Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-020-09816-8

RESEARCH ARTICLE

Energy and environmental impact assessment of a passive remediation bioreactor for antimony-rich mine drainage

Xiaoyu Wang[1,2] · Zengping Ning[3] · Weimin Sun[1,2] · Huaqing Liu[1,2] · Baoqin Li[1,2]

Received: 29 January 2020 / Accepted: 19 June 2020

Abstract

Industrial processes, such as smelting and mining, lead to antimony (Sb) contamination, which poses an environmental and human health risk. In this study, the energy consumption and environmental impacts of a passive biological treatment system were quantitatively evaluated using life cycle assessment (LCA), and the results were compared with that of an adsorption purification system. The results showed that the biosystem had a lower energy consumption compared with the adsorption system, with an energy savings of 27.39%. The environmental impacts of the bioreactor were also lower regarding acidification, ecotoxicity, carcinogens, climate change, resource depletion, and respiratory effects. The construction resulted in the most energy consumption (99%) for the passive bioreactor. Therefore, adopting environmentally friendly construction materials could make the biosystem a more energy-efficient option. Results demonstrated that the bioreactor in this research can have great potential for Sb mine drainage applications in terms of energy savings and environmental remediation without diminishing performance. The study findings can be useful for deciding the most energy effective process for mine drainage remediation. In addition, the identification of the energy and environmental impacts of the processes provide valuable information for the design of future systems that consume less materials and utilize new construction materials.

Keywords Life cycle assessment (LCA) · Sb mine drainage remediation · Energy analysis · Environmental impacts · Passive biological treatment · Adsorption

Introduction

Antimony (Sb) is found in nature as the sulfide mineral stibnite and is widely used in industrial applications such as batteries and flame retardants (Anderson 2001; Bergmann and Koparal 2011; Ilgen et al. 2014). Although Sb occurs at low concentrations and exists in several oxidation states in nature, industrial processes like mining and smelting can lead to accumulation of Sb, ultimately leading to water, soil, and atmospheric contamination (He et al. 2012). Sb pollution tends to destroy vegetation, accelerate soil erosion, pollute water bodies, and increase the possibility of human disease. Sb contamination in water due to mine drainage is especially prominent in China because of high Sb production, generating approximately 77% of the global total production in 2015 and 2016 (Arnold et al. 2019). High levels of Sb pollution have been reported in rivers near the Sb mine of Xikuangshan, Hunan province of China (Wang et al. 2011). A previous study showed toxic effects of Sb on the proliferation of human erythroid progenitor cells that was elicited at the level of the cell membrane (Bregoli et al. 2009). Therefore, the development

Xiaoyu Wang and Zengping Ning contributed equally to this work.

Responsible Editor: Philippe Loubet

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11356-020-09816-8) contains supplementary material, which is available to authorized users.

✉ Weimin Sun
wmsun@soil.gd.cn

1 National-Regional Joint Engineering Research Center for Soil Pollution Control and Remediation in South China, Guangdong Key Laboratory of Integrated Agro-environmental Pollution Control and Management, Guangdong Institute of Eco-environmental Science & Technology, Guangdong Academy of Sciences, 808 Tianyuan Road, Guangzhou 510650, Guangdong, China

2 Guangdong-Hong Kong-Macao Joint Laboratory for Environmental Pollution and Control, 808 Tianyuan Road, Guangzhou 510650, Guangdong, China

3 China State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China

Published online: 25 June 2020

of an effective method for Sb drainage remediation is critical to human health and the ecosystem.

Conventional treatment technologies typically used for the removal of Sb and its compounds from mine drainage areas include adsorption, coagulation/flocculation, ozone oxidation, membrane separation, solvent extraction, ion exchange, and reductive electrolysis. These methods remain widely used for the removal of Sb (Mubarak et al. 2015). The removal efficiency when employing the removal methods can be efficient, but the treatment processes consume high amounts of energy and resources (such as transportation and materials for construction). Conventional methods may also produce mineral-rich sludge that needs to be treated and disposed accordingly, which increases the total cost of the treatment (Kalin 2004; Johnson and Hallberg 2005). Adsorption is an efficient technology for metal removal, and it has the advantages of easy operation, low cost, and small sludge production compared to other chemical treatment methods (Luo et al. 2015). Studies have been conducted on Sb adsorption that have used different types of adsorbents (Luo et al. 2015; Salam and Mohamed 2003; Xi et al. 2011; Xu et al. 2015).

Sb and its compounds can be removed not only using conventional treatments, but can also be transformed using specific microorganisms. Sulfate-reducing bacteria can convert sulfate ions into sulfides that reduce Sb (V) to Sb (III) and form Sb (III) complex as precipitate in Sb mine drainage (Wang et al. 2013). Parameters such as pH, TOC, nitrogen, sulfide, and iron concentration can shape the innate microbial communities in mine drainage contamination remediation (Sun et al. 2020a). Biotic sulfate reduction can even occur in extremely acidic environments in acid mine drainage (Xu et al. 2020). Passive biological treatment has been shown to be a promising method for Sb remediation in mine drainage areas (Sun et al. 2015; Wang et al. 2013). Sb-rich mine water remediation using indigenous microbial communities in an onsite field-scale bioreactor resulted in the efficient removal of soluble Sb with a 95% (± 7%) removal (Sun et al. 2015). The designed system oxidized Fe (II) and Sb (III) and induced partial settling because of the microbial metabolic responses to metal(loid)s. The mechanism is that certain microorganisms can generate alkalinity and immobilize metals and reverse the acid mine generation reaction. Compared to the adsorption method, the passive treatment requires low cost and low maintenance, but there have been no systematic quantitative evaluations of both systems regarding their energy and environmental impacts.

The location of the remediation site, technical requirements, type of contaminants, initial contaminant concentrations, removal rates, and economic costs are usually the primary factors that need to be considered in the choice of a mine drainage remediation method. Environmental impacts also need to be considered during the decision making process (Johnson and Hallberg 2005). A life cycle assessment (LCA) can provide a systematic method to evaluate tradeoffs between various energy options and guide energy choices. It can also be used to assess the environmental impact of a new process that has not been previously applied, and to determine procedures that can be improved. LCA is an International Organization for Standardization (ISO) method for the environmental assessment of industrial systems from cradle to grave (ISO 14040 1997). The "cradle-to-grave" approach begins with the extraction of raw materials from the Earth, includes the production and manufacturing phases, and completes with the disposal or recycling phases (UNEP/SETAC 2005). LCA can also be utilized to compare the environmental impacts of a new process with an existing process. The utilization of LCA for Sb drainage remediation provides the advantages of a comprehensive, quantitative, and "beginning-to-end" assessment of various methods based on specific locations to quantify the energy consumption and environmental impacts.

In this study, LCA was used to evaluate the energy consumption and environmental impacts of a passive biological treatment process for Sb remediation. The results were compared to those of the adsorption treatment process to assess the optimum operational benefits and management strategies (Wang et al. 2019; Vince et al. 2008; Renou et al. 2008). Environmental impact assessments have been applied for acid mine drainage (AMD) treatment research in recent years. For example, Martínez et al. (2019) studied the environmental impacts of AMD treatment methods in the Iberian Pyrite Belt during mining operations to obtain more environmentally friendly remediation solutions. Hengen et al. (2014) compared the environmental impacts of different kinds of bioreactors, mussel shell leaching beds, lime dosages, and lime slaking as AMD treatment methods in the Stockton Coal Mine in New Zealand and demonstrated that active treatment methods generally had higher environmental impacts compared to passive treatment methods. Our research focused on the energy consumption and environmental impact analysis of an innovative passive bioreactor system requiring low energy input and minimal maintenance using indigenous microbial communities. The objective of this study was to determine the energy consumption and quantitative environmental impacts of each phase in the passive biological treatment compared with a chemical treatment method with similar treatment efficiency for Sb removal. The results of this research could be used as guidance when selecting the most energy effective process for mine drainage treatment. Identification of the energy and materials consumption processes for both treatment methods can provide reference for future research.

Methods

The bioreactor system for Sb-rich mine drainage remediation

The Sb passive treatment scenario was based on a study of a biotreatment system that treats Sb-rich mine drainage from an upstream area at the Banpo Sb mine, a rural area in the Guizhou province of Southwest China. The daily treatment flowrate was 15–25 m^3/day of mine water during operation. The system was composed of five main treatment units: a pre-aerobic precipitation unit, two aerobic units, and two microaerobic units (Fig. 1). Between each unit, baffles were set for gravity water flow. The pre-aerobic unit was for partially Fe and Sb oxidization. Two aerobic units were designed with the surfaces exposed to the air. The microaerobic units were amended with organic additives to promote the growth of anaerobic bacteria. In all of the aerobic units, no extra aerating mixers or diffusers were required. The treatment capacity of the system was approximately 20 m^3/day with a residence time of 8 days (Sun et al. 2020a, b). The system had a total volume of 160 m^3 (± 10%), occupying an area of 80 m^2. The total concentration of Sb in the influent ranged from 1431 to 7753 μg/L. In four of the five monitoring time points, no Sb (III) was detected in the effluent of the bioreactor, indicating there was greater than 99.9% Sb (III) removal.

The adsorption system for Sb-rich mine drainage remediation

The adsorption system was based on an adsorption and removal study of Sb using activated alumina (Xu et al. 2001). The basic system was scaled up for the onsite field adsorption treatment system (Kårelid et al. 2017). The assumed flowrate for the system was 20 m^3/day. The system was composed of one initial mixing tank, two reaction tanks with diameters of 0.6 m and heights of 3 m, one sedimentation tank, and a sand filter. Backwash was applied two times per week. According to Xu et al. (2001), activated alumina (AA) can remove greater than 95% Sb from water with an optimal pH of 2.8–4.3, which is effective for mine drainage removal without the need for pH adjustment.

Goal and scope definition

The goal of this research was to quantitively evaluate the cumulative energy demand and environmental impact of the onsite field-scale bioreactor for the passive treatment of Sb contamination in an active mine in Southwest China. The results were compared with the adsorption method under similar treatment conditions.

In this study, it was assumed that both systems shared the same inlet water quality during operation, and the removal efficiency of Sb for both systems was similar (> 95%) throughout the entire operational period. The calculations were based on onsite field laboratory data for the microbial treatment (Sun et al. 2020a, b). The chemical treatment was based on a literature report and was scaled up to a pilot-scale onsite field treatment system (Xu et al. 2001; Kårelid et al. 2017). Both systems were constructed using similar technologies and materials. The systems would be operating for 5 years, and all the construction materials and equipment were obtained from local suppliers.

System boundaries and the functional unit

Figure 2 shows the system boundary that contained all the substantial components and processes used in each of the treatment scenarios. The LCA was evaluated using material inputs, energy consumption, transportation costs, and disposal costs but no labor costs were considered. It was assumed that both treatment processes were installed at the same location in the Banpo mine for the same treatment outcome. A daily drainage treatment rate of 20 m^3/day was used as the functional unit. The flows and processes were normalized corresponding to this functional unit (FU), indicating that the construction, operation, and disposal phase assessments were distributed over a lifetime of 5 years on the basis of daily operation.

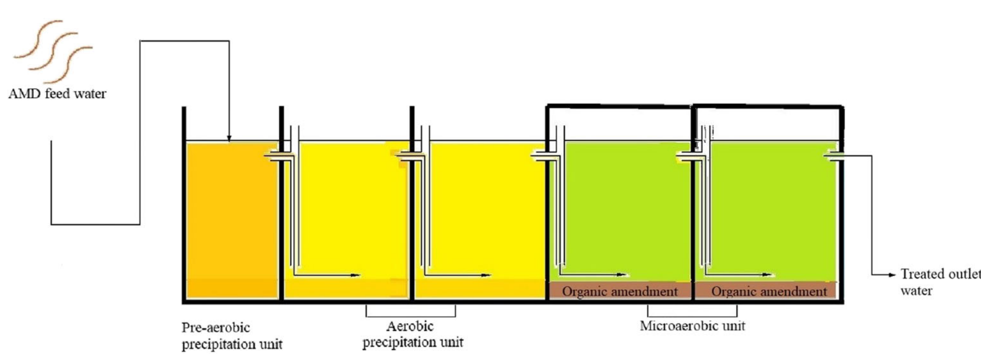


Fig. 1 Schematic diagram of the onsite field-scale bioreactor for antimony-rich mine drainage

Fig. 2 System boundaries of the study for **a** onsite field-scale bioreactor treatment system and **b** onsite pilot-scale adsorption treatment system

Life cycle inventory

The LCA was analyzed using the OpenLCA modeling software (1.9, GreenDelta GmbH, Germany) and the life cycle database Ecoinvent (3.5, Ecoinvent, Switzerland). The construction, operation, and disposal phases were considered for both systems. The processes involved during the construction process were material consumption, energy input, and transportation. The construction materials included clay brick, cement, plastic, and other materials. Adsorbents for the adsorption process were considered consumables, while chicken litter was selected as the organic matter additive for the microaerobic units and was renewed during maintenance. The passive bioreactor was designed to last 5 years. Only the minimum maintenance was considered in the system during treatment operation. For the adsorption treatment systems, adsorbence, pumping, sedimentation, and backwash (energy and treated water inputs) were required during operation.

Impact assessment

To analyze the environmental impacts, the impact assessment methods, CML 2001, ILCD, and Eco-indicator 99 (I, I), were used. The cumulative energy demand was used to quantify the energy consumption. CML, developed by the Institute of Environmental Sciences in Leiden University, is an environmental impact assessment method consisting of more than 1700 different flows (Acero et al. 2016). ILCD represents the International Reference Life Data System (JRC European Commission, 2010) by the Joint Research Center (JRC) of the European Commission, and they analyzed the life cycle impact methodologies of each environmental theme (Acero et al. 2016). Eco-indicator is a life cycle impact assessment tool developed by PRé Consultants B.V. (PRé Consultants B.V., Netherlands). This tool calculates scores by measuring various environmental impacts of materials and processes. The results demonstrated by Eco-indicator were normalized by transforming values using the selected reference values. Therefore, the final results were adjusted using impact weights (Lees 2012). Higher normalization results meant greater impacts than lower normalization results (Heijungs et al. 2007).

Results and discussion

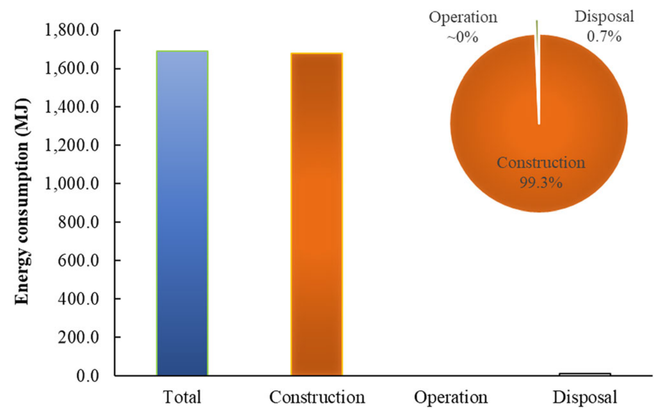
Energy consumption analysis of bioreactor system

The results of the passive bioreactor showed that the construction phase consumed most of the energy, as detailed in Fig. 3. A total of 99.3% of the total energy was consumed during the construction throughout the entire life cycle. The results showed that the passive bioreactor treatment had low energy needs during operation (~ 0%). This was because during operation, the bioreactor included pre-aerobic, aerobic, and microbial units. The system worked like a wetland with no need to pump air.

Figure 4 shows an evaluation of the relative contribution of each input throughout the entire bioreactor life cycle. The clay brick used in the construction consumed most of the energy (91%) throughout the entire treatment lifetime. The traditional clay brick production consumed large amounts of raw resources and electricity and emitted carbon dioxide, sulfur dioxide, and incomplete burning particles. Therefore, this input did not only consume a lot of energy but it also generated emissions as well as other sustainability concerns. When examining the results of the treatment of metal-rich and acid water using the dispersed alkaline substrate treatment method as an acid mine drainage passive treatment technology (Martínez et al. 2019), the construction of the plant also caused environmental impacts during the first years. However, the impact weight decreased with the extension of the lifetimes of the plant. To make the bioreactor system more energy-efficient, other lower energy, innovative construction materials could be considered for the complete system construction. For instance, Ge et al. (2012) tested a mix designed of concrete with recycled clay brick powder that could be used as an innovative construction material. Research has also been conducted to incorporate wastes into the production of bricks, such as rubber, limestone dust, wood sawdust, processed waste tea, fly ash, polystyrene, and sludge (Kadir, 2012).

Figure 5 shows a comparison of the energy consumption of the passive bioreactor and the active adsorption system. The data was distributed according to the daily drainage remediation flow of 20 m^3/day. Although the energy consumption of the construction phase in the adsorption was similar to that of the bioreactor system, the total energy cost in the adsorption system was higher. The adsorption system consumed 27.3% more energy than the biosystem process, and this was primarily due to the adsorption method's operational energy cost, such as production of adsorbents, backwashing, and pumping. In the adsorption treatment system, the construction portion also consumed most of the energy (78.2%). The passive biosystems showed great advantages in energy savings compared to the adsorption process for Sb mine drainage treatment, with a 22% energy savings during the entire life cycle and large amounts of energy savings during the operational phase. Since most of the mine drainage contaminated sites are located in rural valley places or mountainous areas with material and electricity transportation difficulties, greater energy savings are more desirable for the implementation of a specific remediation technology. In this case, the bioreactor's lower energy consumption is a good indicator for its selection of AMD in remote areas.

Fig. 3 Energy consumption during the different phases in the passive bioreactor



Environmental impact analysis

The CML and ILCD methods were used to analyze the potential environmental impacts of each remediation situation. CML provides information on the effects of climate change and resource depletion. The ILCD method was used to assess the effects of the carcinogenic effects and respiratory effects. These areas were selected based on the degree of impacts related to the characteristics of the systems.

Climate change assessment

Climate change was evaluated by examining the global warming potential, which is an environmental impact that is related to the incremental discharge of greenhouses gases (GHG), such as carbon dioxide and methane, to the Earth's atmosphere. The GHG emissions for both systems were calculated in the unit of carbon dioxide equivalents according to the Intergovernmental Panel on Climate Change protocol (Watson et al. 1996). GHGs can last for years in the atmosphere and trap heat from radiation, which contributes to climate change and global warming. Countries around the world have been putting efforts toward preventing climate change by adopting energy-efficient technologies and using cleaner fuels (Houghton 2009). Therefore, the potential for GHG emissions is also an important factor to consider in the treatment of pollutants. Figure 6a shows that the adsorption process had 11.8% higher climate change impacts than that of the passive bioreactor treatment. This resulted from the fossil fuel consumption and the adsorbent materials cost involved in the treatment operation process. Moreover, clay brick consumption still occupied a large portion of the GHG production, especially in the passive bioreactor. The use of a more sustainable material instead of clay brick during construction could greatly reduce GHG emissions.

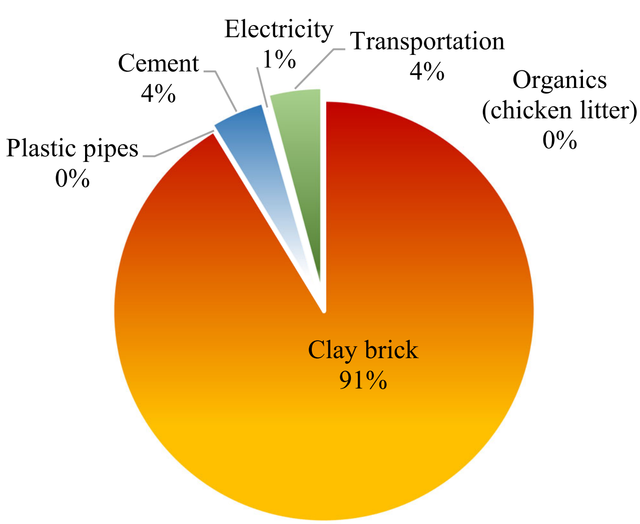


Fig. 4 Energy consumption distribution of the processes in the passive bioreactor treatment

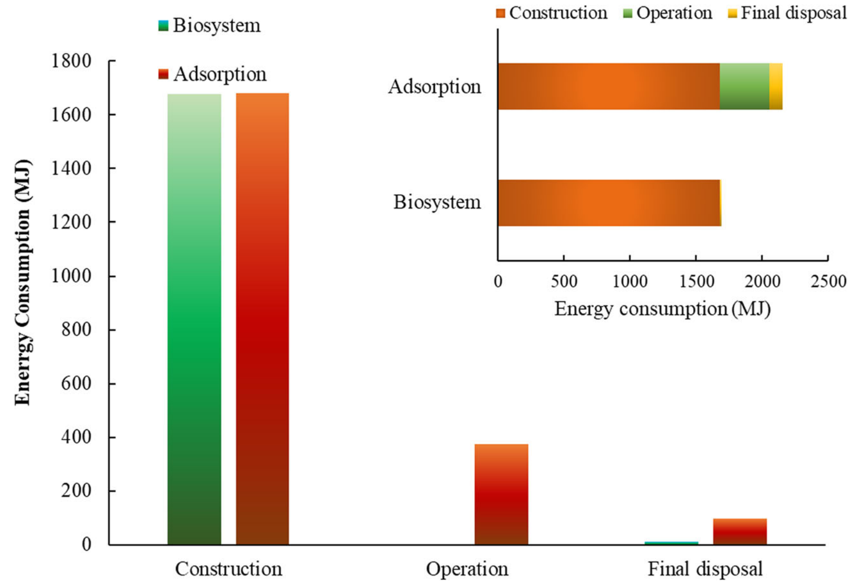
Resource depletion

Resource depletion means the resource consumption during the processes, whether intended or unintended, caused physical disintegration. Resource depletion will cause reduced availability of the corresponding types of resources for future generations (Yellishetty et al. 2011). The reference unit for resource depletion is kg Sb-Eq. The materials involved in the processes were all converted to the reference unit using the corresponding factors. Figure 6b shows the impact of each proposed treatment in terms of resource depletion. The majority of the resource depletion impact contribution for both the bioreactor system and adsorption system came from the construction phase. For the adsorption system, additional resource depletion was found during the operational and final disposal stages, in addition to the construction phase. Therefore, the impact of the bioreactor was 26.3% less than that of adsorption system.

Respiratory assessment

Air pollution is emerging as a severe problem in northern Chinese cities due to an increase in industrial activities. Particles from burning coal and other incomplete combustion

Fig. 5 Energy cost comparison for the passive bioreactor and the adsorption remediation system



form PM 2.5 and PM 10. As these particles are inhaled by people, they penetrate deep into lung tissue and can cause serious health problems (US EPA 2018). Negative respiration effects also come from vehicle transportation, coal power plants, and material production. Other inhale hazards included volatile organic compounds (VOCs), nitrogen oxides (NOx) in the presence of sunlight, sulfur dioxide, benzene, and other compounds. The metric used here for the respiration effects measurement was normalized to the disease incidence in the ILCD method. As displayed in Fig. 6c, the passive bioreactor has less operational costs, does not require the addition of materials, and requires less energy and materials consumption. Finally, the respiratory effects were determined to be 26.4% less for the bioreactor system compared to the adsorption

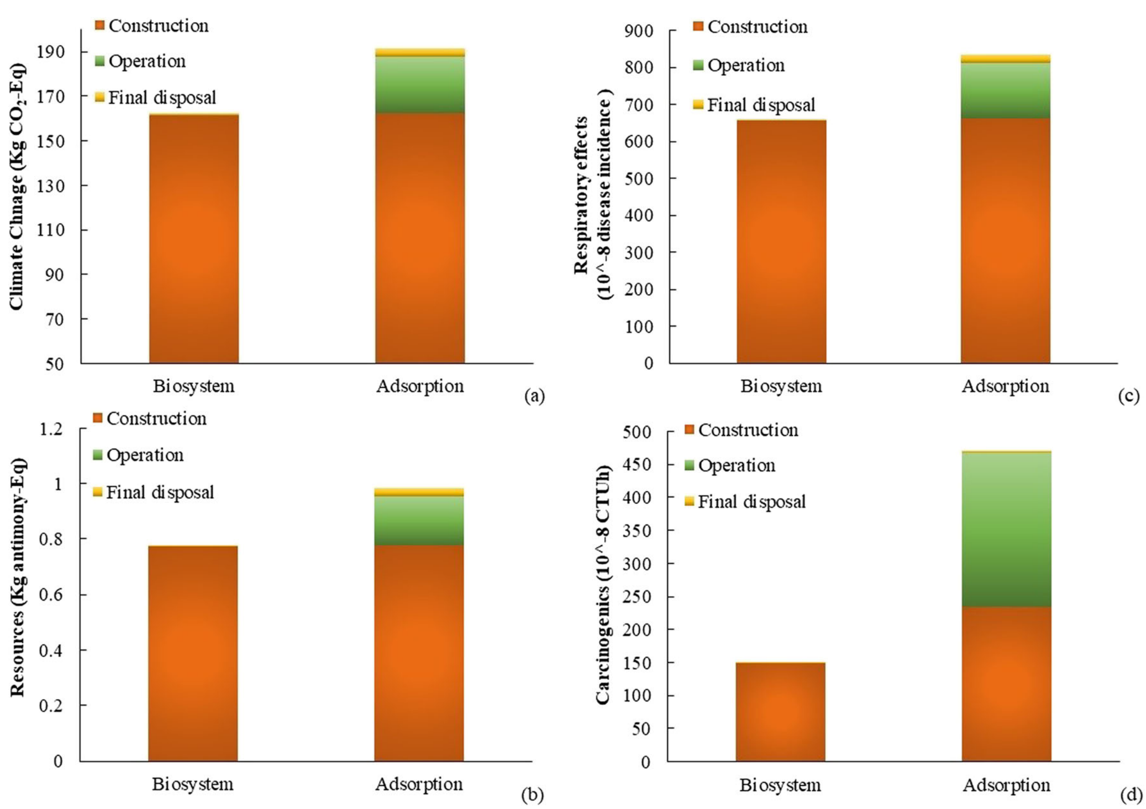


Fig. 6 Environmental impacts of **a** global warming, **b** resource depletion, **c** respiratory effects, and **d** carcinogenic effects of the bioreactor and the adsorption system during mine drainage treatment

method. The reduction in the calculated emissions primarily occurred during the operational phase. Moreover, most of the impacts originated from the construction phase (99.2%) in the bioreactor.

Carcinogenic impacts assessment

The human toxicity potential is a calculated index that reflects the potential damage of a chemical released into the environment. This parameter is based on the intrinsic toxicity of the pollutant and its potential dose (Hertwich et al. 2009). For the human carcinogenic impact, the characterization factors were expressed in terms of comparative toxic units (CTU) and characterized to human toxic units (CTUh). Toxic hazards, such as methamidophos, atrazine, benzene, and heavy metals, were considered in the carcinogenic impacts. Figure 6d shows the carcinogenic impact of the bioreactor was 212.4% lower compared to that of the chemical treatment system due to the low operational impacts during the treatment process.

Normalized impacts during the treatment process

The eco-indicator was applied to normalize the impact analysis. This tool provides information on the effects of acidification and eutrophication, ecotoxicity, carcinogens, climate change, ozone depletion, respiratory effects, and resources. The total normalized effects and the contributions of each process in both systems were also calculated. Figure 7a compares the normalized environmental impacts of the passive bioreactor and adsorption systems. The normalization results were calculated from each impact value with a toxicity weight provided by the eco-indicator. Higher normalization results had greater impacts than lower ones (Heijungs et al. 2007). The total environmental impacts of each phase during the entire life cycle for both systems were also calculated and are shown in Fig. 7b. For the biosystem, climate change, respiratory effects, and resources had relatively high environmental impacts compared with other factors, and these primarily originated during the construction phase (99%). This was due to the material and energy consumption, as well as transportation during the construction phase. Figure 7b also confirms the low operational impacts and footprint of the system during operation (~ 0%). However, in the adsorption system, the carcinogenic, climate change, respiratory, and resources depletion had higher impacts, and the construction and operational phases contributed most to the impacts (59.15% and 39.04%, respectively). Compared to the LCA study of the passive acid mine drainage remediation system by Martínez et al. (2019), the impact of the construction materials contributed to a large portion of the total environmental impacts. However, due to the addition of the alkaline substrate material, the impacts became much less within a few years.

In each environmental impact category, the passive bioreactor also had a much lower impact compared with the adsorption treatment system. Hence, the passive bioreactor has great potential for Sb remediation applications in a more cost-effective and sustainable manner. It had lower environmental impacts in nearly every aspect, as shown in Fig. 7a. Due to the low maintenance during the operational phase, the total normalized environmental impacts of the passive bioreactor were only 48.29% of that of the adsorption treatment, representing a more environmentally friendly treatment system. Since passive treatment systems utilize inherent biogeochemical treatment approaches, their energy and resource requirements are minimal throughout their design life (Hengen et al. 2014). However, chemical treatment methods require continuous materials and energy input for Sb mine drainage treatment.

Selection of remediation technology and possible improvements

Based on the LCA tools utilized in this study, the qualitatively findings suggest that the passive bioreactor treatment had lower environmental impacts compared to the chemical treatment methods, according to Fig. 7a. In addition, they all had similar Sb removal rates. The passive bioreactor had higher energy saving benefits and was more sustainable, which indicates the passives bioreactor is the ideal option for the remediation of acid drainage waste. However, nutrient deficiency, especially bio-available nitrogen deficiency, should be considered in a passive remediation biosystem, as environmental conditions in mine drainages usually impede bioremediation strategies (Moynahan et al. 2002), and nitrogen limitation frequently constrains the growth of microorganisms. While microorganisms (such as diazotrophic taxa) were reported to grow chemolithoautotrophically by oxidizing Sb (Sun et al. 2020b), nutrient limitation in the passive bioreactor should be considered when selecting the Sb mine drainage remediation technology.

Throughout the treatment life cycle of a bioreactor, the impacts of the extraction, production, and the transportation of construction materials and disposal are the highest. For example, the production of clay brick and cement made a larger contribution during the construction phase and increased the environmental cost of the treatment system. Therefore, the use of greener materials would offer enhanced environmental benefits by lowering impacts during the construction and disposal phases. A biosystem could also be designed to apply to a larger treatment system or other site mine drainage treatment systems. Longer life span materials could also improve the sustainability and energy savings, as well as a lower need for maintenance.

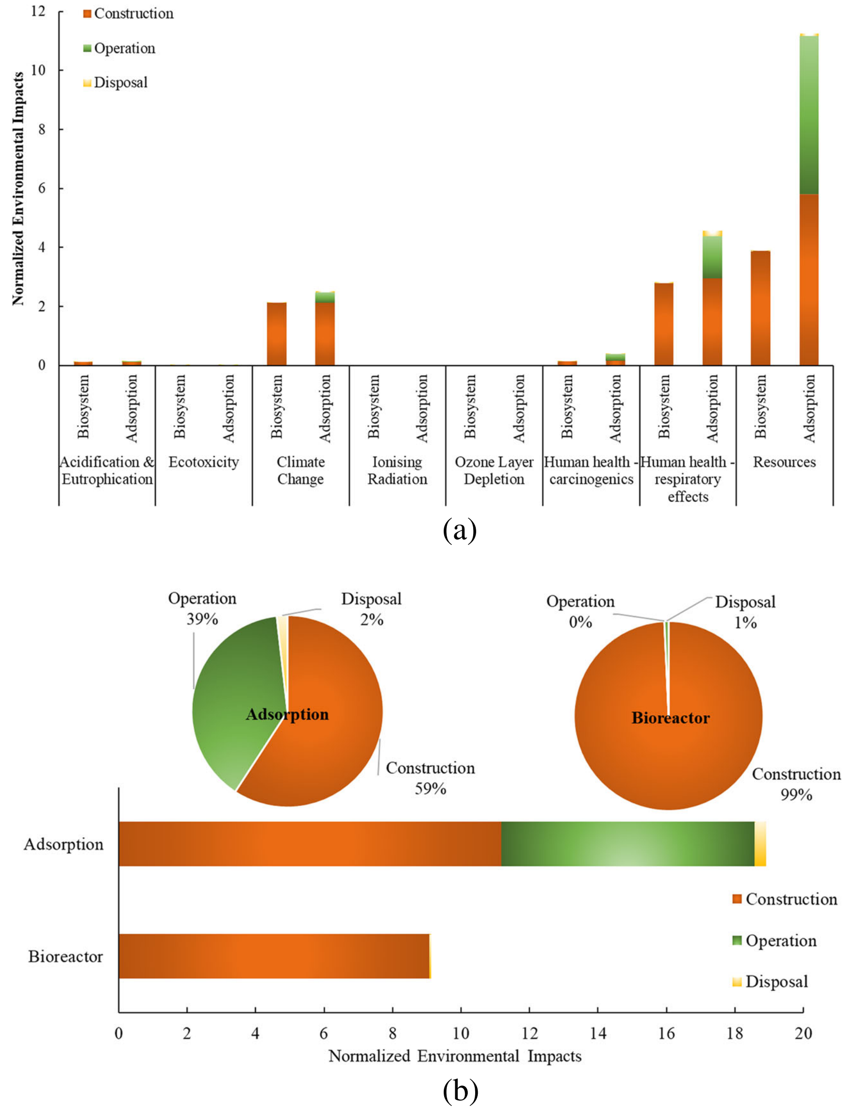


Fig. 7 Comparison of the environmental impact normalization for the passive bioreactor treatment system and the adsorption treatment system shown as **a** differences in impacts of normalized results and **b** contribution results during Sb drainage remediation

Conclusions

In this study, an LCA was used to assess the energy consumption and environmental impacts of a field-scale passive bioreactor system and an adsorption system for Sb-rich mine drainage remediation. The results showed that at a fixed flow of 20 m^3/day, the bioreactor contributed to a more environmentally friendly remediation with regard to both energy consumption and environmental impacts as compared to the adsorption system.

The construction phase of the bioreactor, which includes the production of clay brick, resulted in the most energy consumption and environmental impacts for the 5-year running period. The operation phase had a minimal contribution while maintaining a relatively high removal efficiency for Sb remediation. Higher energy consumption and environmental impacts during the operation and disposal phases were found in the adsorption system. Although clay brick typically has a lower economic cost, the adoption of greener materials during the construction phase could further reduce the bioreactor system's energy and environmental impacts. Moreover, the passive bioreactor showed a lower (48.3%) total normalized environmental impact, especially for resources and respiratory effects.

The results of this research can be useful in the selection of the most energy effective process for mine drainage treatment. In addition, identification of the energy and materials consumption processes provides reference for future research.

Funding information This research was supported by the GDAS' Project of Science and Technology Development (2020GDASYL-20200302007, 2019GDASYL-0103052, 2020GDASYL-20200103088, and 2019GDASYL-0301002), the Science and Technology Planning Project of Guangzhou (202002020072), the National Natural Science Foundation of China (41771301), the Local Innovative and Research Teams Project of Guangdong Pearl River Talents Program (2017BT01Z176), Guangdong Introducing Innovative and Entrepreneurial Talents (2017GC010570), the High-level Leading

Talent Introduction Program of GDAS (2016GDASRC-0103), and Guangdong Foundation for Program of Science and Technology Research (2019B121205006).

Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

References

Acero AP, Rodríguez C, Ciroth A (2016) Impact assessment methods in life cycle assessment and their impact categories. GreenDelta. LCIA methods

Anderson CG (2001) Hydrometallurgically treating antimony-bearing industrial wastes. J Miner Met Mater Soc 53:18–20. https://doi.org/10.1007/s11837-001-0156-y

Arnold M, Kangas P, Mäkinen A, Lakay E, Isomäki N, Lavén G, Gericke M, Pajuniemi P, Kaartinen T, Wendling L (2019) Mine water as a resource: selective removal and recovery of trace antimony from mine-impacted water. Mine Water Environ 38(2):431–446

Bergmann MH, Koparal AS (2011) Electrochemical antimony removal from accumulator acid: results from removal trials in laboratory cells. J Hazard Mater 196:59–65. https://doi.org/10.1016/j.jhazmat.2011.08.073

Bregoli L, Chiarini F, Gambarelli A, Sighinolfi G, Gatti AM, Santi P, Martelli AM, Cocco L (2009) Toxicity of antimony trioxide nanoparticles on human hematopoietic progenitor cells and comparison to cell lines. Toxicology 262(2):121–129. https://doi.org/10.1016/j.tox.2009.05.017

Ge Z, Gao Z, Sun R, Zheng L (2012) Mix design of concrete with recycled clay-brick-powder using the orthogonal design method. Constr Build Mater 31:289–293. https://doi.org/10.1016/j.conbuildmat.2012.01.002

He M, Wang X, Wu F, Fu Z (2012) Antimony pollution in China. Sci Total Environ 421:41–50. https://doi.org/10.1016/j.scitotenv.2011.06.009

Heijungs R, Guinée J, Kleijn R, Rovers V (2007) Bias in normalization: causes, consequences, detection and remedies. Int J Life Cycle Assess 12(4):211–216. https://doi.org/10.1065/lca2006.07.260

Hengen TJ, Squillace MK, O'Sullivan AD, Stone JJ (2014) Life cycle assessment analysis of active and passive acid mine drainage treatment technologies. Conserv Recycl 86:160–167. https://doi.org/10.1016/j.resconrec.2014.01.003

Hertwich EG, Mateles SF, Pease WS, McKone TE (2009) Human toxicity potentials for life cycle assessment and toxics release inventory risk screening. Environ Toxicol Chem 20(4):928–939. https://doi.org/10.1002/etc.5620200431

Houghton J (2009) Global warming: the complete briefing. Cambridge university press

Ilgen AG, Majs F, Barker AJ, Douglas TA, Trainor TP (2014) Oxidation and mobilization of metallic antimony in aqueous systems with simulated groundwater. Geochim Cosmochim Acta 132:16–30. https://doi.org/10.1016/j.gca.2014.01.019

International Standard Organization (1997) ISO 14040: Environmental management-life cycle assessment-principles and framework

Johnson DB, Hallberg KB (2005) Acid mine drainage remediation options: a review. Sci Total Environ 338(1–2):3–14. https://doi.org/10.1016/j.scitotenv.2004.09.002

JRC European Commission (2010) ILCD handbook - international reference life cycle data system. General guide for Life Cycle Assessment – Detailed guidance. Institute for Environment and sustainability

Kadir A (2012) An overview of wastes recycling in fired clay bricks. Int J Integr Eng 4(2):53–69

Kalin M (2004) Passive mine water treatment: the correct approach. Ecol Eng 22(4–5):299–304. https://doi.org/10.1016/j.ecoleng.2004.06.008

Kårelid V, Larsson G, Björlenius B (2017) Pilot-scale removal of pharmaceuticals in municipal wastewater: comparison of granular and powdered activated carbon treatment at three wastewater treatment plants. J Environ Manag 193:491–502. https://doi.org/10.1016/j.jenvman.2017.02.042

Lees F (2012) Lees' loss prevention in the process industries: hazard identification, assessment and control. Butterworth-Heinemann

Luo J, Luo X, Crittenden J, Qu J, Bai Y, Peng Y, Li J (2015) Removal of antimonite (Sb (III)) and antimonate (Sb (V)) from aqueous solution using carbon nanofibers that are decorated with zirconium oxide (ZrO_2). Environ Sci Technol 49(18):11115–11124. https://doi.org/10.1021/acs.est.5b02903

Martínez NM, Basallote MD, Meyer A, Cánovas CR, Macías F, Schneider P (2019) Life cycle assessment of a passive remediation system for acid mine drainage: towards more sustainable mining activity. J Clean Prod 211:1100–1111. https://doi.org/10.1016/j.jclepro.2018.11.224

Moynahan OS, Zabinski CA, Gannon JE (2002) Microbial community structure and carbon-utilization diversity in a mine tailings revegetation study. Restor Ecol 10(1):77–87. https://doi.org/10.1046/j.1526-100X.2002.10108.x

Mubarak H, Chai LY, Mirza N, Yang ZH, Pervez A, Tariq M, Shaheen S, Mahmood Q (2015) Antimony (Sb)–pollution and removal techniques–critical assessment of technologies. Toxicol Environ Chem 97(10):1296–1318. https://doi.org/10.1080/02772248.2015.1095549

Renou S, Thomas JS, Aoustin E, Pons MN (2008) Influence of impact assessment methods in wastewater treatment LCA. J Clean Prod 16(10):1098–1105. https://doi.org/10.1016/j.jclepro.2007.06.003

Salam MA, Mohamed RM (2003) Removal of antimony(III) by multi-walled carbon nanotubes from model solution and environmental samples. Chem Eng Res Des 91(7):1352–1360. https://doi.org/10.1016/j.cherd.2013.02.007

Sun M, Xiao T, Ning Z, Xiao E, Sun W (2015) Microbial community analysis in rice paddy soils irrigated by acid mine drainage contaminated water. Appl Microbiol Biotechnol 99(6):2911–2922. https://doi.org/10.1016/j.envpol.2016.05.008

Sun W, Sun X, Li B, Xu R, Young LY, Dong Y, Zhang M, Kong T, Xiao E, Wang Q (2020a) Bacterial response to sharp geochemical gradients caused by acid mine drainage intrusion in a terrace: relevance of C, N, and S cycling and metal resistance. Environ Int 138:105601

Sun X, Kong T, Haggblom MM, Kolton M, Li F, Dong Y, Huang Y, Li B, Sun W (2020b) Chemolithoautotrophic diazotrophy dominates the nitrogen fixation process in mine tailings. Environ Sci Technol

UNEP/SETAC (2005) Life cycle approaches: the road from analysis to practice. United Nations Environment Program

United States Environmental Protection Agency (2018) Particulate matter (PM) basics. https://wwwepagov/pm-pollution/particulate-matter-pm-basics Access 5 July 2019

Vince F, Aoustin E, Bréant P, Marechal F (2008) LCA tool for the environmental evaluation of potable water production. Desalination 220(1–3):37–56. https://doi.org/10.1016/j.desal.2007.01.021

Wang H, Chen F, Mu S, Zhang D, Pan X, Lee DJ, Chang JS (2013) Removal of antimony (Sb (V)) from Sb mine drainage: biological sulfate reduction and sulfide oxidation–precipitation. Bioresour Technol 146:799–802

Wang X, Anctil A, Masten SJ (2019) Energy consumption and environmental impact analysis of ozonation catalytic membrane filtration system for water treatment. Environ Eng Sci 36(2):149–157. https://doi.org/10.1089/ees.2018.0270

Wang X, He M, Xi J, Lu X (2011) Antimony distribution and mobility in rivers around the world's largest antimony mine of Xikuangshan, Hunan Province, China. Microchem J 97(1):4–11. https://doi.org/10.1016/j.microc.2010.05.011

Watson RT, Zinyowera MC, Moss RH (1996) Technologies, policies and measures for mitigating climate change. Switzerland: Intergovernmental Panel on Climate Change

Xi JH, He MC, Lin CY (2011) Adsorption of antimony(III) and antimony(V) on bentonite: kinetics, thermodynamics and anion competition. Microchem J 97(1):85–91. https://doi.org/10.1016/j.microc.2010.05.017

Xu R, Li B, Xiao E, Young LY, Sun X, Kong T, Kong T, Dong Y, Wang Q, Yang Z, Chen L, Sun W (2020) Uncovering microbial responses to sharp geochemical gradients in a terrace contaminated by acid mine drainage. Environ Pollut 261:114226. https://doi.org/10.1016/j.envpol.2020.114226

Xu W, Liu RP, Qiu JH, Peng RM (2015) Adsorption of antimony(V) onto Mn(II)-enriched surfaces of manganeseoxide and Fe-Mn binary oxide. Chemosphere 138:616–624. https://doi.org/10.1016/j.chemosphere.2015.07.039

Xu Y, Ohki A, Maeda S (2001) Adsorption and removal of antimony from aqueous solution by an activated alumina. Toxicol Environ Chem 80(3–4):133–144. https://doi.org/10.1080/02772240109359004

Yellishetty M, Mudd GM, Ranjith PG (2011) The steel industry, abiotic resource depletion and life cycle assessment: a real or perceived issue. J Clean Prod 19(1):78–90. https://doi.org/10.1016/j.jclepro.2010.08.020

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.