated environments, they can still use sunlight as an energy source and water (H_2O) as an electron donor, releasing molecular oxygen (O_2) as a by-product of photosynthesis. These microorganisms are classified as oxygenic phototrophs. In contrast, other bacteria and archaea perform anoxygenic photosynthesis, using sunlight as an energy source and compounds such as H_2S, elemental sulfur (S^0), H_2, Fe(II), or, in certain metabolic pathways, nitrite (NO_2^-) as electron donors (Newsome and Falagán, 2021).

One representation of anoxygenic photosynthesis involving hydrogen sulfide as an electron donor is expressed by the following equation (Kurniawan, 2020):

$$12H_2S + 6CO_2 \rightarrow C_6H_{12}O_6 + 6H_2O + 12S^0 \quad (1)$$

Among phototrophic microorganisms, bacteria include both oxygenic and anoxygenic phototrophs. Cyanobacteria (phylum Cyanobacteriota; formerly classified as Cyanobacteria) are the predominant group of oxygenic photosynthetic bacteria, whereas anoxygenic photosynthesis occurs in several bacterial groups, particularly green sulfur bacteria and purple sulfur bacteria (Kushkevych et al., 2024; Aleksovski et al., 2025).

Microorganisms also play an important role as chemotrophs. They obtain energy by oxidizing chemical compounds and require carbon for growth and metabolism. Based on their carbon sources and electron donors, chemotrophs are classified into two groups: chemoautotrophs and chemoheterotrophs. Chemoautotrophs (chemolithoautotrophs) use inorganic compounds, such as hydrogen, sulfur, and iron, as electron donors and obtain carbon primarily from carbon dioxide. In contrast, chemoheterotrophs use organic compounds as sources of carbon and electron donors to produce energy for their metabolism (Méndez-García et al., 2015; Newsome and Falagán, 2021).

The characteristics of acid mine drainage can improve, triggering environmental changes that may lead to a shift in microbial populations from chemoautotrophs to chemoheterotrophs (Singh and Chakraborty, 2023). Kurniawan (2020) identifies diverse bacterial phyla in abandoned tin-mined waters with acidic to neutral pH, including Pseudomonadota, Actinomycetota, Planctomycetota, Bacteroidota, and Bacillota, as well as archaeal phyla such as Methanobacteriota and Crenarchaeota.

Pseudomonadota (formerly known as Proteobacteria) is one of the largest and most diverse bacterial phyla, and its members are exclusively Gram-negative. Members of this phylum play important roles in post-mining water systems, particularly in biogeochemical cycling, heavy metal bioremediation, and microbial community stabilization. Because mining environments are often oligotrophic and enriched with toxic metals

(del Pilar Rada Martinez et al., 2026), the metabolic versatility of Pseudomonadota contributes to their potential to act as microbial pioneers in these ecosystems.

In addition to Proteobacteria, the phyla Actinomycetota, Acidobacteriota, Bacteroidota, Planctomycetota, and Bacillota are commonly detected through metagenomic analyses of extreme environments, including acid mine drainage and post-mining pits. Actinomycetota comprises Gram-positive bacteria known for their ability to degrade complex organic compounds, tolerate heavy metal contamination, and survive in acidic environments (Alvarez et al., 2017). Acidobacteriota is one of the most abundant and globally widespread bacterial phyla in soils, exhibiting considerable ecological adaptability to low-pH environments and nutrient-poor (oligotrophic) conditions (Greening et al., 2015). Bacteroidota plays an important ecological role in degrading complex macromolecules, such as carbohydrates and proteins, in aquatic sediments, thereby contributing to global nutrient cycling (Kirchman, 2002). Bacillota exhibits remarkable adaptive capabilities through endospore formation, which enables its members to survive prolonged periods of unfavorable environmental conditions that are lethal to many other microorganisms (Galperin et al., 2016). Planctomycetota also contributes to the functioning of mining-impacted aquatic ecosystems and the treatment of metallurgical wastewater, particularly through nitrogen removal via anaerobic ammonium oxidation (anammox) (Kündgen et al., 2025).

METALS-DEPENDENT OXIDATION AND REDUCTION

Mining activities generate mine-impacted water bodies (MIWs), including those affected by acid mine drainage (AMD). Acid mine drainage is a type of wastewater generated by the exposure and weathering of mineral-bearing materials at mining sites, particularly abandoned mines (Méndez-García et al., 2015). Acid mine drainage also occurs in abandoned tin-mined pits (Syukur et al., 2023). According to Kurniawan (2020), heavy metals are present in abandoned tin-mined pits. Other elements, such as phosphorus (P) and sulfur (S), are also analyzed in abandoned tin-mined environments (Kurniawan et al., 2018). Environments contaminated with heavy metals pose a threat to ecosystems, including aquatic ecosystems.

One of the main characteristics of post-mining sites is low pH, which results in acidic environmental conditions. Several sulfide minerals associated with AMD are classified as potentially acid-forming (PAF) materials. These minerals include chalcopyrite ($CuFeS_2$), pyrite (FeS_2), galena (PbS), and sphalerite ((Zn,Fe)S), which contribute to the development of acidic conditions in aquatic environments (Ngerem et al., 2026).

AMD poses a serious threat to ecosystems because of its low pH, high acidity, and elevated concentrations of various heavy metals. AMD develops through physical, chemical, and biological oxidation processes. These processes are driven primarily by the exposure of sulfide minerals to water and oxygen, as well as by microbial activity, resulting in the formation of sulfuric acid, dissolved metal ions, and sulfate (Naidu et al., 2019). Consequently, AMD-affected waters exhibit high acidity and elevated concentrations of heavy metals, sulfate, and metalloids.

Kurniawan (2017) revealed that abandoned tin-mined waters undergo temporal changes in water characteristics chronosequencetly. A significant pH shift was observed, rising from 1.7 to 4.7. According to Mustikasari et al., (2020), abandoned tin-mined waters exhibited pH shifts reaching 7.79. Figure 3 illustrates that abandoned tin-mined waters initially exhibit low and acidic pH levels. However, over time, chronosequence effects during succession processes lead to increased pH values, eventually reaching neutral levels. The waters of newly formed post-tin mining lakes exhibited acidic properties resulting from sulfide minerals and metal oxidation or potentially acid-forming (PAF). We provided conceptual models of the oxidation process involved physical and chemical reaction and also biological reactions catalyzed by microorganisms secreting oxidizing enzymes, including iron and sulphur oxidases as illustrated as in Figure 4.

In these acidic waters, acidophilic microbial communities dominated by iron-oxidizing and sulfur-oxidizing microorganisms are predominantly found. These communities include both bacteria and archaea, as well as eukaryotic microorganisms, such as fungi and algae (Méndez-García et al., 2015). According to Kurniawan (2020), several bacterial phyla, including Proteobacteria, Actinobacteria, Chloroflexi, Firmicutes, and Acidobacteria, as well as the archaeal phylum

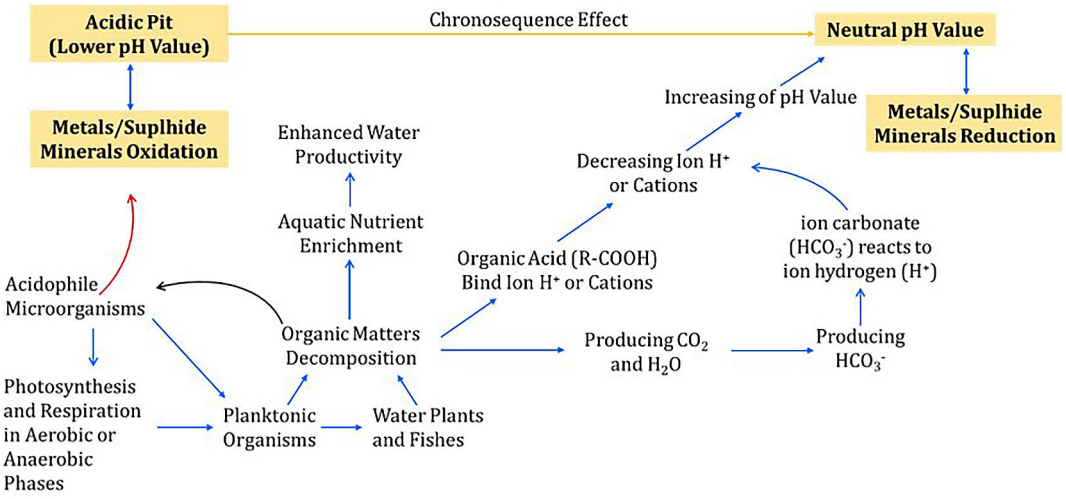

Figure 3. The pathway schematic of pH alteration in abandoned tin-mined water from acidic value to neutral value as chronosequence effect of succession

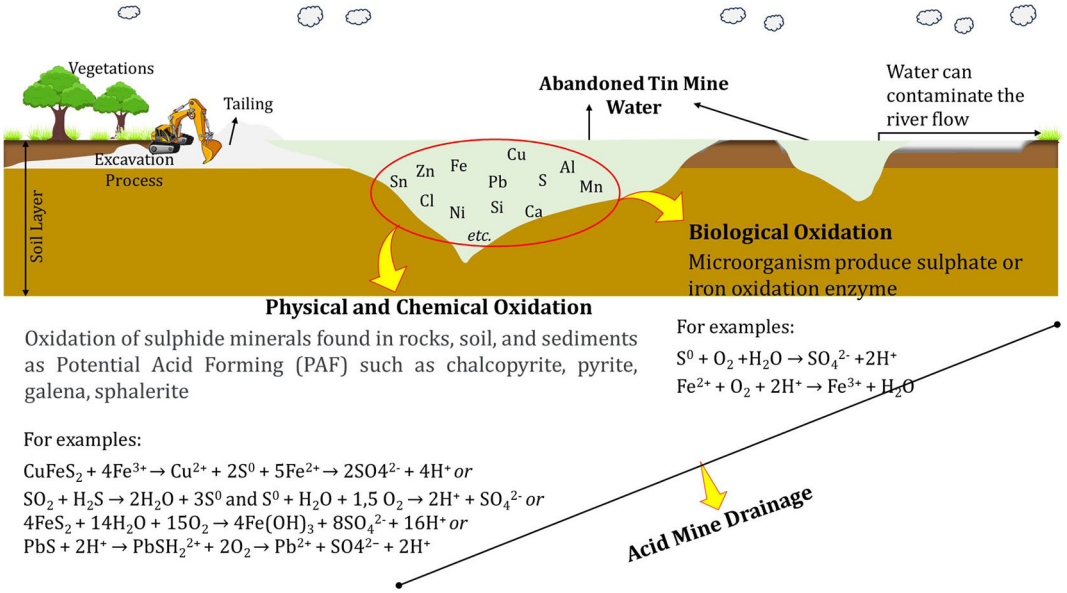

Figure 4. Illustration of oxidation process in abandoned tin-mined pit as acid mine drainage

Euryarchaeota, contribute to the formation of acidic conditions through oxidation processes.

As shown in Figure 4, these microbial groups contribute to the formation and maintenance of acidic conditions in abandoned tin-mined waters. Over time, microbial succession occurs in these waters, accompanied by changes in community composition and ecosystem development. The presence of phytoplankton, such as *Chlorella*, *Closterium*, *Coelastrum*, and *Synedra* (Kurniawan et al., 2023c), together with zooplankton, supports the development of higher trophic levels, including fish, macrozoobenthos, and aquatic plants. These organisms contribute to the accumulation of organic matter in the aquatic environment. Microbially mediated decomposition of organic matter enhances nutrient availability and nutrient cycling, thereby potentially increasing water fertility and aquatic ecosystem productivity. The phylum Bacteroidetes plays an important role in organic matter decomposition in these aquatic environments, while Proteobacteria also contribute to this process through complementary metabolic activities. Bacteroidetes and Proteobacteria contribute to the breakdown of complex organic matter into smaller molecular compounds (Song et al., 2024).

Furthermore, organic matter is decomposed into short-chain organic acids. Rukshana et al. (2011) report that organic acids contain functional

groups, including the carboxyl group (–COOH). Organic acids may contribute to changes in soil pH through their carboxyl groups, which can interact with hydrogen ions (H^+), potentially reducing their concentration and thereby increasing pH over time. Kumaresan et al. (2024) explain that organic matter decomposition also produces carbon dioxide (CO_2) and water (H_2O). Furthermore, Loerting and Bernard (2010) explain that CO_2 reacts with H_2O to form carbonic acid (H_2CO_3), which subsequently dissociates to produce bicarbonate ions (HCO_3^-) and hydrogen ions (H^+), as shown in the following equation:

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons HCO_3^- + H^+ \qquad (2)$$

Ashour et al. (2024) report that photosynthetic microorganisms utilize HCO_3^- to support photosynthesis, which may contribute to an increase in the pH of aquatic environments. These mechanisms are relevant to abandoned tin-mined waters, where increased organic matter availability may be associated with the presence of organic matter-degrading bacteria, including members of the phyla Bacteroidota and Pseudomonadota (formerly Bacteroidetes and Proteobacteria, respectively).

The chronosequence of ecological succession, driven in part by the decomposition of organic matter by Bacteroidota and Pseudomonadota, contributes to pH neutralization. Neutral pH conditions are associated with higher dissolved oxygen availability than acidic conditions. The presence of dissolved oxygen supports aquatic organisms, including photosynthetic microorganisms that thrive under these conditions. During photosynthesis, these microorganisms produce oxygen through the conversion of CO_2 and H_2O into organic matter and O_2 (Mustikasari et al., 2020). Meanwhile, organic matter decomposition releases CO_2 and produces H_2O and other dissolved or particulate organic compounds. The CO_2 and H_2O can subsequently be reused during photosynthesis, generating O_2 and supporting aquatic life.

Changes in pH toward neutral conditions are accompanied by shifts in bacterial community structure. Under neutral pH conditions, Planctomycetes and Cyanobacteria may contribute to ecosystem processes associated with dissolved oxygen dynamics. Higher abundances of Cyanobacteria and Planctomycetes are associated with elevated dissolved oxygen concentrations and neutral pH conditions (Rojas-Jimenez et al., 2021). Acidic conditions, however, can inhibit the growth of microorganisms adapted to neutral pH, whereas neutralization favors the establishment of microbial communities that tolerate or thrive at near-neutral pH. In abandoned tin-mined waters, neutralization is associated with microbial succession and the occurrence of phyla such as Caldiserica, Chladithrix, Lentisphaerae, and Fibrobacter, which are reported exclusively in neutral-pH waters (Kurniawan, 2020).

AMMONIUM-DEPENDENT OXIDATION

The nitrogen cycle is one of the most complex biogeochemical cycles in the environment (Thamdrup, 2012). Nitrogen (N) is an essential nutrient in aquatic ecosystems and plays a crucial role in primary productivity. Acid mine drainage, including that found in abandoned tin-mined pits, is characterized by acidic conditions associated with the oxidation of iron-bearing sulfide minerals and the release of metals, including heavy metals (Kurniawan, 2020). These environmental conditions can influence nitrogen transformations under both aerobic and anaerobic conditions. Under anaerobic conditions, nitrogen transformations can involve the oxidation of ammonium coupled with nitrite reduction (anaerobic ammonium oxidation, or anammox), sulfate reduction (sulfammox), and ferric iron reduction (feammox) (Srivastava et al., 2024).

Ammonium oxidation plays an important role in the biogeochemical nitrogen cycle. Ammonium is produced through the decomposition of nitrogen-containing organic matter and is also associated with the metabolic activities of aquatic organisms in both the water column and sediments (Wan et al., 2022). Some microorganisms mediate anaerobic ammonium oxidation (anammox) in heavy-metal-contaminated waters. Thamdrup (2012) describes emerging pathways and processes that contribute to the global nitrogen cycle. Nitrogen transformations involve oxidation–reduction (redox) reactions, with oxidation processes generally associated with aerobic conditions and reduction processes commonly occurring under anaerobic conditions, although some pathways depend on specific electron acceptors and environmental conditions. The major processes in the nitrogen cycle include nitrogen assimilation, ammonium oxidation, nitrite oxidation, denitrification, nitrogen fixation, dissimilatory nitrate reduction to ammonium (DNRA), and anaerobic ammonium oxidation (anammox) (Figure 5).

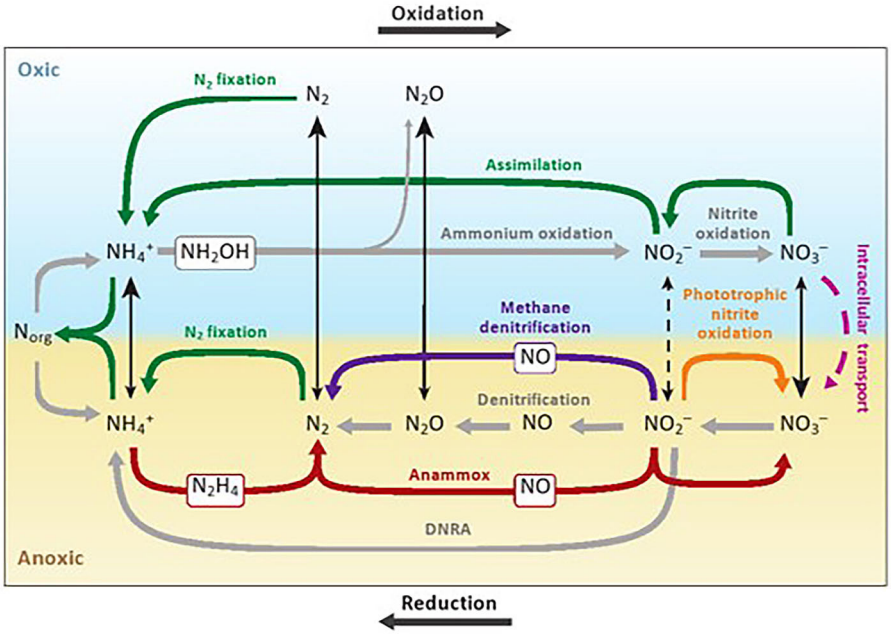

Figure 5. Schematic representation of the nitrogen cycle (Thamdrup, 2012)

Anammox bacteria are primarily associated with the phylum *Planctomycetota* (Srivastava et al., 2024), although members of other bacterial phyla, including *Proteobacteria*, *Nitrospirae*, *Chloroflexi*, *Chlorobi*, *Bacteroidetes*, and *Acidobacteria*, are also reported in anammox-associated microbial communities (Ponce-Jahen et al., 2024).

According to Tal et al. (2005), anammox bacteria lack peptidoglycan in their cell walls. These bacteria carry out the anammox process within a specialized intracellular compartment called the anammoxosome. During this process, ammonium is oxidized with nitrite as the electron acceptor, producing dinitrogen gas (N_2) through intermediates that include hydrazine (N_2H_4) and hydroxylamine (NH_2OH). Furthermore, the transformation of nitrogen compounds, including ammonia, ammonium, nitrate, and organic nitrogen, as an essential component of the nitrogen cycle. Together with nitrite, these compounds participate in interconnected nitrogen transformation pathways, including nitrification, denitrification, and anammox, which contribute to nitrogen cycling and, under appropriate conditions, the production of dinitrogen gas.

Within the nitrogen cycle, ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) oxidize ammonium (NH_4^+) to nitrite (NO_2^-) during the first stage of nitrification. Subsequently, nitrite-oxidizing bacteria (NOB) oxidize nitrite (NO_2^-) to nitrate (NO_3^-) (Zhu et al., 2022a).

In contrast, anaerobic ammonium oxidation (anammox) involves the conversion of ammonium and nitrite into dinitrogen gas (N_2) under anoxic conditions. Wu et al. (2019) describe a partial-nitrification–anammox process in which partial nitrification supplies nitrite for subsequent ammonium oxidation by anammox bacteria. The two processes can be represented by the following simplified equations: (a) partial nitrification:

$$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O \quad (3)$$

and (b) anammox:

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2H_2O \quad (4)$$

In addition, Srivastava et al. (2024) report that anaerobic ammonium-oxidizing (anammox) bacteria use NO_2^- as an electron acceptor to oxidize NH_4^+, producing N_2 gas. The overall reaction is represented by the following equation:

$$NH_4^+ + NO_2^- + HCO_3^- + H^+ \rightarrow N_2 + NO_3^- + CH_2O + N + H_2O \quad (5)$$

Meanwhile, Jetten et al. (1998) describe the reaction using the simplified equation:

$$NH_4^+ + NO_2^- \rightarrow N_2 + H_2O \quad (6)$$

These processes differ from conventional nitrification, in which two distinct functional groups of microorganisms oxidize ammonium to nitrite and subsequently oxidize nitrite to nitrate.

Overall, nitrification and anammox are distinct microbial processes involved in nitrogen transformation. Nitrification is an aerobic process mediated by ammonia-oxidizing bacteria (AOB) or archaea (AOA) and nitrite-oxidizing bacteria (NOB), which sequentially oxidize ammonium to nitrite and nitrite to nitrate. In contrast, anammox is an anaerobic process in which specialized bacteria oxidize ammonium using nitrite as an electron acceptor, primarily producing dinitrogen gas (N_2) (Koch et al., 2019).

Instead of using NO_2^-, anammox can use sulfate (SO_4^{2-}) as an electron acceptor for the oxidation of NH_4^+ under anaerobic conditions. This process is known as sulfammox and is also referred to as sulfate-dependent anaerobic ammonium oxidation (SRAO) (Srivastava et al., 2024). The sulfammox process converts SO_4^{2-} and NH_4^+ into elemental sulfur (S^0), N_2, and H_2O under anaerobic conditions, as described by the following equation:

$$NH_4^+ + SO_4^{2-} \rightarrow N_2 + HS^- + H_2O + H^+ \text{ or}$$
$$NH_4^+ + SO_4^{2-} \rightarrow NO_3^- + HS^- + H_2O + H^+ \text{ (Zhang et al., 2009).} \quad (7)$$

In addition, ammonium can be oxidized to N_2, NO_2^-, or NO_3^- through a process known as Fe(III)-reduction-coupled ammonium oxidation, or Feammox. In this process, ferric iron (Fe(III)) acts as an electron acceptor and is reduced to ferrous iron (Fe(II)) under anaerobic conditions. Fe(III) can serve as an alternative electron acceptor to oxygen because both participate in redox reactions (Wan et al., 2022). Feammox proceeds through the following equations:

$$Fe(OH)_3 + H^+ + NH_4^+ \rightarrow Fe^{2+} + H_2O + N_2 \quad (8)$$

$$Fe(OH)_3 + H^+ + NH_4^+ \rightarrow Fe^{2+} + H_2O + NO_2^- \quad (9)$$

$$Fe(OH)_3 + H^+ + NH_4^+ \rightarrow Fe^{2+} + H_2O + NO_3^- \quad (10)$$

depending on the nitrogen end product: N_2, NO_2^-, or NO_3^- (Zhu et al., 2022b).

Acid mine drainage, including water in abandoned tin-mined pits, exhibits low dissolved oxygen concentrations (Kurniawan et al., 2019). Under these conditions, another biogeochemical process that may occur is complete ammonia oxidation (comammox). Unlike conventional nitrification, which involves two sequential processes—nitritation and nitratation—carried out by two distinct functional groups of microorganisms, comammox microorganisms oxidize ammonia to nitrate within a single cell. Bacteria of the genus *Nitrospira* (phylum *Nitrospirota*) are capable of complete ammonia oxidation, converting ammonium (NH_4^+) to nitrate (NO_3^-) (Costa et al., 2006). Comammox microorganisms employ several enzymes, including ammonia monooxygenase, hydroxylamine dehydrogenase, and nitrite oxidoreductase, to facilitate this oxidation process (Zhu et al., 2022a). Accordingly, Wu et al. (2019) report that *Nitrospira* includes comammox bacteria capable of carrying out the entire conversion of ammonium to nitrate independently within a single cell.

Furthermore, some microorganisms use nitrate as an electron acceptor during respiration and reduce nitrate (NO_3^-) to nitrogen gas (N_2). LaSarre et al. (2024) explain that anaerobic respiration involves the sequential reduction of nitrate (NO_3^-) to nitrite (NO_2^-), nitric oxide (NO), and nitrous oxide (N_2O), ultimately producing dinitrogen gas (N_2) as the end product. Sivalingam et al. (2020) describe the process as follows: $NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$ (nitrification), followed by $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ (denitrification).

Finally, dinitrogen gas (N_2) is produced as the end product of anaerobic ammonium oxidation (anammox). Nitrogen is converted into N_2 through several pathways, including ammonification followed by nitrification and denitrification, which involve different microbial groups, as well as complete ammonia oxidation (comammox), which is carried out by a single microorganism. In the anammox process, ammonium (NH_4^+) is converted into N_2 under anaerobic conditions, playing an important role in the nitrogen cycle (Liu et al., 2021). The anammox pathway and its role in producing N_2 from NH_4^+ are illustrated in Figure 6.

In principle, nitrification is a crucial process in biogeochemical nitrogen cycling. It consists of two sequential steps: ammonia oxidation and nitrite oxidation. Ammonia-oxidizing bacteria (AOB) and ammonia-oxidizing archaea (AOA) are involved in ammonia oxidation, whereas nitrite-oxidizing bacteria (NOB) are responsible for nitrite oxidation. Interestingly, complete ammonia oxidation (comammox) microorganisms can carry out the entire nitrification process within individual cells.

The group comprising Chloroflexi (Chloroflexota), Planctomycetes (Planctomycetota), Actinobacteria (Actinomycetota), Bacteroidetes (Bacteroidota), Firmicutes (Bacillota), and

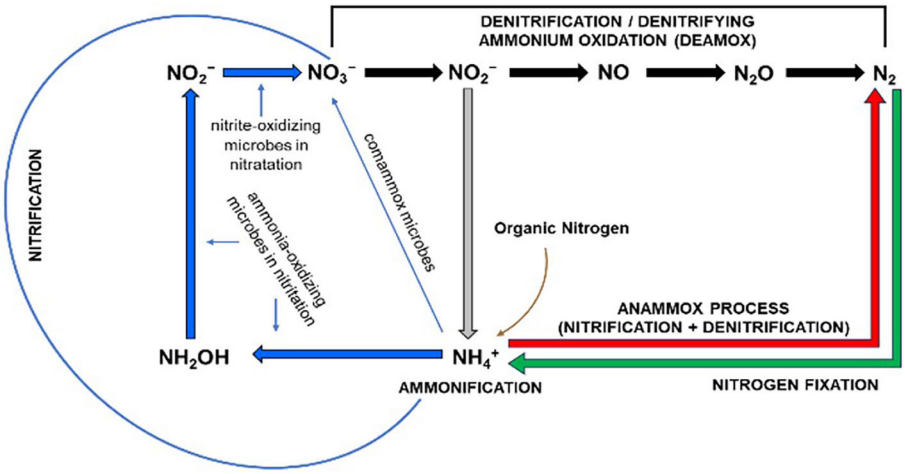

Figure 6. Illustration process in nitrogen cycle of anammox in producing N_2 from NH_4^+ (modified from Alvarez et al., 2014; Sivalingam et al., 2020)

Acidobacteria (Acidobacteriota) (Borowska et al., 2024), along with archaeal phyla such as Euryarchaeota and Crenarchaeota, occurs in abandoned tin-mined waters (Kurniawan, 2020), potentially, can play an important role in biogeochemical nitrogen cycle.

After nitrification, which occurs either in two steps mediated by ammonia-oxidizing and nitrite-oxidizing microorganisms or through complete ammonia oxidation (comammox), nitrate (NO_3^-) is converted into nitrogen gas (N_2) through denitrification or denitrifying ammonium oxidation (deamox). Denitrification involves microorganisms such as *Thiobacillus*, *Alcaligenes*, *Thauera*, *Acinetobacter*, and *Zobellella* belonging to the phylum Proteobacteria (Pseudomonadota); *Bacillus*, *Trichococcus*, *Enterococcus*, *Paenibacillus*, and *Staphylococcus* belonging to the phylum Firmicutes (Bacillota); and *Chryseobacterium* belonging to the phylum Bacteroidetes (Bacteroidota). These microorganisms may cooperate with anammox bacteria in nitrogen removal processes (Yue et al., 2024). The anammox process also produces nitrogen gas (N_2), which returns to the atmosphere and can subsequently be converted into ammonium (NH_4^+) through biological nitrogen fixation (BNF) by nitrogenase enzyme. Nitrogen-fixing microorganisms occur in several bacterial phyla, including Bacteroidetes (Bacteroidota), Proteobacteria (Pseudomonadota), Firmicutes (Bacillota), Actinobacteria (Actinomycetota), Acidobacteria (Acidobacteriota), and Chloroflexi (Chloroflexota), as well as in the domain Archaea (Li et al., 2022).

Phosphorus, alongside nitrogen, serves as a key indicator of aquatic water quality and plays a crucial role in primary productivity. According to Kurniawan et al. (2018), phosphorus concentrations increase with water age in abandoned tin-mined ponds, indicating enhanced aquatic fertility during ecological succession. Several bacterial species are reported in these environments, including *Kurthia* spp., *Micrococcus* sp., *Nitrobacter* spp., *Veillonella* sp., *Actinobacillus equuli*, *Bacillus amyloliquefaciens*, *Moraxella bovis*, *Enterobacter gergoviae*, *E. aerogenes*, and *E. agglomerans*. Tian et al. (2021) explain that phosphate-solubilizing microorganisms (PSMs) increase phosphorus bioavailability in the environment through desorption, dissolution, solubilization, and mineralization (Figure 7).

Management abandoned tin-mined water quality is a critical issue that needs to be addressed. Ecological restoration of abandoned tin-mined waters enhances water quality and supports long-term sustainability (Figure 8).

Water quality management in abandoned tin-mined pits (kolong) represents a critical environmental challenge because post-mining residues and exposed minerals naturally undergo oxidation, which leads to severe water acidification and ecological degradation. To address this challenge, the conceptual framework illustrates a transitional pathway toward ecosystem recovery that is driven by two key factors: human-led anthropogenic interventions, such as active bioremediation, shoreline revegetation, and neutralizer application, and the natural chronosequence effect, which reflects the gradual progression of ecological succession over time. Together, these factors stimulate essential biogeochemical processes within the water column and sediments, systematically neutralize

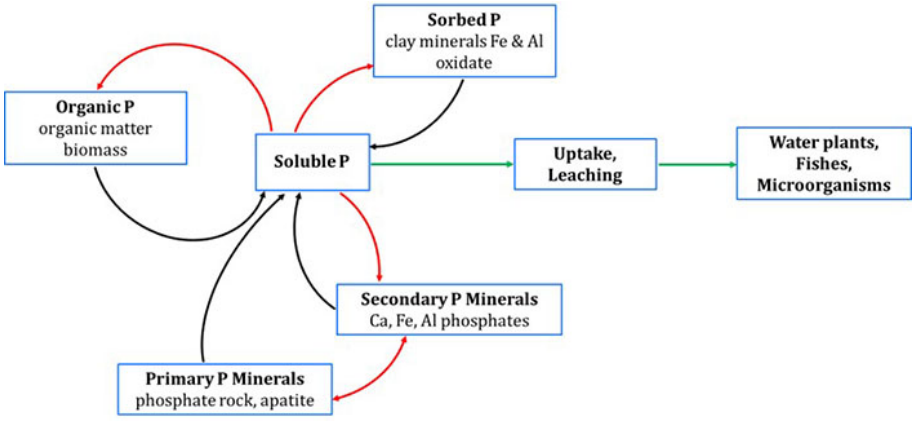

Figure 7. Schematic diagram of phosphorus (P) biogeochemical cycles in abandoned tin-mined water. The red arrows indicated cycle of P geochemical, the black arrows indicated PSM-induced P cycles, and the green arrows indicated P flows to aquatic organisms (modified from Tian et al., 2021)

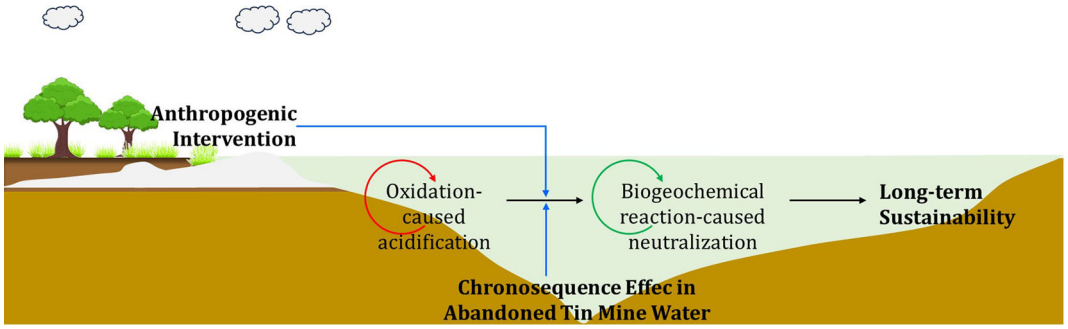

Figure 8. Sustainable water quality management in abandoned tin-mined water

acidity, reduce the mobility of toxic metals, and restore natural biological functions. These interconnected processes ultimately improve overall water quality and transform degraded post-mining pit lakes into stable and resilient aquatic ecosystems that support long-term sustainability and safe socio-ecological reuse.

CONCLUSIONS

This review highlights the diversity of microbial communities, particularly bacteria and archaea, reported in abandoned tin-mined waters and other mining-impacted aquatic environments. The reviewed literature indicates that these environments undergo physicochemical changes over time, including variations in pH, dissolved oxygen, nutrient availability, and metal concentrations. These changes are associated with shifts in microbial community composition and the progression of ecological succession. However, the presence of particular microbial taxa alone does not establish their specific ecological functions or demonstrate that they contribute directly to improvements in water quality.

Several bacterial phyla, including Pseudomonadota, Actinomycetota, Chloroflexota, Acidobacteriota, Bacillota, Planctomycetota, Bacteroidota, and Cyanobacteriota, as well as archaeal groups such as Methanobacteriota and Thermoproteota, have been reported in abandoned tin-mined waters or related mining environments. Previous studies have documented diverse microbial processes associated with iron and sulfur oxidation, nitrogen transformation, organic matter decomposition, and metal interactions in mining-impacted environments. Nevertheless, the specific contributions of these microbial groups to biogeochemical cycling in Bangka Island's abandoned tin-mined pits remain insufficiently characterized. Therefore, taxonomic detection should be complemented by functional analyses to establish the metabolic capabilities and ecological contributions of indigenous microorganisms.

The reviewed literature also indicates that microbial processes may have potential applications in bioremediation and ecological rehabilitation. However, the detection of potentially functional microorganisms does not, by itself, demonstrate effective contaminant removal, metal

immobilization, or successful ecosystem restoration. Further research should integrate microbial community profiling with functional gene analyses, measurements of microbial activity, and assessments of relevant physicochemical parameters, including metal concentrations and their chemical forms. Longitudinal studies across different stages of abandoned tin-mined pit development are also needed to clarify relationships between microbial succession, biogeochemical processes, and changes in water quality. Such evidence would provide a stronger scientific basis for evaluating microbial-based management strategies and developing effective, site-specific approaches to the ecological rehabilitation of abandoned tin-mined waters.

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