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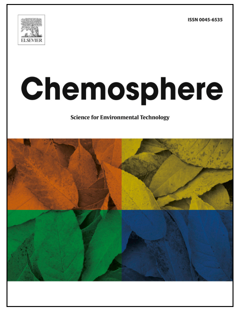

Algae, biochar and bacteria for acid mine drainage (AMD) remediation: A review

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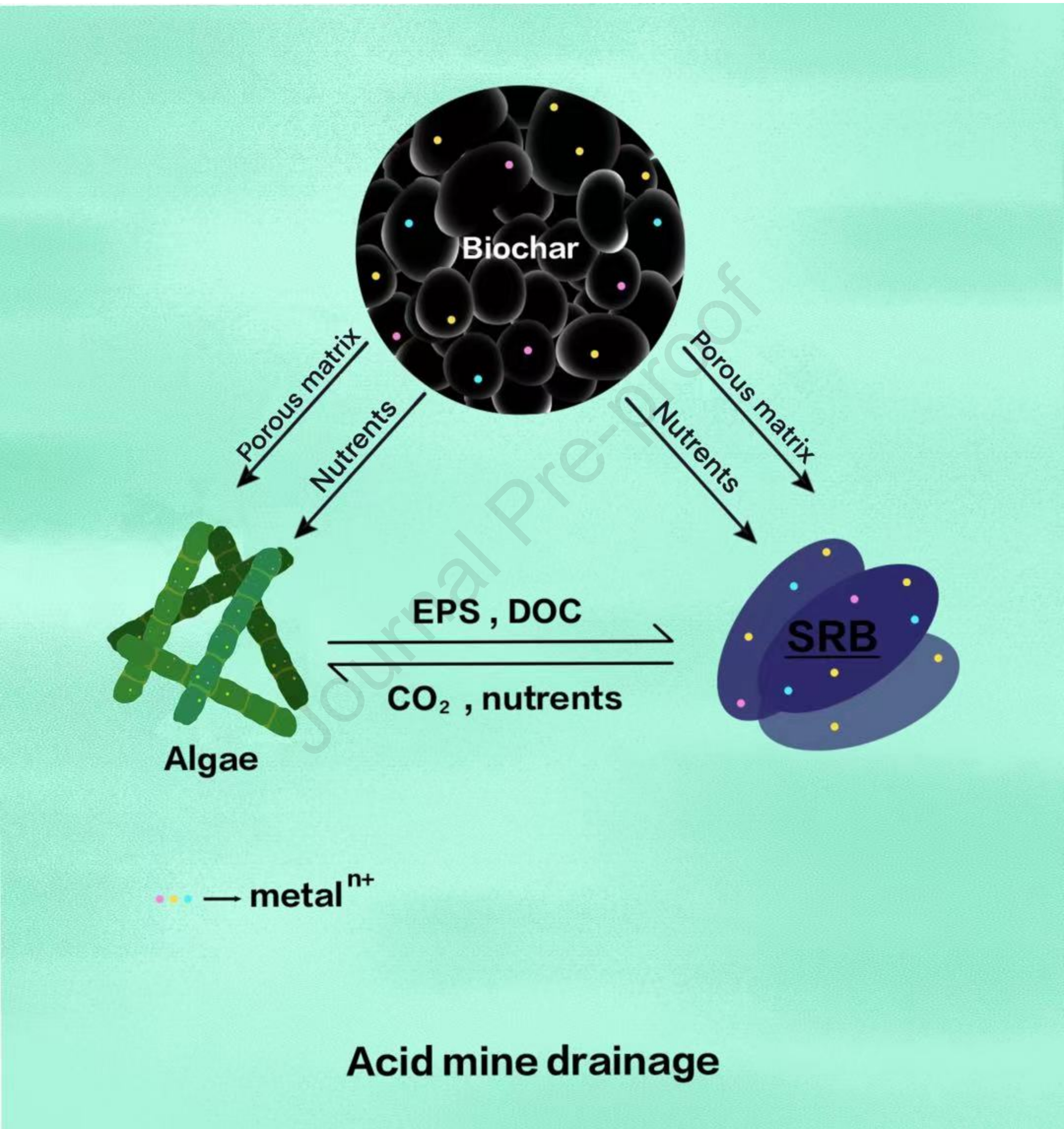
Biochar
Porous matrix
Nutrents
Porous matrix
Nutrents
EPS , DOC
CO2 , nutrents
Algae
SRB
metal n+
Acid mine drainage

Algae, biochar and bacteria for Acid Mine Drainage (AMD) remediation: a review

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Abstract

Acid mine drainage (AMD) is a global issue and causes harmful environmental impacts. AMD has high acidity and contains a high concentration of heavy metals and metalloids, making it toxic to plants, animals, and humans. Traditional treatments for AMD have been widely used for a long time. Nevertheless, some limitations, such as low efficacy and secondary contamination, have led them to be replaced by other methods such as the bio-based AMD treatments. This study reviewed three bio-based treatment methods using algae, biochar, and bacteria that can be used separately and potentially in combination for effective and sustainable AMD treatment to identify the removal mechanisms and essential parameters affecting AMD treatment. All bio-based methods, when applied as a single process and in combination (e.g. algae-biochar and algae-bacteria), were identified as effective treatments for AMD. Also, all these bio-based methods were found to be affected by some parameters (e.g. pH, temperature, biomass concentration and initial metal concentration) when removing heavy metals from AMDs. However, we did not identify any research focusing on the combination of algae-biochar-bacteria as a consortium for AMD treatment. Therefore, due to the excellent performance in AMD treatment of algae, biochar and bacteria and the potential synergism among them, this review provides new insight and

discusses the feasibility of the combination of algae-biochar-bacteria for AMD treatment.

***Keywords*: Acid mine drainage, treatment, sulfate reducing bacteria, bioremediation, heavy metal**

Abbreviations

AMD Acid mine drainage

BET Brunauer-Emmett-Teller

EDX Energy Dispersive X-ray Analysis

EPS Extracellular Polymeric Substances

FTIR Fourier Transform Infrared

ROS Reactive Oxygen Species

SEM-EDX Scanning Electron Microscopy with Energy Dispersive X-ray Analysis

SRB Sulfate reducing bacteria

XRD X-ray Diffraction Analysis

ZVC Zero-valent copper

ZVI Zero-valent iron

1. Introduction

Acid mine drainage (AMD) refers to the deposits and tailings generated by mine site exploration. These deposits and tailings can be exposed to the natural environment (water, air and microbial activity) and develop acidic conditions that lead to the leaching of metals and metalloids (e.g. Fe, Al, Zn, Cu, Cd, Pb, Hg, Ni, Co, Cr, As, Sb) (Alpers and Nordstorm, 1997; Bogush et al., 2016; Favas et al., 2016; Hudson-Edwards et al., 2011; Nordstrom, 2011). Generally, AMD comes from two main sources (Akcali and Kucuksezgin, 2011): 1) Primary sources include mine rock dumps, tailing impoundment, underground and open-pit mine works, pumped natural discharged underground water and construction rocks; 2) Secondary sources include treatment sludge ponds, rock cuts, and stockpiles.

Acid mine drainage is harmful to humans, animals, plants, and aquatic life (Bogush and Lazareva, 2011; Kumari et al., 2010). For example, AMD causes fish death by affecting the function of the gills, and increased turbidity from soil erosion and precipitation layering on the riverbed can change the habitat for aquatic organisms (Bogush and Lazareva, 2011; Kumari et al., 2010). Some metals produced from the mining industry, such as Cd, Pb, Cu, Zn, Ni and Hg, can accumulate in the human body and cause serious diseases. For example, high levels of Hg in the body can cause Minamata disease, a neurological disease that can cause numbness, muscle weakness, and even death.

Elevated Ni levels can cause a dry cough, chest pain, and nausea. High Pb levels in humans can damage the nervous system and cause intellectual disability, and high levels of Zn in the human body can cause vomiting, skin inflammation and fever (Carolin et al., 2017). The biology of plants and aquatic life can also be affected by metal toxicity. Furthermore, these organisms not only act as receptors of the contamination but also as a pathway to humans via food chains (Kumari et al., 2010). Even if the contamination comes from a single point source, the impacts are not restricted to the local area but can also affect distant regions, as water can carry the contamination along rivers or streams (Bogush and Lazareva, 2011; Kumari et al., 2010).

The mining industry has played a vital role in the economies of many countries and has supported their development for a long time. The total annual global mineral production between 2013 and 2017 was approximately 17 billion MT (Abinandan et al., 2018). Notably, the USA, China, Russia, Australia, and India are the top five countries in the mining industry (Reichl et al., 2019). For example, in 2017, China and the USA produced 4.1 and 2.0 billion MT of minerals, respectively (Reichl et al., 2019). While the UK is, at present, not on the list of top producers, with no active metal mining industry, it has a rich mining history as the cradle of the industrial revolution, and therefore it has a legacy of old mines with associated AMD still affecting large areas of the country. Some abandoned mining sites in the UK still contribute significantly to heavy metal contamination of rivers and streams (Johnston et al., 2008). For instance, the Parys Mountain copper mine on the Welsh island of Anglesey discharges 24 tonnes of Zn and 10 tonnes of Cu into the Irish sea every year (Johnston et al., 2008). Because of these abandoned mining sites, 315 out of 7,816 water bodies in the UK, equating to 2,840 km of rivers, are contaminated or potentially contaminated by AMD (Abinandan et al., 2018; Johnston et al., 2008; Jones et al., 2016).

There are several established methods for treating AMD such as precipitation, ion exchange, electrochemical, and membrane separation (Alcolea et al., 2012; Genty et al., 2012; Taylor et al., 2005). For instance, the open limestone channels (OLC) method uses a channel filled with limestone fragments to neutralise and increase the alkalinity of AMD (Alcolea et al., 2012); anoxic limestone drains (ALD) are buried limestone drainage lines with a gentle slope, sealed with a low permeability liner and capped with clay to ensure air cannot flow into the drain during operation (Taylor et al., 2005). These treatments have advantages, including low cost and ease of management. However, they also have certain limitations, for example, the need for a high quantity of limestone and also the generation of a large amount of sludge (secondary contamination), low efficacy, the inability to remove all metals/metalloids, and the need for a relatively large area (Alcolea et al., 2012; Bogush et al., 2016; Dufresne et al., 2015). Therefore, bio-based treatment approaches for AMD should be considered as an attractive alternative due to their higher efficiency, lower secondary contamination and potentially lower costs (I. Kim et al., 2014).

Bio-based treatment generally refers to the use of either dead/processed or living biomass to reduce and remove heavy metals from AMD (I. Kim et al., 2014). The common and suitable bio-based materials usually include algae, biochar, and bacteria (Cai et al., 2021; Loreto et al., 2021; Orandi et al., 2012). It is proven that each of these three treatments can remove metals from AMD effectively and are cost-effective. However, the main bottlenecks of these three AMD treatments are the lack of industrial AMD water treatment case studies for algae, the use of rudimentary technologies in biochar recycling and recovery of metals from biochar, and the need for highly effective carbon sources for preparing sulfate reducing bacteria (SRB) immobilising (Almomani and Bhosale, 2021; Di et al., 2022; Shirvanimoghaddam et al., 2022).

This paper reviews (database: Scopus, Science Direct and Web of Science) the use of algae, biochar, and bacteria separately and in combination for AMD treatment due to their high capacities for metal removal. The paper also discusses the removal mechanisms, parameters affecting metal removal, efficacy, and examples of different treatment applications. The limitations and gaps in existing studies are identified, and the recommendations for future research are outlined.

2. Algae application in AMD treatment

A total of 14 studies were reviewed (screened from 1877 initial literature results from 2006 to 2022) that focused on the use of algae for AMD treatment. Most of these studies reported a relatively high removal efficiency, especially two studies with dry biomass (Bansod & Nandkar, 2016; Khoubestani et al., 2015). In terms of metal removal, most studies focused on Cu and Zn. The details of metal removal by algae reported by different authors are summarised in Table 1 and discussed in the following sub-sections.

Table 1. Algae used for heavy metal removal from AMD.

Algal species	**Growth method**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
Klebsormidium sp.	Algae were collected from the mine site and grown in Lab, Photo-rotating biological contactor (PRBC)	Cu 80-100, Mn 35-40, Mg 85-100, Ca 18-2, Ni 2.0-3.0, Zn 18-20, Na 20-25	Removal efficiency is 35%-50% by order Cu>Mn>Mg>Ca>Ni>Zn>Na	Orandi and Lewis (2013)
1.Oedogonium crissum *2.Klebsormidium klebsii* *3. Microspora tumidula*	Field growth and laboratory experiment	Al 4.8, Fe 79, Mn 51, Zn 550	In all study pH conditions, *Oedogonium crassum* was considered to have the highest metal bioaccumulation rate	Oberholster et al. (2014)

Table 1. Algae used for heavy metal removal from AMD. (Continued).

Algal species	Growth method	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Stichococcus bacillaris	Porous Substrate Bioreactor (PSBR)	Zn 2.0-3.0	Zn 15-19 mg g^{-1}	Li et al. (2015)
Sargassum sp.	Laboratory experiment	Cu 20, Cr 20	Cu 71.4 mg g^{-1}	Jacinto et al. (2009)
Scenedesmus quadricauda	Laboratory experiment with dry biomass	Cr 100	Cr 58.5 mg g^{-1}, Cr 46.5 mg g^{-1}	Khoubestani et al. (2015)
Chlorella sp.	Stabilisation pond system	Zn and Pb 5.0-20	Zn 34.4 mg g^{-1}, Pb 41.8 mg g^{-1}	Kumar and Goyal (2010)

Table 1. Algae used for heavy metal removal from AMD. (Continued).

Algal species	**Growth method**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
Ulothrix sp.	Photorotating biological contactor (PRBC), algae collected from mine site	Cu 80-100, Ni 2-3, Mn 35-45, Zn 18-20, Sb 0.005-0.007, Se 0.03-0.04, Co 0.3-0.5, Al 0.07-0.09	The metal removal efficiency is 20-50% by order Cu>Ni>Mn>Zn>Sb>Se>Co>Al	Orandi et al. (2012)
Nephroselmis sp.	Pipe Insert Microalgae Reactor (PIMR), AMD pre-treated with active treatment	Fe 20.5 ± 9.8	Fe 24.2 mg g^{-1}	Park et al. (2013)
Spirogyra verrucosa	Laboratory experiment with dry biomass	Mn 50	Mn 40.7 mg g^{-1} (80.2%)	Bansod and Nandkar (2016)

155 Table 1. Algae used for heavy metal removal from AMD. (Continued).

Algae species	Growth method	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Nannochloropsis sp.	Lab-scale growth, modified with silica and followed by coating with magnetite particles	Cu 6.4-64	Cu 56 mg g^{-1} (87.5%)	Buhani et al. (2021)
Nannochloropsis oculata	Laboratory growth and experiment	Cu 16	Cu 99.9 ± 0.04% with 89.3 ± 1.92% by metabolism and 5 g/ cell for adsorption	Martínez-Macias et al. (2019)

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Table 1. Algae used for heavy metal removal from AMD. (Continued).

Algae species	**Growth method**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
1. *Phormidium ambiguum* 2. *Pseudochlorococcum typicum* 3. *Scenedesmus quadricauda var quadrispina*	Algae isolated from River Nile and Ain Helwan Spring & laboratory experiment	Cd, Pb and Hg are all 0.01	*P. typicum* had the highest removal efficiency of Hg 15.1 mg g^{-1}, Cd 5.5 mg g^{-1} and Pb 74.5 mg g^{-1}	Shanab et al. (2012)
Chlorella vulgaris	Lab-scale growth	Fe 788, Al 310, Mn 19.4	Removal efficacy for all metals reached approximate 99.9%	Brar et al. (2022)
1. *Spirulina platensis* 2. *Chlorella vulgaris*	Lab-scale growth and dried with 100 ˚C oven	Al, Ni and Cu 2.5-100	*S. platensis* Ni 95%, Al 87%, Cu 62% *C. vulgaris* Ni 87%, Al 79.1% Cu 80%	Almomani and Bhosale (2021)

2.1 Mechanism of metal removal by algae

The process of heavy metal sorption by algae is complex. Generally, two stages are involved (Bwapwa et al., 2017). The first is extracellular sorption, which is rapid and can be assumed to be passive. This happens immediately after algae are in contact with metals and involve the following mechanisms: the interaction between metal ions and anionic cell ligands, micro-precipitation, surface complexing, covalent bonds between metal ions and proteins and other polymers. The second stage is intracellular accumulation. This is slower than the first stage and is assumed to be active. The mechanisms involved are species-specific and include, for example, phytochelation, which forms a metal complex. Figure 1 illustrates some of the mechanisms of metal removal by algae. Heavy metals are incorporated into algal vacuoles and then bonded with proteins, DNA, and lipids. Also, algae cells, especially some resistance cells, can effuse toxic metal complex substances, for example, Cu and Cd (da Costa and de França, 2003; Levy et al., 2008; Worms et al., 2006). In addition, cell walls, nuclei, mitochondria, chloroplasts, and some other parts of the cell may be reinforced by the membrane, which works as a barrier in adapted cells (Chen et al., 2012; Sandau et al., 1996; Tam et al., 1998). In these two stages, some of the metals are taken by the surface, and others may be taken in the inner cell due to metals' type and algae growth preference (Du et al., 2022). Surface adsorption is essential since it represents the largest portion of the absorption process (Chojnacka et al., 2005). Still, the relative importance of surface adsorption may vary depending on the metals and algae (Du et al., 2022). Nevertheless, the complexity of the algae surface makes it possible for various mechanisms to operate simultaneously (Monteiro et al., 2012). Generally, the ability to remove metals by different algal groups shows a decreasing order of *Chlorophyta* > *Phaeophyta* > *Rhodophyta* (Al-Shwafi and Rushdi, 2008). However, knowledge of the distribution of metals in/on the algal cell and the stage involved in metal removal processes still needs to be explored.

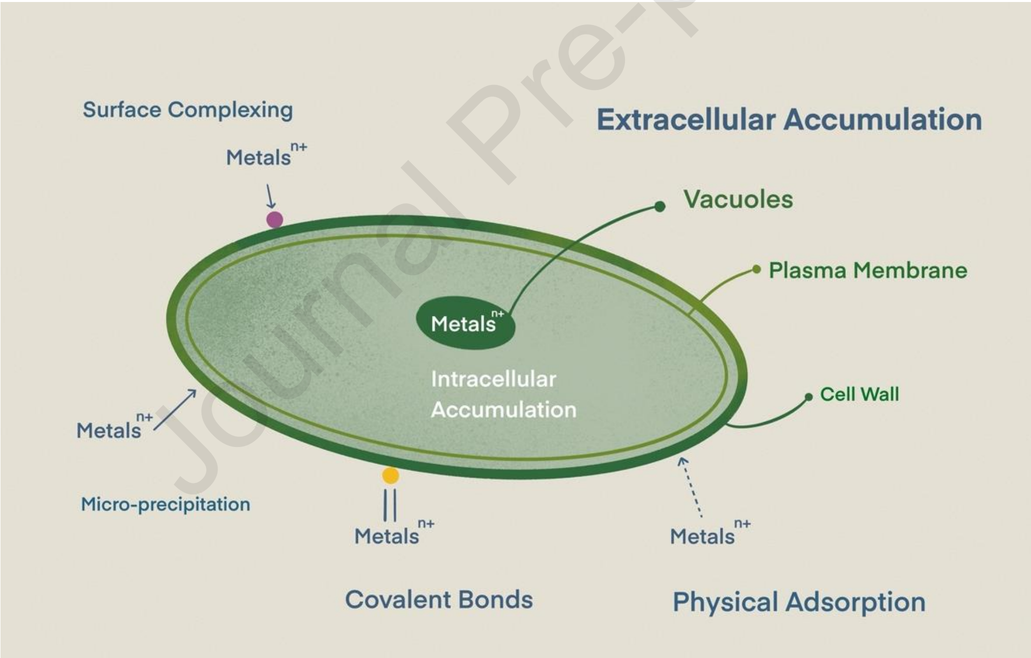

Figure 1. The mechanisms of heavy metal removal by algae. Extracellular accumulation includes surface complexing, micro- precipitation, covalent bonds, and physical adsorption.

2.2 Parameters that affect removal capacity by algae

a) pH

In many studies, pH was considered the most critical parameter affecting the sorption of metals by algae. According to Van Hille et al. (1999), a pH over 8 is required to enable the precipitation of metals as hydroxides. If the pH decreases, the removal of Zn is first to be affected, followed by Cu, Pb, and Fe, because different functional groups can precipitate metals at different pH conditions (Chojnacka et al., 2005). Monteiro et al. (2012) suggested an optimal pH range of 4.0–5.0 to remove Cu and Cd and a pH of 2.0 for Co. Similarly, Khoubestani et al. (2015) indicated that the best pH for Cr adsorption is 6.0, while Bansod and Nandkar (2016) reported that the best pH condition for Mn removal is 5.0.

The differing optimal pH values for metal removal found in the different studies reflect the different metal chemistry and different functional groups involved in the metal removal process. Each functional group has distinct pH ranges for binding metal cations (Monteiro et al., 2012). Under acidic conditions, a positive charge and protonation will happen for specific functional groups associated with H^+ because of the repulsive forces (Khoubestani et al., 2015; Monteiro et al., 2012). Thus, some functional groups are only available within a specific pH value. For instance, carboxyl groups dominate at pH 2-5; phosphate becomes the main group at pH 5-9, while when the pH increases to 9 and then up to 12, carboxyl, phosphate, and hydroxyl/amine groups are all available (Bansod and Nandkar, 2016; Monteiro et al., 2012). The general agreement is that at low pH, positively charged algae surfaces are the main contributors to biosorption because the binding sites, surrounded by H^+, attract metal ions towards the algal surface. However, when the pH increases above 4.0, some divalent metals, e.g. Zn and Cu, readily precipitate as hydroxide, thus reducing biosorption (Bansod and Nandkar, 2016). In most cases, the initial pH of AMD is lower than 4.0. Thus, strategies on how to reduce the negative effects caused by low pH when exploring metal removal by algae should be considered, for example, isolation of superior strains.

b) Initial metal ion concentration

Initial metal ion concentration is another critical parameter that can affect the efficiency of algae in treating AMD. Most studies suggest that metal uptake positively correlates with the initial metal ion concentration (Al-Rub et al., 2004; Monteiro et al., 2012, 2009). This is due to higher initial metals concentration contributing to higher driving force, which can overcome mass transfer resistances of metal ions between biomass and solution and promote uptake (Al-Rub et al., 2004; Cruz et al., 2004). Also, collisions between biomass and metal ions increase under higher metal concentrations, enhancing the metal uptake process (Al-Rub et al., 2004). Monteiro et al. (2011) found that the total Zn removal by *Scenedesmus obliquus* (mg Zn g^{-1} algae) increased more than ten-fold when the initial Zn concentration was increased from 10 mg L^{-1} to 75 mg

L^{-1}. However, metal absorption is more effective at a lower initial metal concentration. For example, Monteiro et al., (2009) reported that, although *Desmodesmus pleiomorphus* adsorbed and totally removed more Zn at the higher initial Zn concentration, it had higher removal efficacy of Zn at a relative lower Zn concentration (1 mg L^{-1}) than higher Zn concentration (5-30 mg L^{-1}). This is because more binding sites are available when the metal concentration is low (Khoubestani et al., 2015; Mehta and Gaur, 2005). Nevertheless, the weakness of the two studies conducted by Monteiro et al. (2011, 2009) is that the Zn concentration set in these studies was relatively low, which cannot fully explain the relationship between initial ion concentration and metal removal especially at high metal concentrations.

However, in a study by Bansod and Nandkar (2016) on Mn removal (with Mn concentration of 10 mg L^{-1} to 100 mg L^{-1}) by *Spirogyra 18errucose*, the total uptake efficiency reached the highest level (40.66 mg g^{-1}) when the Mn concentration was 50 mg L^{-1}. When the concentration was over 50 mg L^{-1}, the percentage removal of Mn did not continue to increase. Instead, it remained constant and even slightly decreased, which is different from most of the studies mentioned above. This may be explained by the research from Monteiro et al. (2012), who reported that this increase tends to reach saturation after the threshold.

c) Temperature

Temperature is always considered an important parameter in both physicochemical and biological reactions. However, based on the available literature, the effect of temperature on heavy metal removal by algae is inconclusive. Some studies have shown a positive correlation between heavy metal removal by algae and temperature (Monteiro et al., 2012). Aksu (2002) reported increased Ni^{2+} biosorption by *Chlorella vulgaris* with increased temperature from 15 to 45 ˚C. One reason for this could be that increasing temperature may promote several active sites on algae to participate in the biosorption (Mehta and Gaur, 2005).

On the other hand, several studies report a negative correlation between temperature and the ability of algae to absorb heavy metals. For example, the biosorption of Cd^{2+} by both *Oedogonium* and *Sargassum* is reported to have a lower sorption efficiency with increased temperature (Cruz et al., 2004; Gupta and Rastogi, 2008). The same result was also reported by Aksu (2001) for Cd removal using *Chlorella vulgaris*. Cd adsorption usually is exothermic, and thus the adsorption decreases with increasing temperature (Aksu, 2001; Cruz et al., 2004).

Another group of studies observed almost no effect of temperature change on algae sorption. For example, Cossich et al. (2002) reported that the use of *Sargassum* to remove Cr showed the effect of temperature was not as significant as the effect of pH. Likewise, these relationships between temperature and metal removal were also reported by Mehta and Gaur, (2005). Overall, the general relationship between temperature and metal removal effectiveness by algae is still unclear based on the discussion above. For example, the types of algae and metal may both affect the results. Also, seasonal parameters, such as precipitation and runoff, may cause the initial metal ion concentration and temperature to vary with time in AMD sites (Du et al., 2022). Therefore, a clear relationship between temperature and metal removal efficiency should be investigated for different combinations of metals and algal species, especially in practical AMD conditions.

d) Biomass concentration

Biomass concentration of algae can have significant effects on metal removal. Mehta and Gaur (2005) reviewed several previous studies and indicated that the cell concentration of *Chlorella* sp*.* negatively correlates with the binding of Cd per unit of mass. Similarly, they reported a decreased sorption capacity per unit of mass of Cu and Ni by increasing the *Chlorella vulgaris* concentration and decreased Pb sorption by increasing *Spirulina maxima*. Monteiro et al. (2012) reviewed some studies and reported this negative correlation. According to the literature, in most conditions, the biomass concentration and metal adsorption capacity negatively correlate per unit mass. The reason for this may be that the increase of biomass can lead to its partial aggregation thus reducing the surface area for adsorption, and the increase of biomass can also decrease the distance between the available adsorption sites (Monteiro et al., 2012).

However, increasing biomass concentration may lead to a higher amount of heavy metal removal (Mehta and Gaur, 2005). For example, Tam et al. (1998) reported that Cu concentration in solution decreased with increasing algae cell concentration. The increased metal removal with increasing biomass may be due simply to the increased availability of metal-binding sites caused by increasing biomass amount (Khoubestani et al., 2015).

Thus, the general agreement is that increasing biomass concentration can reduce the algae removal capacity per unit mass. While it is possible that a higher biomass concentration may increase the total amount of metal removed, this is not a straightforward relationship (Mehta and Gaur, 2005).

3. Biochar application in AMD treatment

A total of 35 studies were reviewed (screened from 3788 initial literature results from 2006 to 2022) which were concerned with biochar treatments for AMD. These studies used biochar with different feedstocks, pyrolysis methods, and modification methods. The studies reported successful removal of heavy metals from AMDs, although with different performances. The details of biochar used for metal removal from AMD reported in different studies are summarised in Table 2 and discussed in the following sub-sections.

309 Table 2. Biochar used for heavy metal removal from AMD.

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Hardwood	450	Cu 256, Zn 260	Cu 6.8 mg g^{-1}, Zn 4.5 mg g^{-1}	Chen et al. (2011)
Corn straw	600	Cu 256, Zn 260	Cu12.5 mg g^{-1}, Zn 11.0 mg g^{-1}	Chen et al. (2011)
Corn straw	400	Cd 20, Pb 20	Cd 38.9 mg g^{-1}, Pb 29.0 mg g^{-1}	Chi et al. (2017)
Hickory wood	Pre-treated by $KMnO_4$ and then 600 ˚C pyrolysed	Pb 100, Cu 30, Cd 30	Pb 153 mg g^{-1}, Cu 34.2 mg g^{-1}, Cd 28.1 mg g^{-1}	H. Wang et al. (2015)
Sugar cane	500	Pb 6.0-223	Pb 87.0 mg g^{-1}	Abdelhafez and Li (2016)

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311 Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Orange peel	500	Pb 6.0-223	Pb 27.9 mg g^{-1}	Abdelhafez and Li (2016)
Almond shell	650	Ni and Co 50-200	Ni 22.2 mg g^{-1}, Co 28.1 mg g^{-1}	Kılıç et al. (2013)
Sewage sludge	550	Pb 100-1000	Pb 30.88 ± 0.95 mg g^{-1}	Lu et al. (2012)
Peanut straw, soybean straw, Canola straw	400	Cu 15-960	Cu 37.12-89.6 mg g^{-1}, peanut> soybean> canola	Tong et al. (2011)
White birch, Black spruce	454, followed by KOH, CO_2 and steam activation	Cu 100	Cu >99%	Braghiroli et al. (2019)

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Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Papermill sludge	270-720	As 22.7, Cd 33.0	As 22.8 mg g^{-1}, Cd 41.6 mg g^{-1}	Yoon et al. (2017)
Nutshells, Plum stones, Wheat straws, Grape stalks and Grape husks	600	Cd 11.2-168, Pb 20.7-310.5	Over 95% removal efficiency for all four biochar	Trakal et al. (2014)
Pistachio green hull	450	Cu 70-270	Cu 19.8 mg g^{-1} (62%)	Jalayeri and Pepe (2019)

317 Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Olive pomace	Hydrothermal 300, pyrolysis 300 and 600	Cu 20	Cu 77.8%	Pellera et al. (2012)
Lolium perenne, Lolium perenne fibre, Miscanthus x giganteus, Salix viminalis, Fraxinus excelsior, Picea sitchensis	300, 450 and 600 slow-pyrolysis process	Zn 18.5 ± 2.10	Lolium perenne fibre has the best performance removal of Zn 93.0%	Hodgson et al. (2016)
Platanus orientalis Linn leaves	400, modified by H_2O_2, $KMnO_4$ and $K_2Cr_2O_7$	Cd 50	$KMnO_4$ modified biochar reached the highest removal efficacy of Cd 54.7 mg g^{-1}	Yin et al. (2022)

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319 Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Rice straw & Fe_3O_4 & $CaCO_3$	400	Cd and As 10-60	Cd 6.34 mg g^{-1}, As 10.1 mg g^{-1}	Wu et al. (2018)
Rice husks	300, 500 and 700	Pb (concentration unknown)	Pb RH300 14.1 mg g^{-1}, RH500 21.7 mg g^{-1}, RH700 26.7 mg g^{-1}	Shi et al. (2019)
Jarrah and pine wood chips	700	Cu 17.3-195, Zn 17.6-173	Cu 4.39 mg g^{-1}, Zn 2.31 mg g^{-1}	Jiang et al. (2016)
Oakwood, Oakbark	400 and 450, followed by magnetic activation	Pb and Cd 1.0-100	Pb 100%, Cd 53%-99%	Mohan et al. (2014)

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Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (°C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Orange peel	400, 500, 600, 700, 800	Cd 100	Cd 115 mg g^{-1}	Tran et al. (2016)
Sewage sludge	500 (for sewage sludge (Cs)), $ZnCl_2$ activated (for sludge-based active carbon (SBAC)), modified by nitric acid at different concentration and temperature (MSBACs)	Pb 100-200	Pb MSBAC 26.6 mg g^{-1}, SBAC 17.0 mg g^{-1}, CS 4.42 mg g^{-1}	Li et al. (2019)

Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Dairy manure	350	Cu 0-320, Zn 0-325, Cd 0-560	Cu 54.4 mg g^{-1}, Zn 32.8 mg g^{-1}, Cd 51.4 mg g^{-1}	Xu et al. (2013)
Poultry litter	400	Al 51, Cu 30.7, Zn 26.8	Al 100%, Cu 100%, Zn 99%	Oh and Yoon (2013)
Sesame straw	700	Pb, Cu, Cd, Zn and Cr are all 2.5-320	Pb 102 mg g^{-1}, Cu 55.0 mg g^{-1}, Cd mg g^{-1}, Zn 34.0 mg g^{-1}, Cr 65 mg g^{-1}	Park et al. (2016)

Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Rice husks	Hydrothermal 300, pyrolysis 300 and 600	Cu 20.0	Cu 90.1%	Pellera et al. (2012)
Common reed (Phragmites australis)	450	Fe 0.36 and 28.8, Al 0.13 and 10.99, Ni 0.07 and 0.39, Zn 0.03 and 0.19, Mn 0.37 and 5.08	Metal removal by 89.0%–98.0% (Fe≈Al>Ni≈Zn>Mn)	Mosley et al. (2015)
Sludge	300 (nano zero-valent)	Sb 10, 20 and 30	Sb 160.40 mg g^{-1}	Wei et al. (2020)
Soy sauce residue	400 and modified by nanoscale FeS and chitosan	Cr 100-550	Cr 70.42 mg g^{-1} (76.07%)	Yang et al. (2021)

Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (°C)	AMD composition ($mg\ L^{-1}$)	Metal removal efficiency	Reference
Oakwood, Oak bark, Pinewood Pine bark	400 and 600, fast pyrolysis	Cd, As, and Pb are all 0.01-0.10	Oak bark has the highest removal efficiency Pb 11.4 mg g^{-1}	Mohan et al. (2007)
Aloe vera shell	700 followed by $NiO.5ZnO.5Fe_2O_4$ magnetic nanoparticles supported	Ag 100	Ag 98.3% (244 mg g^{-1})	Beigzadeh and Moeinpour (2016)

Table 2. Biochar used for heavy metal removal from AMD. (Continued).

Biochar feedstock	Temperature for biochar production (˚C)	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Spent coffee grounds	400	Cd 0.228, Cu 0.194, Pb 0.0156, Zn 0.0222	Cd 99%, Cu 88%, Pb >99%, Zn 99%	M.-S. Kim et al. (2014)
Canna indica	300, 400, 500 and 600	Cd 30-200	Cd 189 mg g^{-1}	Cui et al. (2016)
Coconut shell	400, $MgCl_2$ modification	Pb 1000, Cd 1000	Pb 271.53 mg g^{-1}, Cd 91.95 mg g^{-1}	Wu et al. (2021)
Durian shell, *Robinia pseudoacacia*	500, Fe/Zn modification	Cd 30-300	Cd Durian shell biochar 99.81%, *Robinia pseudoacacia* biochar 71.08%	T. Yang et al. (2021)

3.1 Heavy metal removal mechanisms

Several mechanisms may be involved in removing heavy metals from contaminated solutions using biochar. As presented in Figure 2, these mechanisms include physical sorption, ion exchange, precipitation, complexation, and electrostatic interaction. Solution pH, zero-point charge of biochar, and temperature are the parameters that may affect this process (Inyang et al., 2016).

Surface precipitation between metal ions and mineral components (anions) such as PO_4^{3-}, CO_3^{2-} and OH^- is an essential mechanism in biochar metal removal (Cui et al., 2016). Tran et al. (2016) studied the effects of orange peel biochar on Cd^{2+} removal. They found that Cd^{2+} was removed by surface precipitation, as (Cd, Ca)CO_3 and Cd_3CO_3 were found by XRD after the experiments. Also, the EDX results showed that Ca remained on the surface of biochar, confirming surface precipitation. The same results of Cd^{2+} removal were also reported by Cui et al. (2016) in an experiment conducted using biochar from *Canna indica*. In addition, Cui et al. (2016) found that CO_3^{2-} was the dominant mineral component when biochar was produced at a relatively high pyrolysis temperature (>500 ˚C). More CO_3^{2-} can be released into the solution due to the incomplete cracking of carboxyl when the biochar pyrolysis temperature is high, resulting in Cd^{2+} precipitating with ligands (Cui et al., 2016). Likewise, another study using a pistachio green hull biochar to remove Cu gave similar results (Jalayeri and Pepe, 2019). They reported that Cu-P, Cu-C and Cu-Si were formed during experiments. The SEM-EDX image showed C, O, Cu, P, S, Si, Fe and Ca on the biochar surface, and the FTIR spectra showed the characteristic peaks of PO_4^{3-} and CO_3^{2-}, confirming this result.

Ion exchange, complexation, and electrostatic interaction are all associated with functional groups on biochar (Tan et al., 2015). Under different pH conditions, there would be various mechanisms for different metals. For example, Abdel-Fattah et al. (2015) compared the simultaneous removal of Mg^{2+}, Ca^{2+}, Pb^{2+} and Cr^{6+} by pinewood biochar in solution. They found that at a pH of 6.0–7.0, Mg^{2+}, Ca^{2+} and Pb^{2+} were mainly removed by complexation with C=O, C-O and phenolic O-H functional groups. In addition, it is worth noticing that complexation between oxygen-containing functional groups and heavy metals may be accompanied by H^+ release (Ding et al., 2016). The H^+ release would decrease the solution pH, which can be used as evidence to determine if this complexation happened during the adsorption process (Tran et al., 2016).

However, in acid conditions (pH 1.0) the mechanism of Cr^{6+} removal was mainly electrostatic interaction between positively charged functional groups and negatively charged chromate ion (CrO_4^{2-}) (Abdel-Fattah et al., 2015). This can be explained by the fact that under low pH values, the biochar surface is highly protonated, which promotes electrostatic interaction between ions. Conversely, under high pH, biochar surface protonation is reduced to the lowest level. This condition may contribute to the complexation between oxygen donors in functional groups and metal ions (Abdel-Fattah et al., 2015).

Physical sorption by pores and surface area on the biochar surface is another mechanism for metal removal. It can be concluded from the literature that surface physical sorption had a limited effect or less significant contribution than other mechanisms when using biochar to remove metals from solution. For example, Poo et al. (2018) reported that physical sorption could be disregarded when using algae-based biochar to remove Cu, Cd and Zn. Also, Tran et al. (2016) reviewed several studies and summarised that physical sorption has less importance than oxygen-containing function groups. However, physical sorption was responsible for Mn removal in the simultaneous removal of Fe, Al, Zn, Cu, As, and Mn by poultry litter biochar (Oh and Yoon, 2013). Unlike for other metals, pH changes had no effects on Mn removal. Other mechanisms, such as ion exchange or interactions between cations and electrons, may be responsible for Mn removal, but this is still unclear (Oh and Yoon, 2013). Thus, based on the discussion above, further detailed research is needed on the mechanism of metal removal with biochar and the relative contributions of these mechanisms. In addition, Mn removal by biochar is still poorly understood, and more research is needed to determine the main mechanism of Mn removal.

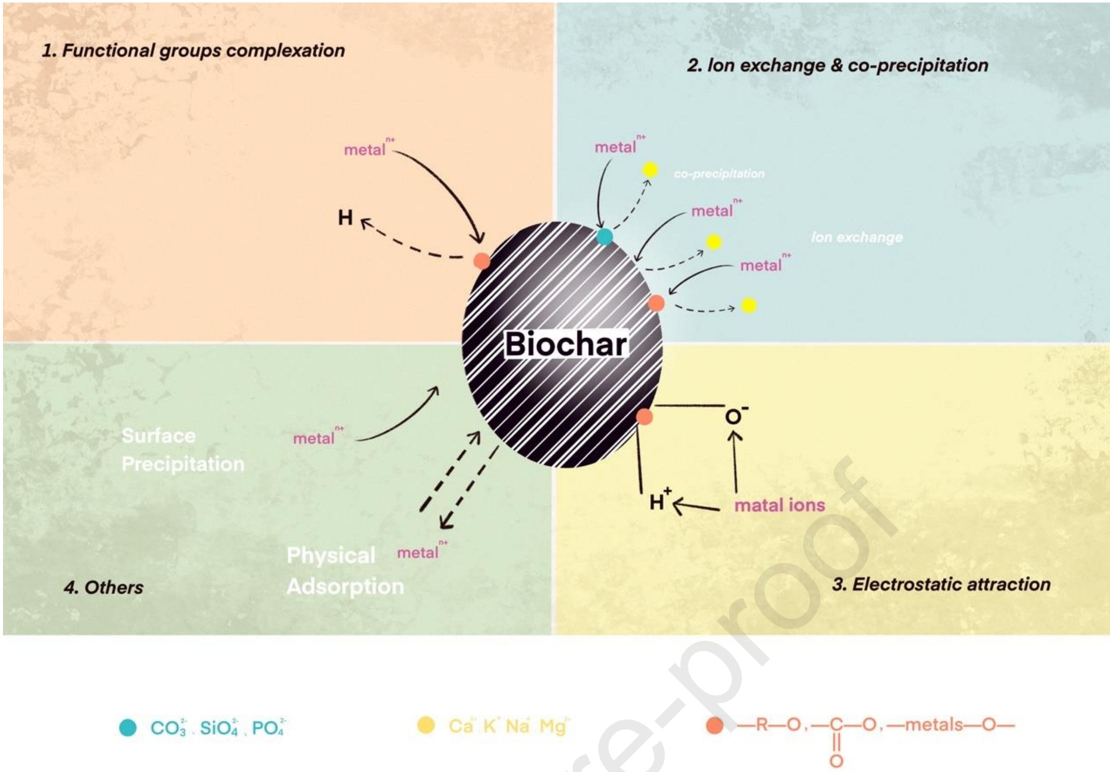

Figure 2. The mechanisms of heavy metal removal by biochar, modified from Tan et al. (2015).

3.2 Novel developments of biochar for AMD treatment

Novel developments of biochar focus mainly on pyrolysis methods and modification processes. Compared with conventional pyrolysis methods, some new trends of pyrolysis can improve the removal capacity of biochar (Wang et al., 2020). For example, Wang et al. (2020) mentioned that microwave-assisted pyrolysis could change biochar morphology (for example, surface area) to make it more suitable for removing metals and organic pollutants. In addition, microwave pyrolysis can increase the number of biochar functional groups, contributing to metal adsorption (Shirvanimoghaddam et al., 2022).

Hydrothermal pyrolysis is another novel pyrolysis method, used mainly for feedstock with high water content, such as animal excreta and sewage sludge (Shan et al., 2020). This method usually heats the feedstock at a relatively low temperature (120-250 ˚C) without pre-drying (Xiang et al., 2020). Wang et al. (2020) reviewed several studies on hydrothermal pyrolysis biochar and concluded that hydrothermal pyrolysis could introduce more oxygen-containing functional groups (-OH and -COOH) into biochar. Furthermore, hydrothermal pyrolysis is a cost-effective and simple method, due to its lower heating temperature, and there is no requirement for oxygen-limited conditions.

Recently, novel modification methods have enhanced biochar performance in metal removal. Yin et al. (2022) compared three types of oxidant-modified *Platanus orientalis* Linn leaf biochar (modified by H_2O_2, $KMnO_4$ and $K_2Cr_2O_7$, respectively) for Cd removal. Among these three types of biochar, the $KMnO_4$ modified biochar had the best performance in removing Cd. It removed 98.57% of Cd with the highest adsorption capacity of 54.7 mg g^{-1}. BET and FTIR analyses confirmed that $KMnO_4$ modified biochar had a higher specific surface, and MnO_x introduced by $KMnO_4$ can form inner-sphere complexes with oxygen-containing groups and has a strong affinity for metal cations (Yin et al., 2022). Ahmed et al. (2021) modified watermelon seed biochar with 30% H_2O_2 and used it to remove Pb from the synthetic AMD water. Results showed that the H_2O_2 could introduce more hydroxyl and carboxyl groups to modified biochar, with a higher adsorption capacity (25.57-44.74 mg g^{-1}) than unmodified biochar (10.82-32.07 mg g^{-1}). In addition, Wang et al. (2021) investigated Pb removal by K_2FeO_4 modified sludge biochar. The adsorption capacity of K_2FeO_4 modified biochar was found to be six times higher than the original biochar due to much more numbers of functional groups on the modified biochar.

Also, biochar modification by nanomaterials is another novel development of biochar for metal removal. The nanomaterials used for biochar modification are usually carbonaceous materials, metal oxides, and metals. Generally, nanomaterial modification biochar has better physicochemical properties and is more dispersible than conventional biochar (Zhao et al., 2021). Yang et al. (2021) studied nano-FeS and chitosan-modified soy sauce residue biochar for Cr removal. The results showed that when nano-FeS:chitosan:biochar mass ratios were 1:1:1, the adsorption capacity reached its highest value of 103.9 mg g^{-1}. This adsorption capacity was almost five times higher than conventional soy sauce residue biochar (22.5 mg g^{-1}). Similar to the oxidant modified biochar, nanomaterials can boost the adsorption capacity by increasing the specific surface area and the number of oxygen-containing functional groups (Zhao et al., 2021).

For the modified biochars mentioned above, almost all studies found that modified biochar has a faster adsorption process when used for AMD treatment. Ahmed et al. (2021), Wang et al. (2021) and Yin et al. (2022) confirmed that the modified biochar could reach the adsorption equilibrium within 1 hour, while conventional biochar may need 2-12 hours. The rapid adsorption process is caused by the number of pore channels and functional groups on the modified biochar that is sufficient to provide active sites (Yin et al., 2022).

In terms of pH, some modified biochar can still be affected by low pH conditions. In general, the favourable pH for maximum adsorption is around 4-5 (Ahmed et al., 2021; Yin et al., 2022). One reason for this is that, in acid conditions, H^+ can inhibit metal removal by strongly competing with metal ions for adsorption, resulting in lower adsorption capacity (Yin et al., 2022). This competition may also happen when using conventional biochar in a lower condition. However, Ahmed et al. (2021) reported that competition for active sites between metal ions and protons may happen in acidic conditions at the initial stages. Nevertheless, the effect of H^+ is considered a promoting factor at a low pH range. They also reported that electrostatic repulsion has an inhibitory effect on metal adsorption at low pH. The same reason (electrostatic repulsion) is also mentioned in Cr adsorption by a nanoscale Fes/chitosan biochar (Y. Yang et al., 2021). However, some modified biochar cannot be affected by extreme low pH and reach the maximum adsorption. For example, Wang et al. (2021) mentioned that K_2FeO_4 modified sludge biochar could reach the maximum Pb adsorption capacity at pH 2. Yang et al.(2021) also reported nanoscale biochar could achieve the maximum adsorption of Cr at pH 2. Compared with other modified and conventional biochars, these biochars have a large abundance of functional groups to resist the effects caused by low pH, which provides more opportunities for complexation (Y. Yang et al., 2021). Thus, some modified biochar may solve the problems caused by extreme low pH, which can be an excellent advantage when used for AMD treatment.

However, both oxidant and nanomaterial introduce additional metals during the modification process. Thus, it is necessary to assess the stability of these methods and their environmental risks in further study. Also, due to the small particle size of nanomaterials, nanomaterial modified biochar is dispersible and difficult to separate from AMD, which may not be favourable for reuse and recycling. Further research should consider an effective isolation and recycling method to solve this problem (Zhao et al., 2021).

3.3 Parameters that affect biochar adsorption capacity

a) Initial heavy metal concentration

The initial heavy metal concentration in AMD solution can affect the adsorption capacity of biochar. Liu and Zhang (2009) showed that with Pb concentration increasing from 10 mg L^{-1} to 20 mg L^{-1}, the adsorption capacity increased approximately two-fold for pinewood and rice husk biochars. Kılıç et al. (2013) used almond shell biochar (produced at 600 ˚C) to remove Ni and Co and found similar trends. However, Pellera et al. (2012) showed that increasing the initial Cu concentration caused an increase in Cu removal per mass unit by biochar but a decrease in total Cu removal produced from rice husk, olive pomace, orange peel, and compost. The observed positive relationship between initial metal concentration and biochar adsorption capacity may have two explanations: firstly, the increased metal concentration may increase the possibility of metal ions coming into contact with biochar; secondly, the increase might be due to more metal ions in the solution inducing the release of H^+ from the surface of biochar, which then leads to more adsorption sites on the biochar (Abdelhafez and Li, 2016; Liu and Zhang, 2009). Also, increasing metal concentration can increase the driving force of mass transfer, which can cause increased metal removal per mass unit (Pellera et al., 2012). The decrease in metal removal by biochar may be explained by the saturation of active sites on the biochar surface (Pellera et al., 2012).

b) Biochar dosage

Many studies have suggested that the biochar dosage is a critical parameter that can affect the heavy metal removal capacity of biochar. Most of the literature found that an increased ratio of biochar to water increased the total amount of heavy metal removal but decreased the biochar removal efficiency. For example, Chen et al. (2011) reported that in a Cu removal experiment by corn straw biochar, the biochar adsorption dropped from 11.82 mg g^{-1} to 1.18 mg g^{-1} when increasing the biochar concentration from 1 g L^{-1} to 50 g L^{-1}. Meanwhile, the Cu removal rate increased from 19.7% to 98.3% due to the increased biochar concentration. These findings are supported by other studies (Pellera et al., 2012; Regmi et al., 2012; S. Wang et al., 2015). Based on the findings from the literature, it is important to use appropriate biochar dosages when removing metal, particularly for practical use. Appropriate biochar dosage can be cost-effective and yield maximum results.

c) pH of contaminated water

The pH of contaminated water is another parameter that controls the mechanisms of heavy metal removal by biochar. Many studies that used biochar to remove Cu, Pb, and Cd demonstrated that a solution with pH around 5-6 was optimal for the highest metal removal efficiency (Abdelhafez and Li, 2016; Chen et al., 2011; Jiang et al., 2016; Liu and Zhang, 2009; Pellera et al., 2012; H. Wang et al., 2015). However, there are also examples of better removal efficiency at solution pH outside this range. For instance, Park et al. (2017) reported that the adsorption of Cd using biochar reached a peak at pH >8. This was explained by electrostatic interaction between the metal ions and biochar surface. At a lower pH, the excessive protonation of the biochar results in competition for binding sites between H_3O^+ and $Cd^{2+,}$ while at a higher pH, the adsorbing sites are vacant for Cd adsorption.

Furthermore, other processes, such as metal precipitation/co-precipitation, can occur at higher pH levels (pH>8) (Park et al., 2017). In contrast, Abdel-Fattah et al. (2015) showed that Cr removal by pinewood biochar (5 g L^{-1}) reached maximum capacity (35.4 mg g^{-1}) at pH of 1. At low pH, the protonation favours the formation of an ion-pair interaction mechanism between chromate anions ($HCrO_4^-$) and the positively charged functional groups (Shaheen et al., 2019).

4. Bacteria application in AMD treatment

Forty studies were identified and selected for review (screened from 4041 initial literature results from 2006 and 2022) from published literature on using microbial treatments for AMD remediation. The metal removal efficiency reported by these studies has a wide range, from 18% to 99%. In addition, these studies used different carbon sources, for example, ethanol and organic waste. A summary of the studies focused on metal removal by bacteria is shown in Table 3 and discussed in the following sub-sections.

Table 3. Bacteria used for heavy metal removal from AMD.

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
Sulfate reducing bacteria (SRB)	Ethanol	Inversed fluidised bed bioreactors (IFBs)	Zn and Cu 25	Zn and Cu >90%	Janyasuthiwong et al. (2015)
SRB	Maise straw	Immobilised SRB sludge beads	Fe 469, Cu 88, Cd 92, Zn 128	Fe, Cu, Cd, and Zn >99.9%	Zhang et al. (2016)
SRB	Chitinous material	Sulfate-reducing bioreactors (SRBRs),	Cd 0.267, Fe 106, Mn 1.50, Zn 72.9	Cd 0.096 mg g^{-1}, Fe 0.748.30 mg g^{-1}, Mn 0.023 mg g^{-1}, Zn 3.07 mg g^{-1}	Al-Abed et al. (2017)

545 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
SRB	Zero-valent iron (ZVI)	Continuous-flow bioreactors	Cu 50.0, Cd 10, Pb 2.4	Cu, Cd, Pb>99.8%	Ayala-Parra et al. (2016a)
SRB		acidophilic and autotrophic biocathode	Zn 15-40	Zn 25 mg g^{-1} (99%)	Teng et al. (2016)
SRB	Algae (*Chlorella sorokiniana*)	Permeable reactive barriers (PRB)	Cu 10-50	Cu >99.5%	Ayala-Parra et al. (2016b)
SRB	Graphene oxide	Laboratory-scale experiment	Ni 59.0, Cu 64, Fe 56, Cd 112, Cr 52, Pb 207, Ti 48	Ni 98.1%, Pb 97.1%, Ti 91%, Cu 89.2%, Fe 77.0%, Cd 51.5%, Cr 12.4%	Yan et al. (2018)

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547 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
SRB	Manures, woodchips and sawdust, sugarcane waste and fodder	Bench-scale bioreactors	Fe 188.9, Cu 22.2, Zn 21.4, Mn 31.9, Ni 10.4, Co 1.2	Fe 51.49%–99.32%, Cu 84.95%–99.97%, Zn 35.11%–99.78%, Ni 17.87%–99.14%, Co 63.55%–99.02%, Mn12.68%–73.86%	Choudhary & Sheoran (2012)
SRB	Ethanol	Anaerobic sequential batch reactor (ASBR)	Fe 100-400, Zn 20-40, Cu 5.0-10	Fe > 99.2%, Zn 100%, Cu > 93.3%	Costa et al. (2017)
Acidithiobacillus ferrooxidans	Glucose	Biomineralization system	Fe 4378	Fe 89%	X. Wang et al. (2021)

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549 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
SRB	Ethanol	Sulfate reducing anaerobic membrane bioreactor (AnMBR)	Fe 37.5 ± 2.7, Cu 12.4 ± 0.7, Zn 2.50 ± 0.42, Co 2.50 ± 0.1, Mn 2.9 ± 0.2, Ni 1.42 ± 0.08, As 1.5 ± 0.18	Fe, Cu, Zn, Co, and Ni > 99.0%, Mn 76.0%-91.0%, As 41.0%-67.0%	Sahinkaya et al. (2019)
Acidithiobacillus ferrooxidans	ZVI	Laboratory-scale experiment	Fe 2234	Fe 98.4%	Wang et al. (2019)
SRB	Ethanol	Anaerobic sequential batch reactor (ASBR)	Fe 100, Zn 20, Cu 5.0	Fe, Zn and Cu > 99.0%	Castro Neto et al. (2018)

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551 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	Carbon source/electron donor	Experiment methods	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
SRB	Ethanol	Laboratory-scale sulfate-reducing columns	Cu 100, Ni 10, Zn 10	Cu, Ni and Zn > 99.2%	Sierra-Alvarez et al. (2006)
SRB	Ethanol	Anaerobic bottles	Cu 10, Fe 55, Zn 32	Cu 99.99%, Fe 87.6%, Zn 99.9%	Zhao et al. (2018)
SRB	Leaves 6%, compost 9%, Fe (0) 3%, silica sand 30%, perlite 30%, limestone 22%	Fixed bed reactor	Cd 11, Cr 51, Cu 64, Zn 65, As 2.0	Cu, Zn, Cr, Cd, and As >98%	Cruz Viggi et al. (2010)

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Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	Carbon source/electron donor	Experiment methods	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
SRB	Limestone 40%, spent mushroom compost 30%, activated sludge 20% and woodchips 10%.	Up-flow anaerobic packed-bed bioreactor	Al 44, Fe 5.8, Cu 4.6, Pb 0.5, Zn 5.9	Fe, Pb, Cu, Zn and Al 87%-100%	Muhammad et al. (2018)
SRB	H_2S	Sulfidogenic bioreactor	Cu 325	Cu 90%	Silva et al. (2019)
SRB	Zero-valent iron (ZVI) and Zero-valent copper (ZVC)	Laboratory-scale experiment	Pb, Zn and Cu 50	Pb, Cu and Zn 100%,	Hu et al. (2018)
SRB	Ethanol	fluidised-bed reactor (FBR)	Cu 300, Fe 150	Cu and Fe >99%	Ucar et al. (2011)

556 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
SRB	Iron	Up-flow anaerobic multiple-bed (UAMB)	Cu 20, Fe 55	Cu 99%, Fe 86%	Bai et al. (2013)
SRB	Rice wine waste	Laboratory-scale experiment	Fe 192, Al 104	Al > 97%, Fe >87%	G.-M. Kim et al. (2014)
Acidithiobacillus (Bacillus licheniformis, Bacillus firmus and *Bacillus megaterium)*	Ethanol	Laboratory-scale experiment	As 100	As 90%-95%	Natarajan (2017)
SRB	Lignite	Activated lignite-immobilised SRB	Cu 10, Zn 20	Cu 99.59%, Zn 99.93%	Di et al. (2022)

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558 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
SRB	Landfill leachate	Sulfidogenic fluidised-bed reactor	Cu 0.014, Fe 4.0, Zn 0.47, Cr 0.55	Cu, Fe, Cr, and Zn 82.0-99.9%	Sahinkaya et al. (2013)
SRB	ZVI	Glass batch reactors	Cr and Zn 10-90	Cr and Zn > 99%	Guo et al. (2017)
SRB	Sodium lactate	Laboratory-scale experiment	Zn 260	Zn under detection	Castillo et al. (2012)
SRB	Cow manure and activated sewage sludge	Cooperation with dried poultry litter pellets (400 °C) biochar	Fe 2460, Al 1295, Pb 1.2, Zn 19.2, Cr 0.3	Al, Cr, Fe, Pb and Zn 100%.	Giachini et al. (2018)
Iron-oxidising bacteria	Tryptone soy broth	Ceramic membrane bioreactor	Fe 250-3000	Fe 99%	Demir et al. (2020)

559 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	Carbon source/electron donor	Experiment methods	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
SRB	Sodium lactate	Sodium alginate immobilised sulfate reducing bacteria	Cu and Zn 50-150	Cu 99%, Zn 95.8%	Gopi Kiran et al. (2018)
SRB	Sodium lactate	Laboratory-scale experiment	Ni, Cd, Zn, Pb, and Fe 5.0-50	Ni 97%, Cd 94.8%, Zn 94.6, Pb 94.4%, Fe 93.9%	Kiran et al. (2017)
SRB	Acetate,	Sulfidogenic up-flow anaerobic sludge blanket (UASB) reactor	Ni 50, Zn 50	Zn 99.99%, Ni 96.87%	Najib et al. (2017)

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561 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	**Carbon source/electron donor**	**Experiment methods**	**AMD composition (mg L^{-1})**	**Metal removal efficiency**	**Reference**
Hermoacidophilic Archaea, Acidianus manzaensis	—	Laboratory-scale experiment	Cu 64, Zn 65	Cu 2.88 mg g^{-1}, Zn 2.17 mg g^{-1}	Li et al. (2020)
SRB	Chicken manure, dairy manure, and sawdust	Column reactor	Fe 599, Mn 29.6, Cu 30, Zn 50.4, Cd 12.2, Ni 16	Removal ability chicken manure > dairy manure > sawdust Cd and Ni 100%, Mn >60%	Zhang and Wang (2014)
SRB	Lactate	Laboratory-scale experiment	Ni 21.5	Ni 100%	Hu et al. (2020)
SRB	Bagasse	Maifanite-reinforced SRB, immobilised	Mn 6	Mn 63.87%	Bao et al. (2021)

562 Table 3. Bacteria used for heavy metal removal from AMD. (Continued).

Bacteria species	Carbon source/electron donor	Experiment methods	AMD composition (mg L^{-1})	Metal removal efficiency	Reference
Fe–Mn oxidising bacteria (*Flavobacterium, Brevundimonas*, *Stenotrophomonas* and *Thermotonus*)	Glucose	Laboratory-scale experiment	Fe 100-1300, Mn 100-700	Fe 99.8%, Mn 99.6%	Hou et al. (2020)
Acidiphilium multivorum *Acidithiobacillus ferrooxidans*	—	Laboratory-scale experiment	Fe 1267	Fe 100%	Jin et al. (2020)
SRB	—	Inverse fluidised bed sulfidogenic bioreactor	Cd, Ni, Pb and Zn 10, Cu 50, Fe 150	Cd, Pb, Zn and Cu > 95%, Fe 90%, Ni 85%,	Kumar and Pakshirajan (2020)

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4.1 Mechanisms of metal removal by sulfate reducing bacteria

Recent studies have focused on biological methods for removing heavy metals from AMDs based on bacteria. Most of these studies used sulfate reducing bacteria (SRB) and showed excellent results (Table 3). SRB are anaerobic microorganisms that use sulfate as an electron acceptor, producing S^{2-} and increasing alkalinity in water, resulting in the generation of insoluble metal sulphates. Thus, SRB can remove metals dissolved in water (Sierra-Alvarez et al., 2006). Other mechanisms can contribute to removing heavy metals from AMD by SRB, as shown in Figure 3. This may depend on different metals, SRB species, and reaction conditions (Zhao et al., 2018). For instance, Cu can be removed by extracellular chelating, whereas Zn and Fe can be removed by bioprecipitation.

For multi-metal contaminated water like AMD, the variety of metal ions can also influence the mechanism of metals removal (Zhao et al., 2018). This phenomenon was also observed by Cruz Viggi et al. (2010), who found it is difficult to distinguish which mechanism is involved in metal removal during the reaction with multi-metal water. Nevertheless, based on the previous study of Cd removal by SRB, Cruz Viggi et al. (2010) showed that sorption accounted for 94% of the removed Cd, and bioreduction took up only 6% of total Cd removed. This result, however, can only explain the Cd removal in this batch experiment. The contribution of different mechanisms for different metals still requires further investigation (Cruz Viggi et al., 2010).

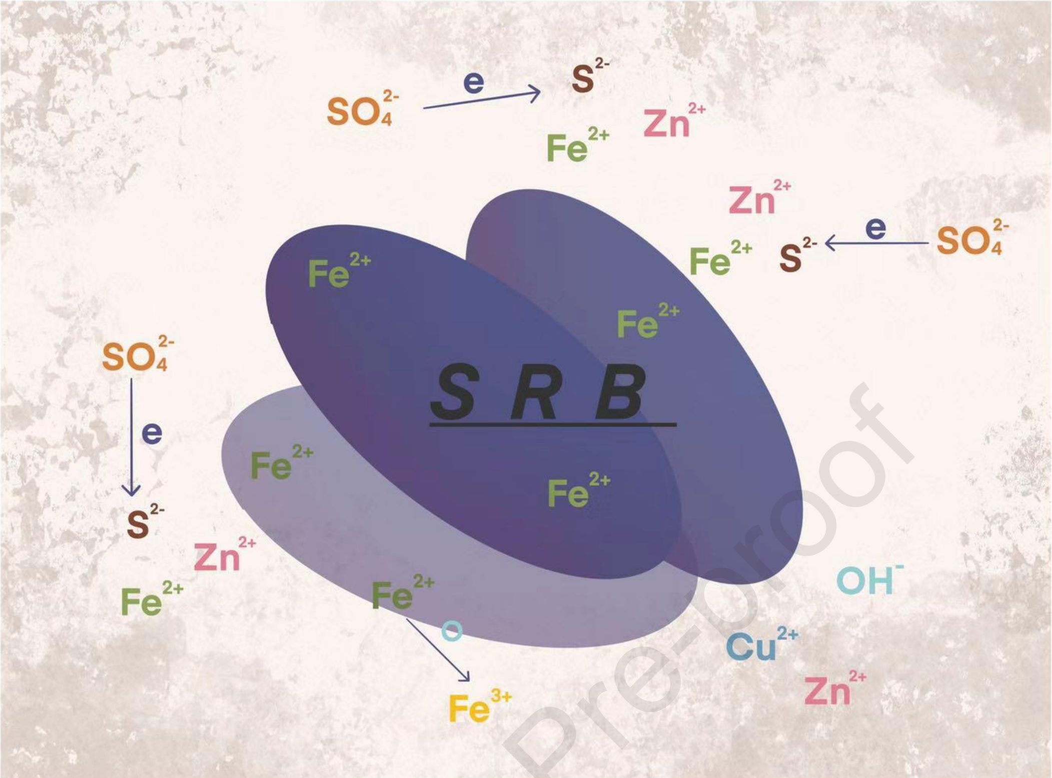

Figure 3. Proposed mechanism for bioremoval of heavy metal ions by SRB, modified from Zhao et al. (2018).

4.2 Metals toxicity affecting sulfate reducing bacteria

Although SRB can successfully remove heavy metals from AMDs, some studies found that heavy metals may be toxic to SRB (Alam and McPhedran, 2019; Gopi Kiran et al., 2018; Kiran et al., 2017; Teng et al., 2016; Wang et al., 2019; Zhang et al., 2016; Zhao et al., 2018). Alam and McPhedran (2019) summarised the findings of several studies regarding metal toxicity to SRB and pointed out that heavy metals mainly influence the activity of enzymes, induce protein denaturation, and compete with cations. These studies also indicated that different metals have different toxicity levels to SRB. For example, Alam and McPhedran (2019) showed that Cd (6 mg L^{-1}), Cr (23 mg L^{-1}), Cu (4 mg L^{-1}), Pb (25 mg L^{-1}), Ni (10 mg L^{-1}) and Zn (13 mg L^{-1}) could inhibit the activity of SRB. However, Zhao et al. (2018) reported that, at 35 ˚C and pH 3, Cu is toxic to SRB at 10 mg L^{-1}. In the study of Teng et al. (2016), Zn was found to have an inhibitory effect on SRB when concentrations reached 40 mg L^{-1}.

However, many other studies observed that even a relatively high concentration of metals in the water had no adverse effects on SRB activity. On the contrary, these high concentrations could improve the ability of SRB to remove metals (Castro Neto et al., 2018; Sierra-Alvarez et al., 2006). For example, Sierra-Alvarez et al. (2006) showed no inhibition process in a column reactor at pH 4.5, even when the Cu concentration reached 50 mg L^{-1}. Another study using an anaerobic stirred batch reactor with Fe (100 mg L^{-1}), Zn (20 mg L^{-1}), and Cu (5 mg L^{-1}), found that these levels did not affect SRB (Castro Neto et al., 2018). Therefore, the inhibition effect is influenced not only by the concentration of metals but also by other experimental conditions (e.g. pH and metal type). In general, pH for experimental inhibition conditions is lower than 5 and higher than 9 (Kushkevych et al., 2019). Also, Hao et al. (2008) indicated the inhibitory concentrations of some metals for SRB i.e. Zn 25-40 mg L^{-1}, Pb 75-80 mg L^{-1}, Cu 4-20 mg L^{-1}, Cd 4-20 mg L^{-1}, Ni 10-20 mg L^{-1} and Cr 60mg L^{-1}.

The difference in metal tolerance in the different experiments may be due to some inorganic cations that can affect heavy metal toxicity for SRB by competing with metals (e.g. Fe, Mg and Ca) for the anionic sites on the SRB surface (Kaksonen and Puhakka, 2007). Also, different metals have different toxicity for SRB (e.g. Cu is higher than Zn), and a combination of various metal toxicity is higher than the sum of the individual metal toxicities (Cossich et al., 2002; Utgikar et al., 2003). Another reason is that the source of the SRB can affect their tolerance to metal toxicity. SRB collected from AMD sites usually has a higher tolerance than those enriched in a batch experiment because of the environment adaption (Kaksonen and Puhakka, 2007).

In order to avoid the toxicity effects on SRB, some studies have used SRB immobilised in beads (Gopi Kiran et al., 2018; Zhang et al., 2016). These beads consisted of a mixture of SRB, maize straw, zero valence iron, silicon sand, polyvinyl alcohol (PVA), and sodium alginate. Immobilised SRB beads provided shelter for SRB, as well as a relatively high specific surface area (Gopi Kiran et al., 2018). In addition, immobilised SRB beads can increase biomass and retention time in reactors (Gopi Kiran et al., 2018; Zhang et al., 2016). Thus, the SRB immobilised beads can be used to avoid the toxicity effect on SRB caused by a high concentration of heavy metals (Zhang et al., 2016). To increase the efficacy of SRB, other methods to reduce the effect of metals' toxicity should be explored in future work.

4.3 Metals removal by SRB

Some metals such as Cu, Fe, Cd, Zn, and Pb can be almost entirely removed from AMD by SRB, while SRB's ability to remove Mn is more varied among published studies (Table 3). The removal efficiency of Mn in the solution was only around 50%, compared to the over 80% for other metals that has been reported by some authors (Bai et al., 2013; Muhammad et al., 2018; Sahinkaya et al., 2013; Zhang and Wang, 2014). There are two possible reasons for these observations. The first is the potentially lower sorption affinity of Mn to organic waste (carbon source). The second reason is the relatively higher solubility of MnS (Ksp = 2.5 x 10^{-13}) compared to the sulfide salt of other metals (Cd, Cu, Zn, and Fe). Thus, Mn^{2+} concentration is higher than other metals in the water. Mn^{2+} presented in a dissolved state for almost the entire reaction time (Muhammad et al., 2018), causing the removal efficiency to be decreased (Zhang and Wang, 2014). Also, because of the complex interaction between Mn and other metals, this solubility of Mn might be affected (Muhammad et al., 2018). However, Mukwevho et al. (2019) reported that Mn removal efficiency could reach 85.9%, which is much higher than the results obtained in previous studies (~50%). Unfortunately, the reason for this is not clear.

The studies mentioned above did not investigate all experimental parameters in their studies, and the higher removal efficiency (80.7%) had a better condition for SRB (pH 6 and 30°C) than that of the lower efficiency (74.8%), with conditions of pH 5 for 30°C and 10°C. Thus, further research needs to be carried out to confirm whether pH and temperature conditions can affect Mn removal by SRB.

4.4 Carbon source and electron donor

In the process of metal removal by SRB, the nature of the carbon source and electron donor is an important factor affecting the metal removal efficiency. In general, lactate is recommended by many studies (Alam and McPhedran, 2019; Gopi Kiran et al., 2018; Kiran et al., 2017), as it supports SRB growth and performs better for metal removal than other carbon sources. Ethanol is another popular carbon source that has been used in many studies (Castro Neto et al., 2018; Janyasuthiwong et al., 2015; Natarajan, 2017; Sahinkaya et al., 2013; Sierra-Alvarez et al., 2006; Ucar et al., 2011). Ethanol has been confirmed as effective in both reactor experiments, e.g. in an anaerobic sequential batch reactor (ASBR) (Costa et al., 2017), and in small lab-scale experiments, e.g. in an anaerobic reactor (Zhao et al., 2018). These studies reported that ethanol could enhance SRB capacity to remove metals. Ethanol is also more competitive in terms of kinetics when compared to lactate under room temperature conditions (Nielsen et al., 2019), and is also cheaper than lactate (Alam and McPhedran, 2019), making it more scalable.

In addition to these simple carbon sources (lactate and ethanol), some studies have used complex organic matter, such as organic waste (e.g. maize straw, leaves and cow manure) as carbon source (Choudhary and Sheoran, 2012; Cruz Viggi et al., 2010;

Giachini et al., 2018; G.-M. Kim et al., 2014; Muhammad et al., 2018; Sahinkaya et al., 2013; Zhang et al., 2016). These organic sources are cheap and can contribute to metal removal because most of them are porous materials. There is evidence that SRB could be enhanced by using complex organic carbon sources (Nielsen et al., 2019). Another advantage of complex organic carbon sources is that they can last longer than simple carbon sources due to their more gradual degradation. Nevertheless, for complex carbon sources, a disadvantage is that sulphate removal yields are lower than those of simple carbon sources (Nielsen et al., 2019).

Besides using organic carbon as the electron donor in the removal of heavy metals by SRB, some metals such as ZVI and ZVC are also used in many studies (Ayala-Parra et al., 2016a; Guo et al., 2017; Wang et al., 2019; Yan et al., 2018). The ZVI can be used by both SRB and *Acidithiobacillus ferrooxidans* in metal removal. Compared with other control studies, ZVI can significantly increase mineral precipitation by enhancing sulfate reduction and generating alkalinity in solution (Hu et al., 2018; Wang et al., 2019). In the combination of ZVI and SRB, ZVI is a reducing agent that can enhance anaerobic conditions and release Fe^{2+}, which is beneficial to SRB hydrogenase (Guo et al., 2017). Also, ZVI can react with heavy metals such as Cr, which can reduce the metals' toxicity to SRB (Guo et al., 2017). However, some disadvantages of ZVI have also been reported, e.g. excessive ZVI is toxic to *Acidithiobacillus ferrooxidans,* and the combination of ZVI and *A. ferrooxidans* results in Fe removal only. The addition of

ZVI did not affect the removal of Zn, Al, and Mn (Wang et al., 2019). Nevertheless, in combination with SRB, ZVI can remove other metals except for Mn (Guo et al., 2017). ZVC has higher removal efficiency than ZVI for Fe, but because ZVC can more easily introduce Cu to the environment, most of the studies only used ZVI (Wang et al., 2019). Overall, carbon sources for SRB in metal removal may vary in different conditions. Factors to consider in selecting a carbon source include metal type, cost, and pH. Further research should focus on finding long-lasting and cost-effective electron donors for practical use.

5. Combination of treatments for AMD

5.1 Combination of algae and biochar

Some studies reported the interactions between biochar and algae (Awad et al., 2017; Jia et al., 2018; Kholssi et al., 2018; Magee et al., 2013; Zhang et al., 2019). In terms of the inhibitory effects between biochar and algae, the result showed that in some conditions, biochar could significantly inhibit the growth of algae. For example, Awad et al. (2017) reported that rice husk biochar might reduce the production of green algae (*Chlamydomonas*. sp and *Scenedesmus*. sp); Zhang et al. (2019) noted that pine needle biochar has adverse effects on algae growth (*Scenedesmus obliquus,* and also the bacterium *Photobacterium phosphoreum*) due to the presence of free radicals; Magee et al. (2013) confirmed that oil mallee biochar could also inhibit the growth of the test algae (*Chlorella vulgaris*) when adding the biochar at an induction phase (12h after incubation of algae); Similar results were also reported by Jia et al. (2018) on the interaction between apple tree biochar and three species of cyanobacteria (*Oscillatoria*. sp, *Phormidium*. sp and *Nostoc*. sp). However, in Kholssi et al.'s (2018) study, the growth of *Anabaena cylindrica* significantly increased with wood biochar solid support compared with liquid media.

The inhibition caused by biochar to algae, as mentioned above, is mainly because 1) porous biochar absorbs algae onto the biochar surface, which blocks nutrient uptake and affects algae growth (Awad et al., 2017); 2) biochar can be suspended in solution and the light intensity reduced, hence reduced algal photosynthesis (Jia et al., 2018; Magee et al., 2013); 3) free radicals in biochar have biotoxicity for algae in solution and reduce algal growth. These free radicals are produced during the biochar pyrolysis processes and are influenced by the pyrolysis temperature. Free radicals may inhibit the germination of seeds, cause growth retardation of roots, and damage the plasma membrane of algae (Zhang et al., 2019); 4) reactive oxygen species (ROS) produced by dissolved biochar can also damage algae by influencing algae photosynthetic growth (Jia et al., 2018; Zhang et al., 2019).

Based on these findings, positive effects between algae and biochar are only valid for specific algae and biochar (Kholssi et al., 2018). Some biochar can boost more extracellular polymeric substances (EPS) of algal origin. These EPS may provide important biological functions by excluding redundant glycogen in algal cells and increasing cell numbers (Kholssi et al., 2018). Also, functional groups on the biochar surface may contribute to the immobilisation of algae and promote algal growth (Shen et al., 2017). In addition, although the porous structure of biochar may have adverse effects on algal growth, porous biochar can serve as a suitable material for attachment and increase the dispersibility of immobilised algae, thus increasing metal sorption processes (Shen et al., 2017). Besides, quick passive adsorption by biochar can increase the viability of algal cells and, and as a result, enhance the metal removal capacity (Shen et al., 2017).

Based on the work reviewed, the biochar-algae system in AMD metal removal has been rarely studied. Two studies did a simple mixture of algae and biochar to remove metals in the solution (Jiang et al., 2022; Shen et al., 2017). Shen et al. (2017) used a combination of *Chlorella* sp. and water hyacinth biochar to investigate Cd removal. The algae and biochar were mixed with a shaker by different algae: biochar ratios (1:4, 2:3, 3:2 and 4:1), and the Cd removal was conducted. It was found that the algal cells were mainly attached to the biochar surface due to the electromagnetic effect. For the Cd removal results, the maximum removal was 217.4 mg g^{-1} when the algae and biochar ratio reached 2:3. This result was better than the metal removals obtained for algae only (169.9 mg g^{-1}) or biochar only (95.8 mg g^{-1}). Likewise, Jiang et al. (2022) performed a similar study using a simple mixture of *Chlorella* sp. and coconut shell biochar to remove Cd from synthetic AMD water. SEM morphology results showed algae were attached very well to the visible pores on the biochar surface. The results also showed that the biochar pores become rough after Cd adsorption. When using algae and biochar together, the biochar became much rougher after Cd adsorption than only biochar adsorption. This also indicated that algae-biochar Cd adsorption had better Cd removal results than Cd adsorption by biochar only. Better Cd removals with a mixture of algae and biochar were due to 1) the algae-biochar consortium has a more negative charge on the surface. Also, the negative charge of the biochar surface can boost the magnetic intensity surrounding the algae, which can enhance the surface potential of biochar (Shen et al., 2017); 2) FTIR results confirmed that the algae-biochar consortium has more types and greater numbers, of functional groups (especially oxygen-containing functional groups) when compared to biochar or algae alone, which may significantly contribute to the removal of Cd (Jiang et al., 2022; Shen et al., 2017). The two studies mentioned above have confirmed that the biochar-algae mixture may have a higher removal efficacy of Cd in solution. However, due to limited studies of algae-biochar consortium on metal removal from AMD, more studies should be conducted in the future to investigate the removal efficacy of this approach to develop new preparation methods for combining algae and biochar. These preparation methods would reduce the potential inhibition of algae growth caused by biochar and potential blockage of the biochar pores by algae, as well as reducing the algae growth-inhibitory caused by biochar, to optimise the metal removal result.

5.2 Combination of algae and bacteria

Several studies also used a combination of algae and bacteria for AMD treatment. Sahoo et al. (2020) reported that an integrated bacteria (SRB)-algal (*Chlorella* sp.) immobilised technology could remove over 95%-99% of metals from AMD in both aerobic and anaerobic conditions. The same technology was also used by Li et al. (2018a), which confirmed that an immobilised SRB-algae (*Scenedesmus obliquus*) bead technology could remove up to 73.58% of sulfate and 98% of Cu. Similar results (74.4% of sulfate and 91.7% of Cu) were also reported by Li et al. (2018a) with the same immobilised technology in the anaerobic reactor *(Chlorella vulgaris*, *Scenedesmus obliquus*, *Selenastrum capricornutum* and *Anabaena spiroides* with SRB). In addition, Ayala-Parra et al. (2016b) reported that a permeable reactive barrier (PRB) technology with SRB and *Chlorella sorokiniana* could remove over 99.5% of Cu from AMD.

Russell et al. (2003) experimented with combining SRB with *Carteria* sp. and *Scenedesmus* sp. for metal removal. The U and Mn were successfully removed, but only *Scenedesmus* sp. showed a relatively high sulfate reduction rate (94.3 g g^{-1} biomass), compared with *Carteria* sp. (43.5 g g^{-1} biomass).

In the algae-SRB system, some studies confirmed that algae could serve as an organic carbon source for SRB (Ayala-Parra et al., 2016b; Das et al., 2009a, 2009b; Faisal et al., 2020; Li et al., 2018b, 2018a; Russell et al., 2003). SRBs are carbon limited in a natural AMD environment and need additional carbon sources for survival and metal removal. Algae can generate dissolved organic carbon to feed the SRB as a carbon source by photosynthesis and under the action of co-existing anaerobic fermentative bacteria (Das et al., 2009a; Li et al., 2018b). EPS produced by algae can also serve as nutrients for SRB (Das et al., 2009a). In return, CO_2 released by bacteria is utilised by algae for growth in AMD conditions (Abinandan et al., 2018). In addition, EPS produced by both microalgae and bacteria can chelate metal ions, decreasing the concentration of the free form, which in turn makes the environment less aggressive for the organisms to thrive in. From an evolutionary viewpoint, bacteria and algae support each other for survival, growth, and even metal removal and sulfate reduction in extreme conditions (Abinandan et al., 2018). The mutualism between SRB and algae for bioremediation in AMD conditions is shown in Figure 4.

Nevertheless, in natural AMD conditions, the metal removal efficacy may be relatively low when using algae as the organic carbon source because other microorganisms compete for electron donors with SRB (Das et al., 2009a; Russell et al., 2003). Immobilised SRB-algae systems and reactors can increase the efficacy of metal removal by algae and SRB (Li et al., 2018b, 2018a; Sahoo et al., 2020). In an immobilised SRB-algae system, SRB can use the secreted carbon source provided by algae more efficiently because immobilised algae are in the vicinity of SRB (Li et al., 2018b). For example, a bioreactor (anaerobic up-flow reactor) can continuously provide a medium for SRB to grow and thus increase the metal removal efficiency (Li et al., 2018b). Thus, it can be concluded that the algae-bacteria system can have a high efficacy of metal removal when compared to individual algal or bacterial systems. Apart from the immobilised method, developing other ways to promote high effectiveness for SRB using algae as a carbon source is still needed.

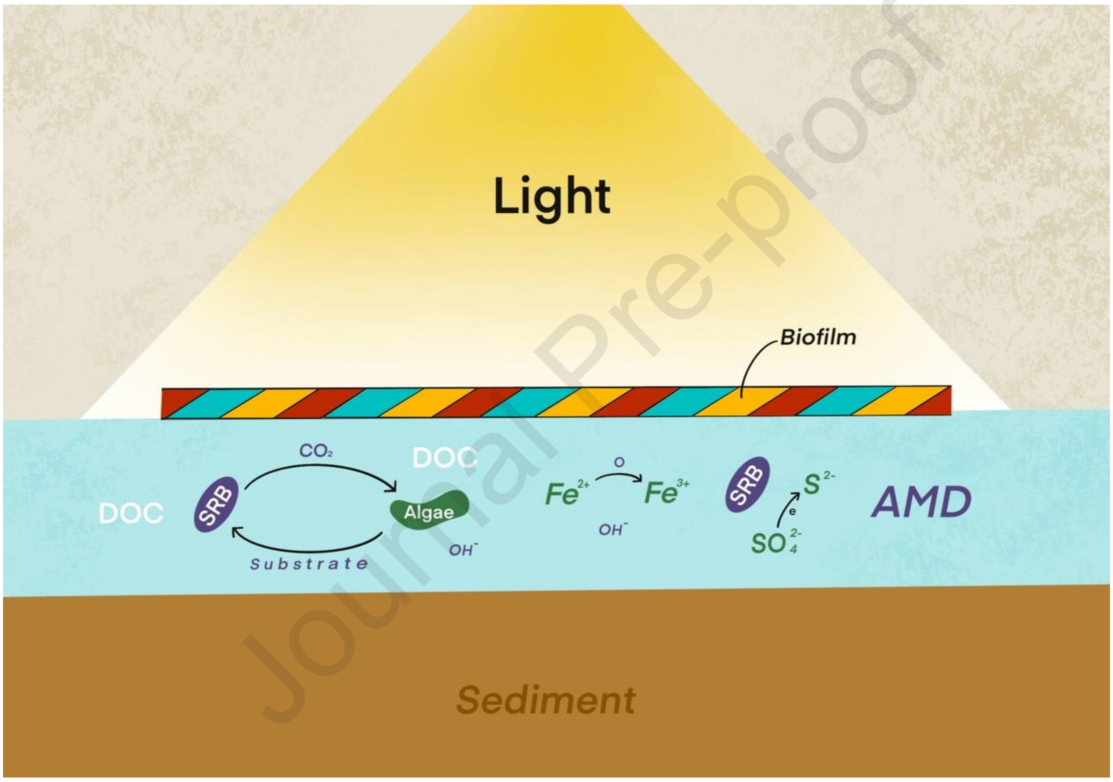

Figure 4. Microalgal-bacteria synergism in biofilms of AMD, modified from Abinandan et al. (2018).

5.3 Algae, bacteria, and biochar

The authors have not found any study that has applied algae, bacteria, and biochar as a consortium to remediate and recover metals from AMD. In a natural AMD environment, bacteria and algae can be present as a consortium (Bernardez and de

Andrade Lima, 2015; Du et al., 2022). In addition, based on the discussion above, one novel aspect of our exploratory approach is to use biochar as a porous support medium for the growth of the algal-bacteria consortium (Figure 5). Biochar can act as the “protective buffer” to provide a porous matrix for bacterial attachment since it can trigger rapid passive uptake of some heavy metal ions, leading to less damage to cells inside (Mehrotra et al., 2021; Retnaningrum et al., 2021). It was mentioned above that algae could serve as a carbon source for bacteria (e.g. SRB), supporting their growth, which in turn produce key nutrients and CO_2 required for the photosynthetic algae. Biochar may not only provide a large surface area for biofilm production but may also facilitate low-cost harvesting of the metal-laden algae and subsequent recovery of the metal from ash by burning. Indeed, harvesting from bulk culture is one of the bottlenecks to the commercialisation of microalgal technologies, as there is no cost-effective harvesting method (Barros et al., 2015; Singh and Patidar, 2018). Moreover, biochar contains K, P, Ca, etc. and would therefore be able to function as a nutrition supply/growth medium for the consortium. Also, if AMD itself is inoculated with nutrients, it may be possible that the biochar will adsorb further nutrients due to its high adsorption capacity, attracting algae to grow on the surface of the biochar (Muñoz and Guieysse, 2006). With the right environmental conditions, biochar may enhance the self-aggregating process of algae-bacteria (Liu et al., 2017), providing an optimised method to remediate and recover metals from AMD. The algae-bacteria-biochar combination may be advantageous for use in AMD treatment with higher initial metal concentration (Mehrotra et al., 2021). Therefore, further research is recommended to explore the effectiveness of algae-bacteria-biochar consortium for AMD treatment.

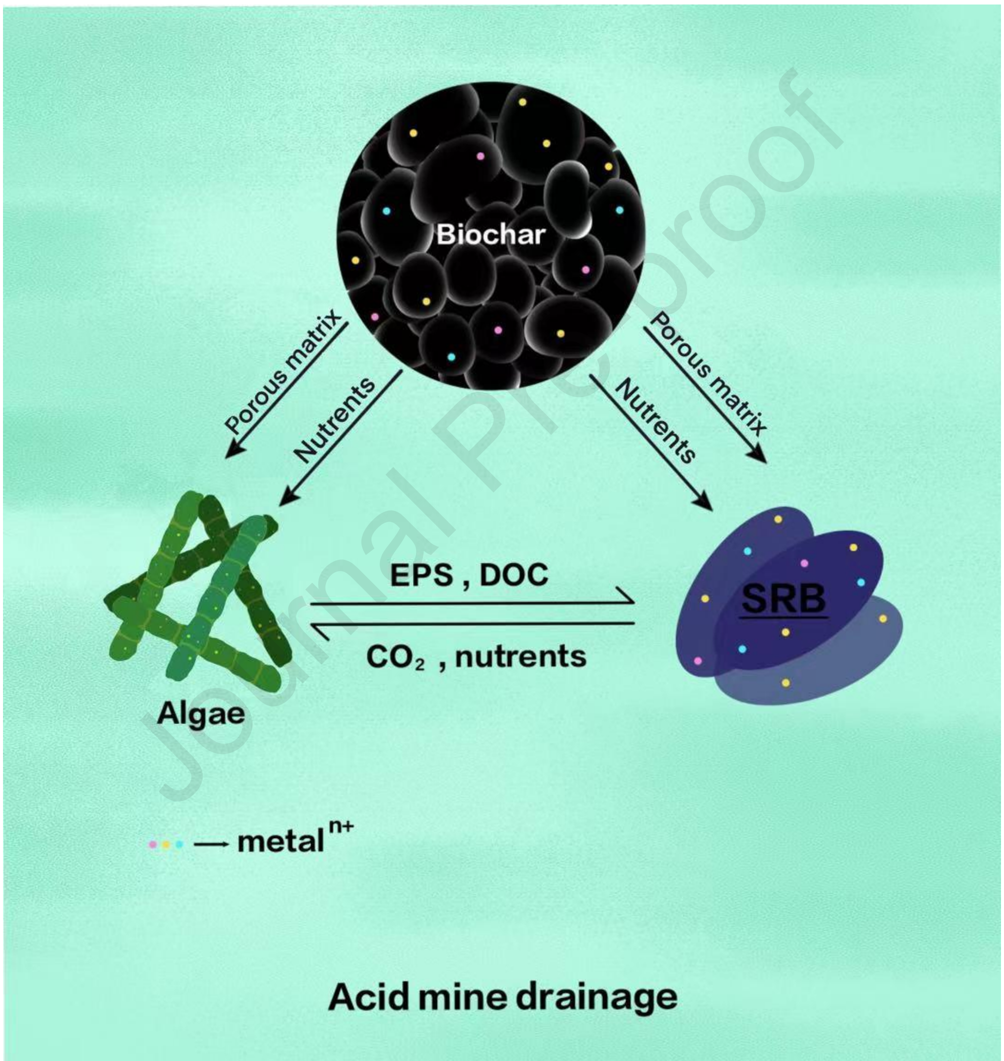

Figure 5. The synergism of algae, bacteria, and biochar consortium in AMD.

6. Conclusion

6.1 Main findings

This review found that all three bio-based methods, when applied as a single process and in combinations (e.g. algae-biochar and algae-bacteria treatments), are effective treatments for AMD. The principal findings of the review are listed below.

- Most algae can reach at least 90% of removal efficacy via an extracellular stage and then an intracellular stage when removing Cu, Zn, Fe, Cd and Cr from AMD. *Chlorella vulgaris*, *Spirulina maxima*, *Oedogonium crissum* and some other types of algae were found to be effective (over 70 mg. g^{-1}) in metal removal from AMDs.
- Feedstock and pyrolysis temperature are two factors that can affect biochar properties and influence the metal removal capacity of biochar. Most of the biochar, for example, hardwood and fruit peel biochar, can reach a relatively high metal removal efficacy (over 100 mg. g^{-1}). The mechanisms are mainly physical sorption, ion exchange, precipitation, complexation, and electrostatic interaction.
- SRB are the most common bacteria used in AMD treatments. It was found that SRB has high metal and sulfate removal ability (60%-100%), mainly by producing insoluble metal sulfide. SRB removal efficacy may be affected by the carbon source. In general, complex carbon sources such as lactate works better than simple carbon such as ethanol. In addition, *Acidithiobacillus*

ferrooxidans was also found to be an effective bacteria method for Fe removal from AMDs.

- The combination of the bio-based methods (i.e. algae-biochar and algae-bacteria) for AMD treatment was found to provide a relatively high removal efficiency (over 200 mg. g^{-1}). Such methods have been observed to have higher metal removal efficiency than those used as a single treatment.

6.2 Limitations and future research

The main limitations identified in previous studies and recommendations for future research are:

- Algae may be inhibited by low pH when removing heavy metals from AMDs. Thus, it needs to be further investigated to facilitate treatment. For example, studies on isolating novel algae strains and modifying algae prior to treatment to avoid the effects caused by pH and increase the removal efficacy should be developed.
- The relationship between temperature and metal removal efficacy by algae is still unclear. Further studies may focus on this to clarify this relationship and establish the optimal temperature conditions for metal removal by algae.
- Secondary contamination and post-treatment recycling are the challenges in AMD treatments by using biochar. The development of novel modifications to overcome the limitations and increase metal removal capacity still needs to be

considered in future work. Also, recycling methods of metals and biochar, especially nanoscale modified biochar, should be further investigated.

- When using bacteria in AMD treatment, the continuous addition of electron donors is still a limitation. This may reduce the effectiveness of remediation processes. Therefore, research may focus on effective alternative electron donors, such as slow-release electron donors and low sulfate condition electron donors. To reduce the toxicity caused by metals, the immobilised method for bacteria may be considered.
- No studies focusing on the algae-bacteria-biochar combination for AMD treatment were found. The authors of this review believe that this consortium may provide a more sustainable and effective process to remove and recover metals from AMD. Therefore, it is recommended that future studies investigate the potential of this consortium.
- However, biochar may inhibit algae's growth, and algae and bacteria may block the pore of biochar. Thus, preparation methods to combine algae, biochar, and bacteria as a consortium are required. Also, the recovery of metals through the consortium algae-biochar-bacteria should also be investigated. This should be tested in lab and pilot-scale experiments for future practical applications.

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Author contributions

Tianhao Du: Investigation, methodology, writing - original draft, visualisation. **Anna Bogush:** Conceptualisation, supervision, writing - review & editing. **Ondřej Mašek**: Conceptualisation, writing - review & editing. **Saul Purton**: Conceptualisation, supervision, writing - review & editing. **Luiza C. Campos**: Conceptualisation, supervision, project administration, writing - review & editing.

Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

References

Abdel-Fattah, T.M., Mahmoud, M.E., Ahmed, S.B., Huff, M.D., Lee, J.W., Kumar, S., 2015. Biochar from woody biomass for removing metal contaminants and carbon sequestration. Journal of Industrial and Engineering Chemistry 22, 103–109. https://doi.org/10.1016/j.jiec.2014.06.030

Abdelhafez, A.A., Li, J., 2016. Removal of Pb(II) from aqueous solution by using biochars derived from sugar cane bagasse and orange peel. Journal of the Taiwan Institute of Chemical Engineers 61, 367–375. https://doi.org/10.1016/j.jtice.2016.01.005

Abinandan, S., Subashchandrabose, S.R., Venkateswarlu, K., Megharaj, M., 2018. Microalgae–bacteria biofilms: a sustainable synergistic approach in remediation of acid mine drainage. Appl Microbiol Biotechnol 102, 1131–1144. https://doi.org/10.1007/s00253-017-8693-7

Ahmed, W., Mehmood, S., Núñez-Delgado, A., Ali, S., Qaswar, M., Shakoor, A., Mahmood, M., Chen, D.-Y., 2021. Enhanced adsorption of aqueous Pb(II) by modified biochar produced through pyrolysis of watermelon seeds. Science of The Total Environment 784, 147136. https://doi.org/10.1016/j.scitotenv.2021.147136

Akcali, I., Kucuksezgin, F., 2011. A biomonitoring study: Heavy metals in macroalgae from eastern Aegean coastal areas. Marine Pollution Bulletin 62, 637–645. https://doi.org/10.1016/j.marpolbul.2010.12.021

Aksu, Z., 2002. Determination of the equilibrium, kinetic and thermodynamic parameters of the batch biosorption of nickel(II) ions onto Chlorella vulgaris. Process Biochemistry 38, 89–99. https://doi.org/10.1016/S0032-9592(02)00051-1

Aksu, Z., 2001. Equilibrium and kinetic modelling of cadmium(II) biosorption by C. 6ulgaris in a batch system: effect of temperature. Separation and Purification Technology 285–294.

Al-Abed, S.R., Pinto, P.X., McKernan, J., Feld-Cook, E., Lomnicki, S.M., 2017. Mechanisms and effectivity of sulfate reducing bioreactors using a chitinous substrate in treating mining influenced water. Chemical Engineering Journal 323, 270–277. https://doi.org/10.1016/j.cej.2017.04.045

Alam, R., McPhedran, K., 2019. Applications of biological sulfate reduction for remediation of arsenic – A review. Chemosphere 222, 932–944. https://doi.org/10.1016/j.chemosphere.2019.01.194

Alcolea, A., Vázquez, M., Caparrós, A., Ibarra, I., García, C., Linares, R., Rodríguez, R., 2012. Heavy metal removal of intermittent acid mine drainage with an open limestone channel. Minerals Engineering 26, 86–98. https://doi.org/10.1016/j.mineng.2011.11.006

Almomani, F., Bhosale, R.R., 2021. Bio-sorption of toxic metals from industrial wastewater by algae strains Spirulina platensis and Chlorella vulgaris: Application of isotherm, kinetic models and process optimization. Science of The Total Environment 755, 142654. https://doi.org/10.1016/j.scitotenv.2020.142654

Alpers, C.N., Nordstorm, D.K., 1997. Geochemical Modeling of Water-Rock Interactions in Mining Environments. The Environmental Geochemistry of Mineral Deposits 289–323. https://doi.org/10.5382/Rev.06.14

Al-Rub, F.A.A., El-Naas, M.H., Benyahia, F., Ashour, I., 2004. Biosorption of nickel on blank alginate beads, free and immobilized algal cells. Process Biochemistry 39, 1767–1773. https://doi.org/10.1016/j.procbio.2003.08.002

Al-Shwafi, N.A., Rushdi, A.I., 2008. Heavy metal concentrations in marine green, brown, and red seaweeds from coastal waters of Yemen, the Gulf of Aden. Environ Geol 55, 653–660. https://doi.org/10.1007/s00254-007-1015-0

Awad, Y.M., Lee, S.-E., Ahmed, M.B.M., Vu, N.T., Farooq, M., Kim, I.S., Kim, H.S., Vithanage, M., Usman, A.R.A., Al-Wabel, M., Meers, E., Kwon, E.E., Ok, Y.S., 2017. Biochar, a potential hydroponic growth substrate, enhances the nutritional status and growth of leafy vegetables. Journal of Cleaner Production 156, 581–588. https://doi.org/10.1016/j.jclepro.2017.04.070

Ayala-Parra, P., Sierra-Alvarez, R., Field, J.A., 2016a. Treatment of acid rock drainage using a sulfate-reducing bioreactor with zero-valent iron. Journal of Hazardous Materials 308, 97–105. https://doi.org/10.1016/j.jhazmat.2016.01.029

Ayala-Parra, P., Sierra-Alvarez, R., Field, J.A., 2016b. Algae as an electron donor promoting sulfate reduction for the bioremediation of acid rock drainage. Journal of Hazardous Materials 317, 335–343. https://doi.org/10.1016/j.jhazmat.2016.06.011

Bai, H., Kang, Y., Quan, H., Han, Y., Sun, J., Feng, Y., 2013. Treatment of acid mine drainage by sulfate reducing bacteria with iron in bench scale runs. Bioresource Technology 128, 818–822. https://doi.org/10.1016/j.biortech.2012.10.070

Bansod, S.R., Nandkar, P.B., 2016. Biosorption of Mn (II) by Spirogyra verrucosa collected from Manganese Mine Water. Plant Sci. Today 3, 282. https://doi.org/10.14719/pst.2016.3.3.244

Bao, S., Di, J., Dong, Y., Wang, X., Xue, L., Sun, J., 2021. Optimization of preparation conditions of sulfate-reducing bacteria (SRB) immobilization particles strengthened by maifanite and its treatment of wastewater containing Mn^{2+}. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 1–14. https://doi.org/10.1080/15567036.2021.2009062

Barros, A.I., Gonçalves, A.L., Simões, M., Pires, J.C.M., 2015. Harvesting techniques applied to microalgae: A review. Renewable and Sustainable Energy Reviews 41, 1489–1500. https://doi.org/10.1016/j.rser.2014.09.037

Beigzadeh, P., Moeinpour, F., 2016. Fast and efficient removal of silver (I) from aqueous solutions using aloe vera shell ash supported Ni0.5Zn0.5Fe2O4 magnetic nanoparticles. Transactions of Nonferrous Metals Society of China 26, 2238–2246. https://doi.org/10.1016/S1003-6326(16)64341-8

Bernardez, L.A., de Andrade Lima, L.R.P., 2015. Improved method for enumerating sulfate-reducing bacteria using optical density. MethodsX 2, 249–255. https://doi.org/10.1016/j.mex.2015.04.006

Bogush, A.A., Lazareva, E.V., 2011. Behavior of heavy metals in sulfide mine tailings and bottom sediment (Salair, Kemerovo region, Russia). Environ Earth Sci 64, 1293–1302. https://doi.org/10.1007/s12665-011-0947-6

Bogush, A.A., Voronin, V.G., Tikhova, V.D., Anoshin, G.N., 2016. Acid Rock Drainage Remediation and Element Removal Using a Peat-Humic Agent with Subsequent Thermal Treatment of the Metal–Organic Residue. Mine Water Environ 35, 536–546. https://doi.org/10.1007/s10230-015-0380-2

Braghiroli, F.L., Bouafif, H., Neculita, C.M., Koubaa, A., 2019. Performance of Physically and Chemically Activated Biochars in Copper Removal from Contaminated Mine Effluents. Water Air Soil Pollut 230, 178. https://doi.org/10.1007/s11270-019-4233-7

Brar, K.K., Etteieb, S., Magdouli, S., Calugaru, L., Brar, S.K., 2022. Novel approach for the management of acid mine drainage (AMD) for the recovery of heavy metals along with lipid production by Chlorella vulgaris. Journal of Environmental Management 308, 114507. https://doi.org/10.1016/j.jenvman.2022.114507

Buhani, Wijayanti, T.A., Suharso, Sumadi, Ansori, M., 2021. Application of modified green algae Nannochloropsis sp. as adsorbent in the simultaneous adsorption of methylene blue and Cu(II) cations in solution (preprint). In Review. https://doi.org/10.21203/rs.3.rs-64063/v2

Bwapwa, J.K., Jaiyeola, A.T., Chetty, R., 2017. Bioremediation of acid mine drainage using algae strains: A review. South African Journal of Chemical Engineering 24, 62–70. https://doi.org/10.1016/j.sajce.2017.06.005

Cai, T., Liu, X., Zhang, J., Tie, B., Lei, M., Wei, X., Peng, O., Du, H., 2021. Silicate-modified oiltea camellia shell-derived biochar: A novel and cost-effective sorbent for cadmium removal. Journal of Cleaner Production 281, 125390. https://doi.org/10.1016/j.jclepro.2020.125390

Carolin, C.F., Kumar, P.S., Saravanan, A., Joshiba, G.J., Naushad, Mu., 2017. Efficient techniques for the removal of toxic heavy metals from aquatic environment: A review. Journal of Environmental Chemical Engineering 5, 2782–2799. https://doi.org/10.1016/j.jece.2017.05.029

Castillo, J., Pérez-López, R., Caraballo, M.A., Nieto, J.M., Martins, M., Costa, M.C., Olías, M., Cerón, J.C., Tucoulou, R., 2012. Biologically-induced precipitation of sphalerite–wurtzite nanoparticles by sulfate-reducing bacteria: Implications for acid mine drainage treatment. Science of The Total Environment 423, 176–184. https://doi.org/10.1016/j.scitotenv.2012.02.013

Castro Neto, E.S., Aguiar, A.B.S., Rodriguez, R.P., Sancinetti, G.P., 2018. ACID MINE DRAINAGE TREATMENT AND METAL REMOVAL BASED ON A BIOLOGICAL SULFATE-REDUCING PROCESS. Braz. J. Chem. Eng. 35, 543–552. https://doi.org/10.1590/0104-6632.20180352s20160615

Chen, C.-Y., Chang, H.-W., Kao, P.-C., Pan, J.-L., Chang, J.-S., 2012. Biosorption of cadmium by CO2-fixing microalga Scenedesmus obliquus CNW-N. Bioresource Technology 105, 74–80. https://doi.org/10.1016/j.biortech.2011.11.124

Chen, X., Chen, G., Chen, L., Chen, Y., Lehmann, J., McBride, M.B., Hay, A.G., 2011. Adsorption of copper and zinc by biochars produced from pyrolysis of hardwood and corn straw in aqueous solution. Bioresource Technology 102, 8877–8884. https://doi.org/10.1016/j.biortech.2011.06.078

Chi, T., Zuo, J., Liu, F., 2017. Performance and mechanism for cadmium and lead adsorption from water and soil by corn straw biochar. Frontiers of Environmental Science & Engineering 11. https://doi.org/10.1007/s11783-017-0921-y

Chojnacka, K., Chojnacki, A., Górecka, H., 2005. Biosorption of Cr3+, Cd2+ and Cu2+ ions by blue–green algae Spirulina sp.: kinetics, equilibrium and the mechanism of the process. Chemosphere 59, 75–84. https://doi.org/10.1016/j.chemosphere.2004.10.005

Choudhary, R.P., Sheoran, A.S., 2012. Performance of single substrate in sulphate reducing bioreactor for the treatment of acid mine drainage. Minerals Engineering 39, 29–35. https://doi.org/10.1016/j.mineng.2012.07.005

Cossich, E.S., Granhen Tavares, C.R., Kakuta Ravagnani, T.M., 2002. Biosorption of chromium(III) by Sargassum sp. biomass. Electron. J. Biotechnol. 5, 0–0. https://doi.org/10.2225/vol5-issue2-fulltext-4

Costa, J.M., Rodriguez, R.P., Sancinetti, G.P., 2017. Removal sulfate and metals Fe +2 , Cu +2 , and Zn +2 from acid mine drainage in an anaerobic sequential batch reactor. Journal of Environmental Chemical Engineering 5, 1985–1989. https://doi.org/10.1016/j.jece.2017.04.011

Cruz, C.C.V., da Costa, A.C.A., Henriques, C.A., Luna, A.S., 2004. Kinetic modeling and equilibrium studies during cadmium biosorption by dead Sargassum sp. biomass. Bioresource Technology 91, 249–257. https://doi.org/10.1016/S0960-8524(03)00194-9

Cruz Viggi, C., Pagnanelli, F., Cibati, A., Uccelletti, D., Palleschi, C., Toro, L., 2010. Biotreatment and bioassessment of heavy metal removal by sulphate reducing bacteria in fixed bed reactors. Water Research 44, 151–158. https://doi.org/10.1016/j.watres.2009.09.013

Cui, X., Fang, S., Yao, Y., Li, T., Ni, Q., Yang, X., He, Z., 2016. Potential mechanisms of cadmium removal from aqueous solution by Canna indica derived biochar. Science of The Total Environment 562, 517–525. https://doi.org/10.1016/j.scitotenv.2016.03.248

da Costa, A.C.A., de França, F.P., 2003. Cadmium Interaction with Microalgal Cells, Cyanobacterial Cells, and Seaweeds; Toxicology and Biotechnological Potential for Wastewater Treatment. Mar. Biotechnol. 5, 149–156. https://doi.org/10.1007/s10126-002-0109-7

Das, B.K., Roy, A., Koschorreck, M., Mandal, S.M., Wendt-Potthoff, K., Bhattacharya, J., 2009a. Occurrence and role of algae and fungi in acid mine drainage environment with special reference to metals and sulfate immobilization. Water Research 43, 883–894. https://doi.org/10.1016/j.watres.2008.11.046

Das, B.K., Roy, A., Singh, S., Bhattacharya, J., 2009b. Eukaryotes in acidic mine drainage environments: potential applications in bioremediation. Rev Environ Sci Biotechnol 8, 257–274. https://doi.org/10.1007/s11157-009-9161-3

Demir, E.K., Yaman, B.N., Çelik, P.A., Sahinkaya, E., 2020. Iron oxidation in a ceramic membrane bioreactor using acidophilic bacteria isolated from an acid mine drainage. Journal of Water Process Engineering 38, 101610. https://doi.org/10.1016/j.jwpe.2020.101610

Di, J., Jiang, Y., Wang, M., Dong, Y., 2022. Preparation of biologically activated lignite immobilized SRB particles and their AMD treatment characteristics. Sci Rep 12, 3964. https://doi.org/10.1038/s41598-022-08029-y

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, Y., Zheng, B., Cai, X., 2016. Competitive removal of Cd(II) and Pb(II) by biochars produced from water hyacinths: performance and mechanism. RSC Advances 6, 5223–5232. https://doi.org/10.1039/C5RA26248H

Du, T., Bogush, A., Edwards, P., Stanley, P., Lombardi, A.T., Campos, L.C., 2022. Bioaccumulation of metals by algae from acid mine drainage: a case study of Frongoch Mine (UK). Environ Sci Pollut Res. https://doi.org/10.1007/s11356-022-19604-1

Dufresne, K., Neculita, C., Brisson, J., Genty, T., 2015. Metal Retention Mechanisms in Pilot-Scale Constructed Wetlands Receiving Acid Mine Drainage 6.

Faisal, M., Saquib, Q., Alatar, A.A., Al-Khedhairy, A.A. (Eds.), 2020. Cellular and Molecular Phytotoxicity of Heavy Metals, Nanotechnology in the Life Sciences. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-45975-8

Favas, P.J.C., Sarkar, S.K., Rakshit, D., Venkatachalam, P., Prasad, M.N.V., 2016. Acid Mine Drainages From Abandoned Mines, in: Environmental Materials and Waste. Elsevier, pp. 413–462. https://doi.org/10.1016/B978-0-12-803837-6.00017-2

Genty, T., Bussière, B., Potvin, R., Benzaazoua, M., Zagury, G.J., 2012. Dissolution of calcitic marble and dolomitic rock in high iron concentrated acid mine drainage: application to anoxic limestone drains. Environmental Earth Sciences 66, 2387–2401. https://doi.org/10.1007/s12665-011-1464-3

Giachini, A.J., Sulzbach, T.S., Pinto, A.L., Armas, R.D., Cortez, D.H., Silva, E.P., Buzanello, E.B., Soares, Á.G., Soares, C.R.F.S., Rossi, M.J., 2018. Microbially-enriched poultry litter-derived biochar for the treatment of acid mine drainage. Arch Microbiol 200, 1227–1237. https://doi.org/10.1007/s00203-018-1534-y

Gopi Kiran, M., Pakshirajan, K., Das, G., 2018. Heavy metal removal from aqueous solution using sodium alginate immobilized sulfate reducing bacteria: Mechanism and process optimization. Journal of Environmental Management 218, 486–496. https://doi.org/10.1016/j.jenvman.2018.03.020

Guo, J., Kang, Y., Feng, Y., 2017. Bioassessment of heavy metal toxicity and enhancement of heavy metal removal by sulfate-reducing bacteria in the presence of zero valent iron. Journal of Environmental Management 203, 278–285. https://doi.org/10.1016/j.jenvman.2017.07.075

Gupta, V.K., Rastogi, A., 2008. Equilibrium and kinetic modelling of cadmium(II) biosorption by nonliving algal biomass Oedogonium sp. from aqueous phase. Journal of Hazardous Materials 153, 759–766. https://doi.org/10.1016/j.jhazmat.2007.09.021

Hao, O.J., Huang, L., Chen, J.M., Buglass, R.L., 2008. Effects of metal additions on sulfate reduction activity in wastewaters. Toxicological & Envirinmental Chemistry 46, 197–212. https://doi.org/Effects of metal additions on sulfate reduction activity in wastewaters

Hodgson, E., Lewys-James, A., Rao Ravella, S., Thomas-Jones, S., Perkins, W., Gallagher, J., 2016. Optimisation of slow-pyrolysis process conditions to maximise char yield and heavy metal adsorption of biochar produced from different feedstocks. Bioresource Technology 214, 574–581. https://doi.org/10.1016/j.biortech.2016.05.009

Hou, D., Zhang, P., Wei, D., Zhang, J., Yan, B., Cao, L., Zhou, Y., Luo, L., 2020. Simultaneous removal of iron and manganese from acid mine drainage by acclimated bacteria. Journal of Hazardous Materials 396, 122631. https://doi.org/10.1016/j.jhazmat.2020.122631

Hu, K., Xu, D., Chen, Y., 2020. An assessment of sulfate reducing bacteria on treating sulfate-rich metal-laden wastewater from electroplating plant. Journal of Hazardous Materials 393, 122376. https://doi.org/10.1016/j.jhazmat.2020.122376

Hu, X., Lin, B., Gao, F., 2018. Enhanced biotreatment of acid mine drainage in the presence of zero-valent iron and zero-valent copper. J Water Reuse Desalination jwrd2018014. https://doi.org/10.2166/wrd.2018.014

Hudson-Edwards, K.A., Jamieson, H.E., Lottermoser, B.G., 2011. Mine Wastes: Past, Present, Future. Elements 7, 375–380. https://doi.org/10.2113/gselements.7.6.375

Inyang, M.I., Gao, B., Yao, Y., Xue, Y., Zimmerman, A., Mosa, A., Pullammanappallil, P., Ok, Y.S., Cao, X., 2016. A review of biochar as a low-cost adsorbent for aqueous heavy metal removal. Critical Reviews in Environmental Science and Technology 46, 406–433. https://doi.org/10.1080/10643389.2015.1096880

Jacinto, M.L.J.A.J., David, C.P.C., Perez, T.R., De Jesus, B.R., 2009. Comparative efficiency of algal biofilters in the removal of chromium and copper from wastewater. Ecological Engineering 35, 856–860. https://doi.org/10.1016/j.ecoleng.2008.12.023

Jalayeri, H., Pepe, F., 2019. Novel and high-performance biochar derived from pistachio green hull biomass: Production, characterization, and application to Cu(II) removal from aqueous solutions. Ecotoxicology and Environmental Safety 168, 64–71. https://doi.org/10.1016/j.ecoenv.2018.10.058

Janyasuthiwong, S., Rene, E.R., Esposito, G., Lens, P.N.L., 2015. Effect of pH on Cu, Ni and Zn removal by biogenic sulfide precipitation in an inversed fluidized bed bioreactor. Hydrometallurgy 158, 94–100. https://doi.org/10.1016/j.hydromet.2015.10.009

Jia, R., Qu, Z., You, P., Qu, D., 2018. Effect of biochar on photosynthetic microorganism growth and iron cycling in paddy soil under different phosphate levels. Science of The Total Environment 612, 223–230. https://doi.org/10.1016/j.scitotenv.2017.08.126

Jiang, S., Huang, L., Nguyen, T.A.H., Ok, Y.S., Rudolph, V., Yang, H., Zhang, D., 2016. Copper and zinc adsorption by softwood and hardwood biochars under elevated sulphate-induced salinity and acidic pH conditions. Chemosphere 142, 64–71. https://doi.org/10.1016/j.chemosphere.2015.06.079

Jiang, X., Yin, X., Tian, Y., Zhang, S., Liu, Y., Deng, Z., Lin, Y., Wang, L., 2022. Study on the mechanism of biochar loaded typical microalgae Chlorella removal of cadmium. Science of The Total Environment 813, 152488. https://doi.org/10.1016/j.scitotenv.2021.152488

Jin, D., Wang, X., Liu, L., Liang, J., Zhou, L., 2020. A novel approach for treating acid mine drainage through forming schwertmannite driven by a mixed culture of Acidiphilium multivorum and Acidithiobacillus ferrooxidans prior to lime neutralization. Journal of Hazardous Materials 400, 123108. https://doi.org/10.1016/j.jhazmat.2020.123108

Johnston, D., Jones, C., Rolley, S., Waston, I., Pritchard, J., 2008. Abandoned mines and the water environment. Environment Agency, Bristol.

Jones, D., Taylor, J., Pape, S., McCullough, C., Brown, P., Garvie, A., Appleyard, S., Miler, S., Unger, C., Laurencont, T., Slater, S., Williams, D., Scott, P., Fawcwtt, M., Waggitt, P., Robertson, A., 2016. Preventing Acid and Metalliferous Drainage. Australia.

Kaksonen, A.H., Puhakka, J.A., 2007. Sulfate Reduction Based Bioprocesses for the Treatment of Acid Mine Drainage and the Recovery of Metals. Eng. Life Sci. 7, 541–564. https://doi.org/10.1002/elsc.200720216

Kholssi, R., Marks, E.A.N., Montero, O., Maté, A.P., Debdoubi, A., Rad, C., 2018. The growth of filamentous microalgae is increased on biochar solid supports. Biocatalysis and Agricultural Biotechnology 13, 182–185. https://doi.org/10.1016/j.bcab.2017.12.011

Khoubestani, R.S., Mirghaffari, N., Farhadian, O., 2015. Removal of three and hexavalent chromium from aqueous solutions using a microalgae biomass-derived biosorbent. Environmental Progress & Sustainable Energy 34, 949–956. https://doi.org/10.1002/ep.12071

Kim, G.-M., Kim, D.-H., Kang, J.-S., Baek, H., 2014. Treatment of synthetic acid mine drainage using rice wine waste as a carbon source. Environ Earth Sci 71, 4603–4609. https://doi.org/10.1007/s12665-013-2852-7

Kim, I., Lee, M., Wang, S., 2014. Heavy metal removal in groundwater originating from acid mine drainage using dead Bacillus drentensis sp. immobilized in polysulfone polymer. Journal of Environmental Management 146, 568–574. https://doi.org/10.1016/j.jenvman.2014.05.042

Kim, M.-S., Min, H.-G., Koo, N., Park, J., Lee, S.-H., Bak, G.-I., Kim, J.-G., 2014. The effectiveness of spent coffee grounds and its biochar on the amelioration of heavy metals-contaminated water and soil using chemical and biological assessments. Journal of Environmental Management 146, 124–130. https://doi.org/10.1016/j.jenvman.2014.07.001

Kiran, M.G., Pakshirajan, K., Das, G., 2017. Heavy metal removal from multicomponent system by sulfate reducing bacteria: Mechanism and cell surface characterization. Journal of Hazardous Materials 324, 62–70. https://doi.org/10.1016/j.jhazmat.2015.12.042

Kılıç, M., Kırbıyık, Ç., Çepelioğullar, Ö., Pütün, A.E., 2013. Adsorption of heavy metal ions from aqueous solutions by bio-char, a by-product of pyrolysis. Applied Surface Science 283, 856–862. https://doi.org/10.1016/j.apsusc.2013.07.033

Kumar, M., Pakshirajan, K., 2020. Continuous removal and recovery of metals from wastewater using inverse fluidized bed sulfidogenic bioreactor. Journal of Cleaner Production 124769. https://doi.org/10.1016/j.jclepro.2020.124769

Kumar, R., Goyal, D., 2010. Waste water treatment and metal (Pb2+, Zn2+) removal by microalgal based stabilization pond system. Indian Journal of Microbiology 50, 34–40. https://doi.org/10.1007/s12088-010-0063-4

Kumari, S., G. Udayabhanu, Prased, B., 2010. Studies on environmental impact of acid mine drainage generation and its treatment: an appraisal. Indian Journal of Environmental Protection 30, 953–967.

Kushkevych, I., Dordević, D., Vítězová, M., 2019. Analysis of pH dose-dependent growth of sulfate-reducing bacteria. Open Medicine 14, 66–74. https://doi.org/10.1515/med-2019-0010

Levy, J.L., Angel, B.M., Stauber, J.L., Poon, W.L., Simpson, S.L., Cheng, S.H., Jolley, D.F., 2008. Uptake and internalisation of copper by three marine microalgae: Comparison of copper-sensitive and copper-tolerant species. Aquatic Toxicology 12.

Li, L.Y., Gong, X., Abida, O., 2019. Waste-to-resources: Exploratory surface modification of sludge-based activated carbon by nitric acid for heavy metal adsorption. Waste Management 87, 375–386. https://doi.org/10.1016/j.wasman.2019.02.019

Li, M., Huang, Y., Yang, Y., Wang, H., Hu, L., Zhong, H., He, Z., 2020. Heavy metal ions removed from imitating acid mine drainages with a thermoacidophilic archaea: Acidianus manzaensis YN25. Ecotoxicology and Environmental Safety 190, 110084. https://doi.org/10.1016/j.ecoenv.2019.110084

Li, T., Lin, G., Podola, B., Melkonian, M., 2015. Continuous removal of zinc from wastewater and mine dump leachate by a microalgal biofilm PSBR. Journal of Hazardous Materials 297, 112–118. https://doi.org/10.1016/j.jhazmat.2015.04.080

Li, Y., Yang, X., Geng, B., 2018a. Preparation of Immobilized Sulfate-Reducing Bacteria-Microalgae Beads for Effective Bioremediation of Copper-Containing Wastewater. Water Air Soil Pollut 229, 54. https://doi.org/10.1007/s11270-018-3709-1

Li, Y., Yang, X., Geng, B., Liu, X., 2018b. Effective bioremediation of Cu(II) contaminated waters with immobilized sulfate-reducing bacteria-microalgae beads in a continuous treatment system and mechanism analysis: Immobilized SRB-microalgae beads for Cu(II) removal. J. Chem. Technol. Biotechnol 93, 1453–1461. https://doi.org/10.1002/jctb.5513

Liu, P., Zhu, M., Leong, Y., Zhang, Y., Zhang, Z., Zhang, D., 2017. An Experimental Study of the Rheological Properties and Stability Characteristics of Biochar-Algae-Water Slurry Fuels. Energy Procedia 105, 125–130. https://doi.org/10.1016/j.egypro.2017.03.290

Liu, Z., Zhang, F.-S., 2009. Removal of lead from water using biochars prepared from hydrothermal liquefaction of biomass. Journal of Hazardous Materials 167, 933–939. https://doi.org/10.1016/j.jhazmat.2009.01.085

Loreto, C.D., Monge, O., Martin, A.R., Ochoa-Herrera, V., Sierra-Alvarez, R., Almendariz, F.J., 2021. Effect of carbon source and metal toxicity for potential acid mine drainage (AMD) treatment with an anaerobic sludge using sulfate-reduction. Water Science and Technology 83, 2669–2677. https://doi.org/10.2166/wst.2021.163

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S., Qiu, R., 2012. Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. Water Research 46, 854–862. https://doi.org/10.1016/j.watres.2011.11.058

Magee, E., Zhou, W., Yang, H., Zhang, D., 2013. The Effect of Biochar Application in Microalgal Culture on the Biomass Yield and Cellular Lipids of Chlorella vulgaris. Engineers Australia 870–874.

Martínez-Macias, M. del R., Correa-Murrieta, Ma.A., Villegas-Peralta, Y., Dévora-Isiordia, G.E., Álvarez-Sánchez, J., Saldivar-Cabrales, J., Sánchez-Duarte, R.G., 2019. Uptake of copper from acid mine drainage by the microalgae Nannochloropsis oculata. Environmental Science and Pollution Research 26, 6311–6318. https://doi.org/10.1007/s11356-018-3963-1

Mehrotra, T., Dev, S., Banerjee, A., Chatterjee, A., Singh, R., Aggarwal, S., 2021. Use of immobilized bacteria for environmental bioremediation: A review. Journal of Environmental Chemical Engineering 9, 105920. https://doi.org/10.1016/j.jece.2021.105920

Mehta, S.K., Gaur, J.P., 2005. Use of Algae for Removing Heavy Metal Ions From Wastewater: Progress and Prospects. Critical Reviews in Biotechnology 25, 113–152. https://doi.org/10.1080/07388550500248571

Mohan, D., Kumar, H., Sarswat, A., Alexandre-Franco, M., Pittman, C.U., 2014. Cadmium and lead remediation using magnetic oak wood and oak bark fast pyrolysis bio-chars. Chemical Engineering Journal 236, 513–528. https://doi.org/10.1016/j.cej.2013.09.057

Mohan, D., Pittman, C.U., Bricka, M., Smith, F., Yancey, B., Mohammad, J., Steele, P.H., Alexandre-Franco, M.F., Gómez-Serrano, V., Gong, H., 2007. Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production. Journal of Colloid and Interface Science 310, 57–73. https://doi.org/10.1016/j.jcis.2007.01.020

Monteiro, C.M., Castro, P.M.L., Malcata, F.X., 2012. Metal uptake by microalgae: Underlying mechanisms and practical applications. Biotechnology Progress 28, 299–311. https://doi.org/10.1002/btpr.1504

Monteiro, C.M., Castro, P.M.L., Xavier Malcata, F., 2011. Biosorption of zinc ions from aqueous solution by the microalga Scenedesmus obliquus. Environ Chem Lett 9, 169–176. https://doi.org/10.1007/s10311-009-0258-2

Monteiro, C.M., Marques, A.P.G.C., Castro, P.M.L., Xavier Malcata, F., 2009. Characterization of Desmodesmus pleiomorphus isolated from a heavy metal-contaminated site: biosorption of zinc. Biodegradation 20, 629–641. https://doi.org/10.1007/s10532-009-9250-6

Mosley, L.M., Willson, P., Hamilton, B., Butler, G., Seaman, R., 2015. The capacity of biochar made from common reeds to neutralise pH and remove dissolved metals in acid drainage. Environ Sci Pollut Res 22, 15113–15122. https://doi.org/10.1007/s11356-015-4735-9

Muhammad, S.N., Kusin, F.M., Madzin, Z., 2018. Coupled physicochemical and bacterial reduction mechanisms for passive remediation of sulfate- and metal-rich acid mine drainage. Int. J. Environ. Sci. Technol. 15, 2325–2336. https://doi.org/10.1007/s13762-017-1594-6

Mukhethwa, M., Chirwa Evans, Maharajh Dheepak, 2019. The Effect of Ph, Temperature and Hydraulic Retention Time on Biological Sulphate Reduction in a Down-flow Packed Bed Reactor. Chemical Engineering Transactions 74, 517–522. https://doi.org/10.3303/CET1974087

Muñoz, R., Guieysse, B., 2006. Algal–bacterial processes for the treatment of hazardous contaminants: A review. Water Research 40, 2799–2815. https://doi.org/10.1016/j.watres.2006.06.011

Najib, T., Solgi, M., Farazmand, A., Heydarian, S.M., Nasernejad, B., 2017. Optimization of sulfate removal by sulfate reducing bacteria using response surface methodology and heavy metal removal in a sulfidogenic UASB reactor. Journal of Environmental Chemical Engineering 5, 3256–3265. https://doi.org/10.1016/j.jece.2017.06.016

Natarajan, K.A., 2017. Use of Bioflocculants for Mining Environmental Control. Trans Indian Inst Met 70, 519–525. https://doi.org/10.1007/s12666-016-1012-7

Nielsen, G., Coudert, L., Janin, A., Blais, J.F., Mercier, G., 2019. Influence of Organic Carbon Sources on Metal Removal from Mine Impacted Water Using Sulfate-Reducing Bacteria Bioreactors in Cold Climates. Mine Water Environ 38, 104–118. https://doi.org/10.1007/s10230-018-00580-3

Nordstrom, D.K., 2011. Mine Waters: Acidic to Circmneutral. Elements 7, 393–398. https://doi.org/10.2113/gselements.7.6.393

Oberholster, P.J., Cheng, P.-H., Botha, A.-M., Genthe, B., 2014. The potential of selected macroalgal species for treatment of AMD at different pH ranges in temperate regions. Water Research 60, 82–92. https://doi.org/10.1016/j.watres.2014.04.031

Oh, S.-Y., Yoon, M.-K., 2013. Biochar for Treating Acid Mine Drainage. Environmental Engineering Science 30, 589–593. https://doi.org/10.1089/ees.2013.0063

Orandi, S., Lewis, D.M., 2013. Biosorption of heavy metals in a photo-rotating biological contactor—a batch process study. Applied Microbiology and Biotechnology 97, 5113–5123. https://doi.org/10.1007/s00253-012-4316-5

Orandi, S., Lewis, D.M., Moheimani, N.R., 2012. Biofilm establishment and heavy metal removal capacity of an indigenous mining algal-microbial consortium in a photo-rotating biological contactor. Journal of Industrial Microbiology & Biotechnology 39, 1321–1331. https://doi.org/10.1007/s10295-012-1142-9

Park, C.M., Han, J., Chu, K.H., Al-Hamadani, Y.A.J., Her, N., Heo, J., Yoon, Y., 2017. Influence of solution pH, ionic strength, and humic acid on cadmium adsorption onto activated biochar: Experiment and modeling. Journal of Industrial and Engineering Chemistry 48, 186–193. https://doi.org/10.1016/j.jiec.2016.12.038

Park, J.-H., Ok, Y.S., Kim, S.-H., Cho, J.-S., Heo, J.-S., Delaune, R.D., Seo, D.-C., 2016. Competitive adsorption of heavy metals onto sesame straw biochar in aqueous solutions. Chemosphere 142, 77–83. https://doi.org/10.1016/j.chemosphere.2015.05.093

Park, Y.-T., Lee, H., Yun, H.-S., Song, K.-G., Yeom, S.-H., Choi, J., 2013. Removal of metal from acid mine drainage using a hybrid system including a pipes inserted microalgae reactor. Bioresource Technology 150, 242–248. https://doi.org/10.1016/j.biortech.2013.09.136

Pellera, F.-M., Giannis, A., Kalderis, D., Anastasiadou, K., Stegmann, R., Wang, J.-Y., Gidarakos, E., 2012. Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products. Journal of Environmental Management 96, 35–42. https://doi.org/10.1016/j.jenvman.2011.10.010

Poo, K.-M., Son, E.-B., Chang, J.-S., Ren, X., Choi, Y.-J., Chae, K.-J., 2018. Biochars derived from wasted marine macro-algae (Saccharina japonica and Sargassum fusiforme) and their potential for heavy metal removal in aqueous solution. Journal of Environmental Management 206, 364–372. https://doi.org/10.1016/j.jenvman.2017.10.056

Regmi, P., Garcia Moscoso, J.L., Kumar, S., Cao, X., Mao, J., Schafran, G., 2012. Removal of copper and cadmium from aqueous solution using switchgrass biochar produced via hydrothermal carbonization process. Journal of Environmental Management 109, 61–69. https://doi.org/10.1016/j.jenvman.2012.04.047

Reichl, D.C., Schatz, Mag.M., Masopust, A., Resel, Mag.W., 2019. World Mining Data 2019. Internation Organizing Committee for the World Mining Congresses, Vienna.

Retnaningrum, E., Wilopo, W., Warmada, I.W., 2021. Enhancement of manganese extraction in a biochar-enriched bioleaching column with a mixed culture of indigenous bacteria. Biodiversitas 22. https://doi.org/10.13057/biodiv/d220560

Russell, R.A., Holden, P.J., Wilde, K.L., Neilan, B.A., 2003. Demonstration of the use of Scenedesmus and Carteria biomass to drive bacterial sulfate reduction by Desulfovibrio alcoholovorans isolated from an artificial wetland. Hydrometallurgy 71, 227–234. https://doi.org/10.1016/S0304-386X(03)00160-9

Sahinkaya, E., Dursun, N., Ozkaya, B., Kaksonen, A.H., 2013. Use of landfill leachate as a carbon source in a sulfidogenic fluidized-bed reactor for the treatment of synthetic acid mine drainage. Minerals Engineering 48, 56–60. https://doi.org/10.1016/j.mineng.2012.10.019

Sahinkaya, E., Isler, E., Yurtsever, A., Coban, I., 2019. Sulfidogenic treatment of acid mine drainage using anaerobic membrane bioreactor. Journal of Water Process Engineering 31, 100816. https://doi.org/10.1016/j.jwpe.2019.100816

Sahoo, H., Senapati, D., Thakur, I.S., Naik, U.C., 2020. Integrated bacteria-algal bioreactor for removal of toxic metals in acid mine drainage from iron ore mines. Bioresource Technology Reports 11, 100422. https://doi.org/10.1016/j.biteb.2020.100422

Sandau, E., Sandau, P., Pulz, O., 1996. Heavy metal sorption by microalgae. Acta Biotechnol. 16, 227–235. https://doi.org/10.1002/abio.370160402

Shaheen, S.M., Niazi, N.K., Hassan, N.E.E., Bibi, I., Wang, H., Tsang, D.C.W., Ok, Y.S., Bolan, N., Rinklebe, J., 2019. Wood-based biochar for the removal of potentially toxic elements in water and wastewater: a critical review. International Materials Reviews 64, 216–247. https://doi.org/10.1080/09506608.2018.1473096

Shan, R., Han, J., Gu, J., Yuan, H., Luo, B., Chen, Y., 2020. A review of recent developments in catalytic applications of biochar-based materials. Resources, Conservation and Recycling 162, 105036. https://doi.org/10.1016/j.resconrec.2020.105036

Shanab, S., Essa, A., Shalaby, E., 2012. Bioremoval capacity of three heavy metals by some microalgae species (Egyptian Isolates). Plant Signaling & Behavior 7, 392–399. https://doi.org/10.4161/psb.19173

Shen, Y., Li, H., Zhu, W., Ho, S.-H., Yuan, W., Chen, J., Xie, Y., 2017. Microalgal-biochar immobilized complex: A novel efficient biosorbent for cadmium removal from aqueous solution. Bioresource Technology 244, 1031–1038. https://doi.org/10.1016/j.biortech.2017.08.085

Shi, J., Fan, X., Tsang, D.C.W., Wang, F., Shen, Z., Hou, D., Alessi, D.S., 2019. Removal of lead by rice husk biochars produced at different temperatures and implications for their environmental utilizations. Chemosphere 235, 825–831. https://doi.org/10.1016/j.chemosphere.2019.06.237

Shirvanimoghaddam, K., Czech, B., Abdikheibari, S., Brodie, G., Kończak, M., Krzyszczak, A., Al-Othman, A., Naebe, M., 2022. Microwave synthesis of biochar for environmental applications. Journal of Analytical and Applied Pyrolysis 161, 105415. https://doi.org/10.1016/j.jaap.2021.105415

Sierra-Alvarez, R., Karri, S., Freeman, S., Field, J.A., 2006. Biological treatment of heavy metals in acid mine drainage using sulfate reducing bioreactors. Water Science and Technology 54, 179–185. https://doi.org/10.2166/wst.2006.502

Silva, P.M.P., Lucheta, A.R., Bitencourt, J.A.P., Carmo, A.L.V. do, Cuevas, I.P.Ñ., Siqueira, J.O., Oliveira, G.C. de, Alves, J.O., 2019. Covellite (CuS) Production from a Real Acid Mine Drainage Treated with Biogenic H2S. Metals 9, 206. https://doi.org/10.3390/met9020206

Singh, G., Patidar, S.K., 2018. Microalgae harvesting techniques: A review. Journal of Environmental Management 217, 499–508. https://doi.org/10.1016/j.jenvman.2018.04.010

Tam, N.F.Y., Wong, yuk-S., Simpson, C.G., 1998. Removal of Copper by Free and Immobilizea Microalga, Chlorella vulgaris. Verlag and Landes Bioscience.

Tan, X., Liu, Y., Zeng, G., Wang, X., Hu, X., Gu, Y., Yang, Z., 2015. Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere 125, 70–85. https://doi.org/10.1016/j.chemosphere.2014.12.058

Taylor, J., Pape, S., Murphy, N., 2005. A Summary of Passive and Active Treatment Technologies for Acid and Metalliferous Drainage (AMD) 49.

Teng, W., Liu, G., Luo, H., Zhang, R., Xiang, Y., 2016. Simultaneous sulfate and zinc removal from acid wastewater using an acidophilic and autotrophic biocathode. Journal of Hazardous Materials 304, 159–165. https://doi.org/10.1016/j.jhazmat.2015.10.050

Tong, X., Li, J., Yuan, J., Xu, R., 2011. Adsorption of Cu(II) by biochars generated from three crop straws. Chemical Engineering Journal 172, 828–834. https://doi.org/10.1016/j.cej.2011.06.069

Trakal, L., Bingöl, D., Pohořelý, M., Hruška, M., Komárek, M., 2014. Geochemical and spectroscopic investigations of Cd and Pb sorption mechanisms on contrasting biochars: Engineering implications. Bioresource Technology 171, 442–451. https://doi.org/10.1016/j.biortech.2014.08.108

Tran, H.N., You, S.-J., Chao, H.-P., 2016. Effect of pyrolysis temperatures and times on the adsorption of cadmium onto orange peel derived biochar. Waste Management & Research 34, 129–138. https://doi.org/10.1177/0734242X15615698

Ucar, D., Bekmezci, O.K., Kaksonen, A.H., Sahinkaya, E., 2011. Sequential precipitation of Cu and Fe using a three-stage sulfidogenic fluidized-bed reactor system. Minerals Engineering 24, 1100–1105. https://doi.org/10.1016/j.mineng.2011.02.005

Utgikar, V.P., Tabak, H.H., Haines, J.R., Govind, R., 2003. Quantification of toxic and inhibitory impact of copper and zinc on mixed cultures of sulfate-reducing bacteria. Biotechnol. Bioeng. 82, 306–312. https://doi.org/10.1002/bit.10575

Van Hille, R.P., Boshoff, G.A., Rose, P.D., Duncan, J.R., 1999. A continuous process for the biological treatment of heavy metal contaminated acid mine water. Resources, Conservation and Recycling 27, 157–167. https://doi.org/10.1016/S0921-3449(99)00010-5

Wang, H., Gao, B., Wang, S., Fang, J., Xue, Y., Yang, K., 2015. Removal of Pb(II), Cu(II), and Cd(II) from aqueous solutions by biochar derived from KMnO4 treated hickory wood. Bioresource Technology 197, 356–362. https://doi.org/10.1016/j.biortech.2015.08.132

Wang, J., Wang, T., Zhu, Q., Zhang, S., Shi, Q., Chovelon, J.-M., Wang, H., 2021. Preparation of a novel sludge-derived biochar by K2FeO4 conditioning to enhance the removal of Pb2+. Colloid and Interface Science Communications 42, 100417. https://doi.org/10.1016/j.colcom.2021.100417

Wang, L., Ok, Y.S., Tsang, D.C.W., Alessi, D.S., Rinklebe, J., Wang, H., Mašek, O., Hou, R., O'Connor, D., Hou, D., 2020. New trends in biochar pyrolysis and modification strategies: feedstock, pyrolysis conditions, sustainability concerns and implications for soil amendment. Soil Use Manage 36, 358–386. https://doi.org/10.1111/sum.12592

Wang, N., Fang, D., Zheng, G., Liang, J., Zhou, L., 2019. A novel approach coupling ferrous iron bio-oxidation and ferric iron chemo-reduction to promote biomineralization in simulated acidic mine drainage. RSC Adv. 9, 5083–5090. https://doi.org/10.1039/C8RA09887E

Wang, S., Gao, B., Zimmerman, A.R., Li, Y., Ma, L., Harris, W.G., Migliaccio, K.W., 2015. Removal of arsenic by magnetic biochar prepared from pinewood and natural hematite. Bioresource Technology 175, 391–395. https://doi.org/10.1016/j.biortech.2014.10.104

Wang, X., Jiang, H., Zheng, G., Liang, J., Zhou, L., 2021. Recovering iron and sulfate in the form of mineral from acid mine drainage by a bacteria-driven cyclic biomineralization system. Chemosphere 262, 127567. https://doi.org/10.1016/j.chemosphere.2020.127567

Wei, D., Li, B., Luo, L., Zheng, Y., Huang, L., Zhang, J., Yang, Y., Huang, H., 2020. Simultaneous adsorption and oxidation of antimonite onto nano zero-valent iron sludge-based biochar: Indispensable role of reactive oxygen species and redox-active moieties. Journal of Hazardous Materials 391, 122057. https://doi.org/10.1016/j.jhazmat.2020.122057

Worms, I., Simon, D.F., Hassler, C.S., Wilkinson, K.J., 2006. Bioavailability of trace metals to aquatic microorganisms: importance of chemical, biological and physical processes on biouptake. Biochimie 88, 1721–1731. https://doi.org/10.1016/j.biochi.2006.09.008

Wu, J., Huang, D., Liu, X., Meng, J., Tang, C., Xu, J., 2018. Remediation of As(III) and Cd(II) co-contamination and its mechanism in aqueous systems by a novel calcium-based magnetic biochar. Journal of Hazardous Materials 348, 10–19. https://doi.org/10.1016/j.jhazmat.2018.01.011

Wu, J., Wang, T., Wang, J., Zhang, Y., Pan, W.-P., 2021. A novel modified method for the efficient removal of Pb and Cd from wastewater by biochar: Enhanced the ion exchange and precipitation capacity. Science of The Total Environment 754, 142150. https://doi.org/10.1016/j.scitotenv.2020.142150

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., Hu, X., Tsang, D.C.W., Ok, Y.S., Gao, B., 2020. Biochar technology in wastewater treatment: A critical review. Chemosphere 252, 126539. https://doi.org/10.1016/j.chemosphere.2020.126539

Xu, X., Cao, X., Zhao, L., Wang, H., Yu, H., Gao, B., 2013. Removal of Cu, Zn, and Cd from aqueous solutions by the dairy manure-derived biochar. Environmental Science and Pollution Research 20, 358–368. https://doi.org/10.1007/s11356-012-0873-5

Yan, J., Ye, W., Jian, Z., Xie, J., Zhong, K., Wang, S., Hu, H., Chen, Z., Wen, H., Zhang, H., 2018. Enhanced sulfate and metal removal by reduced graphene oxide self-assembled Enterococcus avium sulfate-reducing bacteria particles. Bioresource Technology 266, 447–453. https://doi.org/10.1016/j.biortech.2018.07.012

Yang, T., Xu, Y., Huang, Q., Sun, Y., Liang, X., Wang, L., Qin, X., Zhao, L., 2021. Adsorption characteristics and the removal mechanism of two novel Fe-Zn composite modified biochar for Cd(II) in water. Bioresource Technology 333, 125078. https://doi.org/10.1016/j.biortech.2021.125078

Yang, Y., Zhang, Y., Wang, G., Yang, Z., Xian, J., Yang, Yuanxiang, Li, T., Pu, Y., Jia, Y., Li, Y., Cheng, Z., Zhang, S., Xu, X., 2021. Adsorption and reduction of Cr(VI) by a novel nanoscale FeS/chitosan/biochar composite from aqueous solution. Journal of Environmental Chemical Engineering 9, 105407. https://doi.org/10.1016/j.jece.2021.105407

Yin, K., Wang, J., Zhai, S., Xu, X., Li, T., Sun, S., Xu, S., Zhang, X., Wang, C., Hao, Y., 2022. Adsorption mechanisms for cadmium from aqueous solutions by oxidant-modified biochar derived from Platanus orientalis Linn leaves. Journal of Hazardous Materials 428, 128261. https://doi.org/10.1016/j.jhazmat.2022.128261

Yoon, K., Cho, D.-W., Tsang, D.C.W., Bolan, N., Rinklebe, J., Song, H., 2017. Fabrication of engineered biochar from paper mill sludge and its application into removal of arsenic and cadmium in acidic water. Bioresource Technology 246, 69–75. https://doi.org/10.1016/j.biortech.2017.07.020

Zhang, M., Wang, H., 2014. Organic wastes as carbon sources to promote sulfate reducing bacterial activity for biological remediation of acid mine drainage. Minerals Engineering 69, 81–90. https://doi.org/10.1016/j.mineng.2014.07.010

Zhang, M., Wang, H., Han, X., 2016. Preparation of metal-resistant immobilized sulfate reducing bacteria beads for acid mine drainage treatment. Chemosphere 154, 215–223. https://doi.org/10.1016/j.chemosphere.2016.03.103

Zhang, Y., Yang, R., Si, X., Duan, X., Quan, X., 2019. The adverse effect of biochar to aquatic algae- the role of free radicals. Environmental Pollution 248, 429–437. https://doi.org/10.1016/j.envpol.2019.02.055

Zhao, C., Wang, B., Theng, B.K.G., Wu, P., Liu, F., Wang, S., Lee, X., Chen, M., Li, L., Zhang, X., 2021. Formation and mechanisms of nano-metal oxide-biochar composites for pollutants removal: A review. Science of The Total Environment 767, 145305. https://doi.org/10.1016/j.scitotenv.2021.145305

Zhao, Y., Fu, Z., Chen, X., Zhang, G., 2018. Bioremediation process and bioremoval mechanism of heavy metal ions in acidic mine drainage. Chem. Res. Chin. Univ. 34, 33–38. https://doi.org/10.1007/s40242-018-7255-6

Highlights

- Algae-biochar-bacteria consortium is proposed as a novel method for acid mine drainage remediation.
- Sulfate reducing bacteria have little effect on Mn removal.
- Biochar can protect bacteria in heavy metals conditions by rapid removal of heavy metals.
- Algae growth may be inhibited by biochar in acid mine drainage conditions.

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: