The life of *Aplocheilus panchax* in abandoned post-tin mining waters: A review

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Abstract. Bangka Belitung Islands Province is the second-largest tin producer in the world. Tin (Sn) has been exploited for hundreds of years. In the region, tin was exploited by an open-pit mining system that created an artificial lake or pit called "kolong". The characteristics of some pits are acidic water, low dissolved oxygen, low organic matter content, and heavy metal contamination. This review aimed to elaborate on the life of *Aplocheilus panchax* in abandoned post-tin mining water for future management strategies. *A. panchax* was found in abandoned post-tin mining pits with low water quality. *A. panchax* is a pioneer species in abandoned post-tin mining pits. The presence of *A. panchax* in this habitat can contribute to environmental health and the management of water quality. The conservation status of *A. panchax* is "least concern" (LS).

Key Words: abandoned waters, *Aplocheilus panchax*, Bangka Belitung, biological life, tin mining.

Introduction. The Bangka Belitung Islands Province is the biggest tin producer in Indonesia and one of the largest tin producers in the world (Meyana et al 2015; Haryadi et al 2022). Tin mining activities in Bangka Belitung Islands formed puddles and pit lakes called "kolong". One of the problems that can be generated by tin mining activity is the acidic water in the abandoned tin mining lakes. The acidic condition of water is influenced by hydrogen (H^+) ions (LeBaron & Sharpe 2022). Furthermore, the presence of sulfide minerals and metals, such as Fe, Pb, Mn, Cu, Al, S, etc., that are exposed and oxidized can produce acidic waters with a low pH value, namely acid mine drainage (AMD) (Nurcholis et al 2013; Kurniawan et al 2019; Kurniawan et al 2023).

AMD problems in abandoned mines have become a global environmental concern (Wang et al 2021). The main characteristics of this water are high acidity, high concentration of sulfate, and heavy metal ions, such as Cu^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+}, and Pb^{2+} (McCauley et al 2009; Liao et al 2017; Esmaeili et al 2019). AMD is formed by the oxidation process of sulfide minerals that are exposed to water and air during mining activity (Skuosen et al 2000), and by biogeochemical processes of minerals potentially acid forming (PAF), such as sphalerite, galena, chalcopyrite, bornite, molybdenite, arsenopyrite, enargite, and pyrites (Abraitis et al 2004; Hakkou et al 2008; Dold 2014; Pozo-Antonio et al 2014).

Some treatments have been done to neutralize the acidic condition of AMD, such as utilizing several kinds of lime, namely agricultural lime $CaCO_3$, calcined lime CaO, wall lime $Ca(OH)_2$, dolomite $CaMg(CO_3)_2$, and silica lime ($CaSiO_3$) (Utami et al 2020). AMD contains some toxic metals, particularly Mn, Fe, Cu, Zn, As, Cd, Pb, Al, and others (Kurniawan 2020), that can be treated with the addition of neutralizing agents such as slaked and quick limes that form hydroxides, carbonates, surface complexation, and/or coprecipitation with ferrihydrite ($Fe(OH)_3$), gibbsite ($Al(OH)_3$), calcium carbonate ($CaCO_3$) (Fuchida et al 2020; Nguyen et al 2022).

Apart from the problems of dealing with low pH values and heavy metals, the life of organisms in AMD waters should not be ignored. Some organisms can live in this conditions, including acidophilic and acidotolerant eukaryotic microorganisms, which are mostly composed by algae (diatoms and unicellular and filamentous algae), protozoa, fungi, fungi-like protists, unsegmented pseudocoelomata such as Rotifera, micro/macro-invertebrates (Luís et al 2022), such as *Nematalosa erebi*, *Neosilurus ater*, (Jeffree et al 2014), *Pethia conchonius*, *Ailia coilia*, *Clupisoma garua*, *Garo khajuriai*, *Sisor rhabdophorus*, *Salmostoma bacaila*, *Nandus nandus*, *Xenentodon cancila*, *Monopteus cuchia*, and others (Mallik et al 2015).

However, there are not many research publications that reveal the existence of organisms and their lives in the abandoned post-tin mining waters. Knowledge of the organisms and their lives is important as a basic concept for assessing the potential of the waters, water quality management, treatment systems, and the utilization of these waters for aquaculture. Therefore, the main objective of this review was to summarize the scientific literature related to AMD, focusing on abandoned post-tin mining waters and *Aplocheilus panchax*.

Abandoned Post-tin Mining Water Overview. AMD refers to the effluent generated from active as well as abandoned mines. The rocks and land that contain ferrous or ferric sulfide minerals are exposed to water and oxygen, producing acidic conditions. Microbial activity can also accelerate the oxidation of sulfide minerals and the formation of acidic waters (Chen et al 2014; Saha & Sinha 2018; Acharya & Kharel 2020). The main sources of AMD are leachate from abandoned mines and underground deposits, open pits, tailings pits, and waste rock dumps, as well as wastewater discharged during ore flotation and smelting (Lin et al 2020; Araujo et al 2022; Yuan et al 2022).

Pyrite (FeS_2) is unstable in oxidizing environments, and it is the most common precursor of AMD. When pyrite is exposed to air and water and oxidized by microbes, it releases water-soluble components, such as Fe^{2+}, SO_4^{2-}, and H^+. The Fe^{2+} is oxidized into Fe^{3+}, then Fe^{3+} is hydrolyzed into amorphous Fe-oxides or oxidizes pyrite to release acids (Sahoo et al 2013). Pyrite can also undergo rapid weathering, resulting in the production of sulfuric acid and dissolved ferric ions, which in turn increase the dissolution of pyrite and accelerate the release of toxic metals from coexisting minerals (Ouyang et al 2015). Byrne et al (2012) explain the process of pyrite weathering in a deep metal mine. There are four general equations that describe the chemistry of pyrite weathering and AMD production: (1) the equations of oxidation reaction of pyrite by oxygen and water to generate dissolved ferrous iron and sulfuric acid; (2) the equations of oxidation reaction of dissolved ferrous iron to ferric iron; (3) the equations of ferric iron hydrolysis with water to produce iron hydroxide precipitate and acidity; and (4) the oxidation of additional pyrite by the ferric iron generated in reaction (2) to produce dissolved ferrous iron and sulfuric acid (Figure 1).

The acidic and heavy metal-contaminated waters are also found in abandoned post-tin mining pits. Kurniawan et al (2019) and Kurniawan (2020) have described the physico-chemical characteristics of abandoned post-tin mining pits. There are sixteen heavy metals identified in the pits in Bangka Regency, Indonesia, namely As, Co, Cu, Cr, Fe, Ga, Hf, Sn, Ta, Te, Th, Mn, Ni, Pb, Zn, and V. Sonone et al (2020) explain that these metals can produce acidity and toxicity for the environment and danger for organisms, including aquatic organisms, which might impact human health through the food chain.

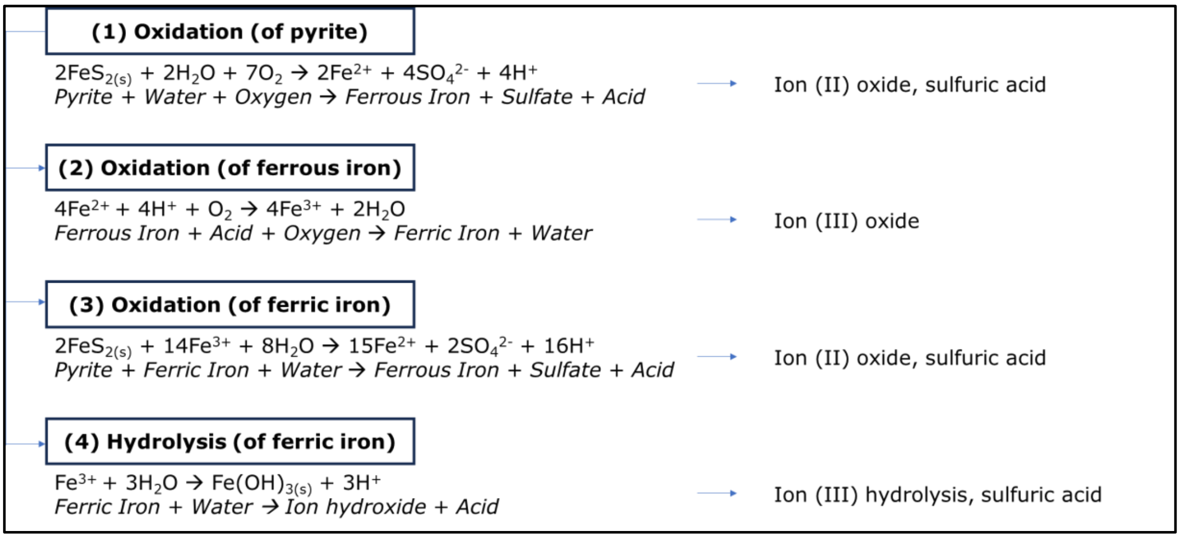

Figure 1. The process of pyrite weathering in a deep metal mine to generate acid mine drainage (Byrne et al 2012).

The Life of *Aplocheilus panchax* in Abandoned Post-tin Mining Pits. In this type of habitat, some organisms can survive and live normally. They are identified as extremophile organisms (Kurniawan & Mustikasari 2021). These organisms can tolerate and even grow in toxic waste, low nutrient content, and heavy metal pollution (Rampelotto 2013).

Kurniawan et al (2023) describe the food chain and energy flow in abandoned post-tin mining environments with life present. There are water plants, phytoplankton, zooplankton, and fish. Blue panchax (*Aplocheilus panchax*) is a unique fish found in abandoned post-tin mining pits. It has a silver spot like tin on its head, so in Bangka Island it is locally called "kepala timah fish" (Figure 2).

Figure 2. *Aplocheilus panchax* collected from abandoned post-tin mining pit.

A. panchax is one of the species from the genus *Aplocheilus*, family Aplocheilidae, suborder Aplocheiloidei, order Cyprinodontiformes, and class Actinopterygii (Parenti & Hartel 2011; Zhang 2011; Sedlacek et al 2014; Furness et al 2015; Mustikasari et al 2020a,b; Mustikasari et al 2022) and its IUCN red list status is "least concern" (LS). *A. panchax* is a native species in Andaman, Pakistan, India, Bangladesh, Sri Lanka, Vietnam, Cambodia, Thailand, Singapura, Malaysia, and Indonesia, while *A. panchax* found in Philippines and Timor-Leste is introduced (Figure 3) (Mustikasari 2023).

Order Cyprinodontiformes has a diverse group of small fishes living in freshwater and estuarine environments. Killifishes are among the most important experimental species used as model organisms for a large spectrum of scientific areas (Pohl et al 2015; Braganca et al 2018). Fish from the genus *Aplocheilus* have a terminal type mouth, may have a rhomboid (tapered) caudal fin (in *A. panchax*), or a rounded type caudal fin (in *A. andamanicus*), and have black spots on the dorsal fin (Katwate et al 2018). Fish with a sagittiform body type have ambush predator behavior (Senay et al 2017). Mustikasari et al (2023) confirm that *A. panchax* has a terminal mouth and sagittiform body type, and is a predator, with insects as its natural food (Figure 4). It is also confirmed that *A. panchax* is a surface feeder fish, a carnivorous, larvivorous and insectivorous fish.

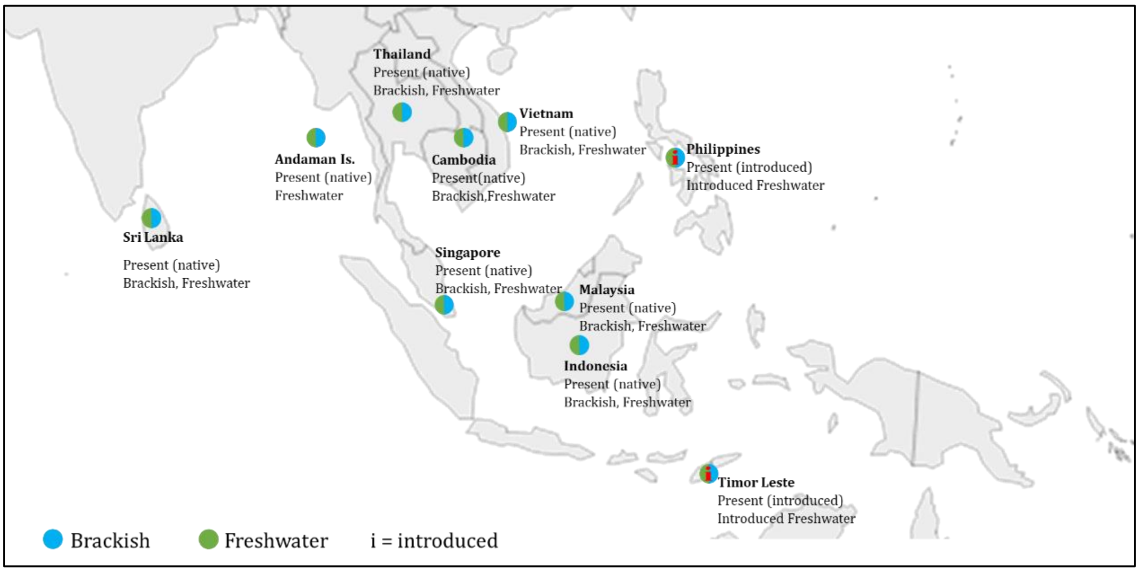

Figure 3. Distribution area of *Aplocheilus panchax*.

Figure 4. Food habit of *Aplocheilus panchax* (Mustikasari et al 2023).

Mustikasari (2023) notes that *A. panchax* can be found in abandoned post-tin mining pits in Bangka Island. Some characters of *A. panchax* habitats in Bangka Island, in open and closed waters are presented in Table 1. *A. panchax* can live in a wide range of water quality parameters, being especially tolerant to low pH values and low dissolved oxygen (DO).

Table 1

Habitat characteristics of *Aplocheilus panchax* in Bangka Island

Parameters	*Environmental characteristics*
Water temperature	31.28-31.7°C
pH	3.81-7.79
E_h	0.011-0.198 V
Conductivity	19.03-198,67 μS cm^{-1}
TDS	12.4-132 ppm
DO	5.33-7.2 ppm
BOD	2.65-4.34 ppm
COD	6.21-7.21 ppm
Water flow	Low water flow and no water flow.
Water plants	There were few water plants with medium density.
Vegetation around the water	Initially, there was no vegetation, then vegetation started to grow around the waters.
Organic matter sources	There were woods, roots, grass, and water plants in the waters

Note: E_h - oxidation-reduction potential; TDS - total dissolved solids; DO - dissolved oxygen; BOD - biological oxygen demand; COD - chemical oxygen demand; source: Mustikasari (2023).

The Important Role of *Aplocheilus panchax* in Abandoned Post-tin Mining Pits. The acidic conditions and heavy metal contamination of abandoned post-tin mining waters must be addressed before using the water for other activities. The acidic conditions can cause the destruction of gill tissue and increased mucus production in fish, which can asphyxiation (Islam et al 2016; Ibrahim et al 2020). Contamination with heavy metals has intensified global issues due to its impact and risks on fish and consumers of fish (Atici et al 2010).

The presence and metabolism of *A. panchax* as extremophile fish can be used for aquatic quality management. The ability of *A. panchax* as a larvivorous fish can be utilized for the biological control of mosquito larvae. This species is known to be effective in regulating the population of mosquitoes (Manna et al 2011). The species have been suggested as a means of eradicating mosquitoe larvae in an environment, including in abandoned post-tin mining pits.

In addition, *A. panchax* can maintain permanent populations in such habitats by undergoing diapause during the embryonic stages to survive periodic droughts (Matias & Adrias 2010). *A. panchax*, as an extremophile fish, has emerged as a veritable model for investigations in integrative biology because it can survive under environmental stressors. Annual killifish embryos can experience monthly to annual dormancy (Dolfi et al 2014). The non-annual killifish group, including *A. panchax*, even though they do not experience the diapause phase, especially diapause II, they still experience delayed hatching for a period of days, weeks, or months (Berois et al 2014; Furness 2015; Furness et al 2018; Kurniawan & Mustikasari 2021).

The ability of *A. panchax* to survive in this extreme habitat can be a supporter of organic matter production in the water. Their metabolism can produce organic matter and organic compounds from organic matter are dissociated by hydrolysis or decomposition by microorganisms to produce COOH and OH groups. Organic matter decomposed will produce $COOH^-$ and OH^- ions, which can bind H^+ ions, causing a decrease in H^+ ion, and the pH will increase to neutral (Kurniawan et al 2023). The addition of organic acids, such as acetic, malic, citric, and benzoic acids reduce the pH immediately due to H^+ ions dissociation (Rukshana et al 2011). They can also increase the negative charge in the environment, thereby increasing the cation exchange capacity to increase environmental fertility (Santoso et al 2021). Groups of $COOH^-$ and OH^- can also bind metals or heavy metal cation ions, decreasing the oxidation activity of heavy metals, which can increase pH value and decrease heavy metal levels (Igiri et al 2018; Ejaz et al 2023).

Figure 5 offers a schematic of *A. panchax* contribution to water quality improvement by providing organic matter that can be utilized by micro- and macro-organisms. *A. panchax*, directly or indirectly, can impact the decrease of heavy metal contamination and the increase of pH values in abandoned post-tin mining pits. The metabolism of *A. panchax* can be an organic matter source in this habitat. The organic matter is decomposed to produce ions that can bind H^+ cations and heavy metals. This mechanism impacts heavy metals toxicity reduction or detoxification and also increases the pH value. This process can take place over a certain period of time and it can improve water quality.

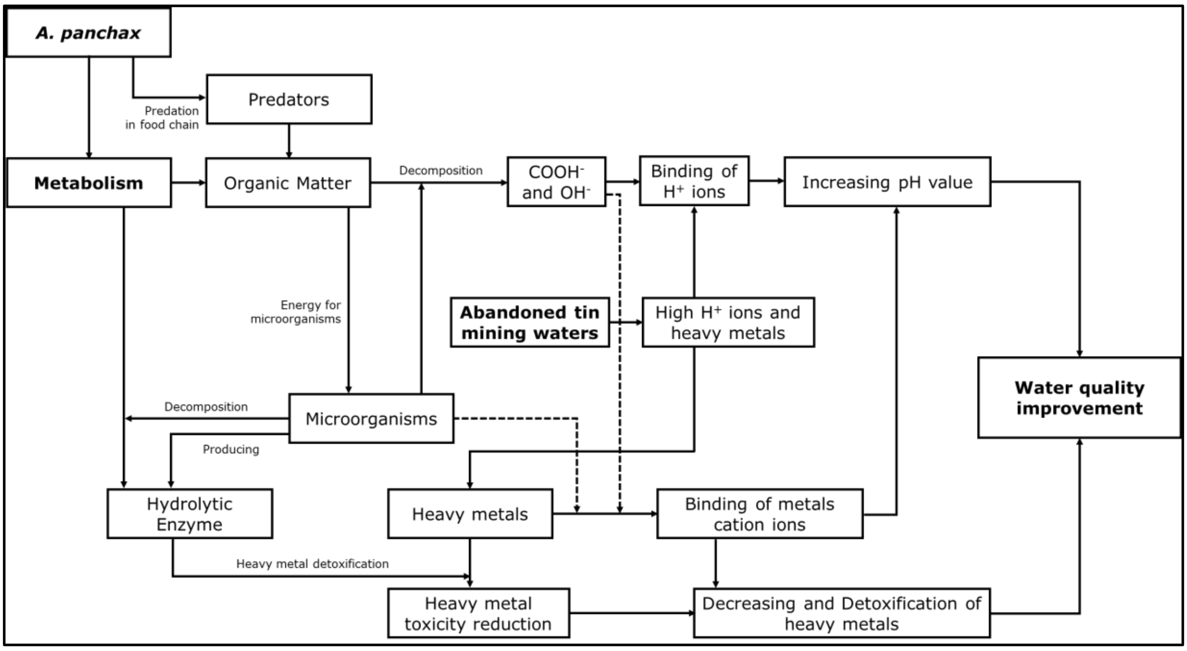

Figure 5. Schematic view of water quality improvement by increasing organic matter produced by *Aplocheilus panchax*.

Conclusions. The presence of *A. panchax* as one of the pioneer species in abandoned post-tin mining pits is important. This short review has described the life of *A. panchax* in abandoned post-tin mining pits and the potential of *A. panchax* for environmental health and management of water quality improvement.

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Conflict of Interest. The authors declare that there is no conflict of interest.

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