minerals

MDPI

*Editorial*

# Editorial for Special Issue “Novel and Emerging Strategies for Sustainable Mine Tailings and Acid Mine Drainage Management”

**Carlito Baltazar Tabelin [1,*], Kyoungkeun Yoo [2] and Jining Li [3]**

[1] School of Minerals and Energy Resources Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[2] Department of Energy and Resources Engineering, Korea Maritime and Ocean University, Busan 49112, Korea; kyoo@kmou.ac.kr
[3] School of Environment, Nanjing Normal University, Nanjing 10830, China; ljn006@126.com
* Correspondence: c.tabelin@unsw.edu.au

**Citation:** Tabelin, C.B.; Yoo, K.; Li, J. Editorial for Special Issue “Novel and Emerging Strategies for Sustainable Mine Tailings and Acid Mine Drainage Management”. *Minerals* **2021**, *11*, 902. https://doi.org/10.3390/min11080902

Received: 16 August 2021
Accepted: 17 August 2021
Published: 20 August 2021



Climate change is one of the most pressing problems facing humanity this century. In a recent report by the Intergovernmental Panel on Climate Change (IPCC), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$) and methane ($CH_4$) were found to have reached annual averages of 410, 332 and 1866 ppm in 2019, respectively, leading to the global surface temperature increasing by 0.84–1.10 °C compared to measured values about a century ago [1]. Notably, the IPCC report showed significantly higher atmospheric $CO_2$ concentration in 2019 than historical values in the last two million years [1].

Spearheaded by the United Nations (UN) as enshrined in its sustainable development goals (UN-SDG 13 “Climate Action”), governments, companies and the research community have banded together to develop low-carbon alternatives to fossil-fuel-based technologies that dominate the transportation and heat/electricity generation sectors [2]. These alternatives include electric-based vehicles (EVs), clean storage and renewable energy technologies such solar, wind, geothermal and hydroelectric, along with secondary electricity storage media, such as lithium-ion batteries and flow-battery cells. There is, however, a big catch to all this. Low-carbon technologies are more metal, mineral and material intensive than conventional fossil-fuel-based technologies. Electric cars, for example, require up to 11 times more copper than conventional cars [3]. In addition to copper, the World Bank Group has identified aluminum, chromium, cobalt, graphite, indium, iron, lead, lithium, manganese, molybdenum, neodymium, nickel, silver, titanium, vanadium and zinc as critical elements/materials for the clean energy transition to succeed [4]. Thus, the successful transition from fossil-fuel-based to low-carbon technologies would require more extensive mining to maintain the stable supply of raw materials, such as metals and minerals, in the next 30–50 years.

The expansion of mining and mineral processing operations would mean more mining-related wastes, such as tailings, waste rocks and acid mine drainage (AMD), which are notorious for their devastating and long-term destructive impacts on the environment. Tailings are waste materials generated during the processing of ores, which are typically disposed of in tailings storage facilities (TSFs). The tonnage of tailings generated by a mine depends on the deposit. For example, large porphyry copper mining operations, such as those of Escondida and Antamina, could generate 50–150 million tons of tailings per year [3]. Waste rocks or overburden are the rocks, soils and sediments removed for access and exploitation of a deposit and could amount to about three times the tonnage of ore extracted in open-pit mining operations. Finally, AMD, the effluent generated in mine sites due to the oxidation of sulfide minerals like pyrite ($FeS_2$), is acidic and contains strictly regulated contaminants not only destructive to the surrounding ecosystem but also hazardous to human health. Moreover, sustainable AMD treatment is difficult because of the complex and site-specific nature of AMD and its long-term generation, which could persist for several centuries or even a few millennia [5]. Sustainable management of these three types of mine wastes remains a huge challenge for the resource sector. Most techniques and strategies employed by the sector are outdated and/or ineffective, so alternative novel ways to manage these wastes are needed, including improvements to existing waste management strategies employed in mine sites around the world [6,7].

In this Special Issue, two promising sustainable strategies for mine waste management, namely repurposing/reprocessing (i.e., valorization) and cost reduction, were explored. Longos et al. [8] repurposed nickel laterite mine waste and industrial wastes, such as coal fly ash, into geopolymers with unconfined compressive strengths around 20 MPa. Meanwhile, Wu et al. [9] demonstrated the potential use of tailings as specialty building materials resistant to corrosion when exposed to saline environments. Waste minimization via repurposing of tailings for construction and/or backfill materials is also gaining traction in the resource industry [10–12]. As high-grade ores are depleted, tailings from historic mine sites could be reprocessed to recover residual valuable metals and minerals [13]. Jung et al. [14], for example, recovered residual scheelite ($CaWO_4$) from tungsten mine tailings by flotation through reagent regime optimization. Meanwhile, Lazo and Lazo [15] utilized native plant species in Chile, such as *Oxalis gigantea*, *Cistanthe grandiflora*, *Puya berteroniana* and *Solidago chilensis*, to rehabilitate mine tailings and found that these plants could sequester molybdenum, copper and lead from the wastes and concentrate them in plant tissues. These native plants show promise for phytomining of mine wastes in the future.

For cost reduction and improved sustainability of AMD treatment, articles in this Special Issue investigated AMD volume reduction, utilization of cheaper alternative neutralizing materials and sequestration of valuable materials during treatment. Yamaguchi et al. [16] modeled up to 30% reduction of AMD generation from underground mine workings of a closed mine in Japan when mine waste was implemented for backfilling. Meanwhile, the use of cheaper, locally available materials like dolomite [17], and alkaline wastes, such as red mud [18,19], calcareous mine waste rocks [20] and demolition wastes [21], were effective alternatives to commercially available neutralizers [22].

From the perspectives of a circular economy and resource conservation, AMDs can be considered as future resources because they contain considerable amounts of valuable and critical metals. Aghaei et al. [23] demonstrated >95% copper and lead recovery from simulated mine/processing wastewater using aluminum-based bimetallic materials. Bimetallic materials, also known as bimetals, bimetallic particles and bimetallic catalysts, are promising because their action relies on reduction and galvanic interactions that specifically target redox-active elements, such as copper, nickel, gold, silver and most heavy metals [24]. The only drawback of this approach is the expensive reagent-grade aluminum powder needed for synthesis, but the idea of using aluminum wastes or scraps as raw material is recently gaining traction [24]. Another promising sustainable approach for AMD management based on circular economy concepts is the use of microbial fuel cells (MFCs) to simultaneously recover target metals and generate electricity. Ai et al. [25] demonstrated the treatment of AMD using MFCs and the recovery of copper in the cathode as elemental copper. MFCs could be a promising approach, especially in regions where the mine site is located close to cities with an abundant supply of organic-rich wastewaters.

Mine wastes exposed to the environment for a long time can also act as a natural laboratory where microorganisms evolve and develop resistance to high acidity and heavy metal concentrations, which can be isolated, cultured, grown and applied to improve existing bioleaching technologies. Chen et al. [26] studied AMD from Clarabelle Mill, Canada, and successfully isolated and identified new species of *Acidithiobacillus ferridurans* that can be used for the bioleaching of low-grade porphyry copper ores.

The Special Issue is completed with articles on the critical roles of redox conditions and galvanic interactions in the weathering of sulfide-bearing mine wastes when disposed of on land and under the sea [27], the importance of hydrogeochemical conditions on waste rock weathering [28] and the potential impacts of climate change on AMD formation in abandoned and closed mines [29].

The adoption of clean storage and renewable energy technologies is a classic example of the proverbial "double-edged sword". The benefits of transitioning to low-carbon technologies to mitigate climate change should be balanced with the socio-environmental impacts of extensive mining required to supply critical metals and materials. The collection of research and review articles in this Special Issue shows that the impacts of mining can be mitigated and managed more sustainably using circular economy concepts and the development of novel techniques to reprocess, repurpose and decontaminate mine waste streams, such as tailings, waste rocks and AMD.

**Author Contributions:** Writing—original draft preparation, C.B.T.; writing—review and editing, K.Y. and J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. IPCC 2021 Summary for Policymakers. *In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I.; et al., Eds.; Cambridge University Press: Cambridge, UK, 2021, in press.
2. Tabelin, C.B.; Dallas, J.; Casanova, S.; Pelech, T.; Bournival, G.; Saydam, S.; Canbulat, I. Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives. *Miner. Eng.* **2021**, *163*, 106743.
3. Tabelin, C.B.; Park, I.; Phengsaart, T.; Jeon, S.; Villacorte-Tabelin, M.; Alonzo, D.; Yoo, K.; Ito, M.; Hiroyoshi, N. Copper and critical metals production from porphyry ores and E-wastes: A review of resources availability, processing/recycling challenges, socio-environmental aspects, and sustainability issues. *Resour. Conserv. Recy.* **2021**, *170*, 105610.
4. WBG (World Bank Group). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. 2020. Available online: http://pubdocs.worldbank.org/en/961711588875536384/Minerals-for-Climate-Action-The-Mineral-Intensity-of-the-Clean-Energy-Transition.pdf (accessed on 30 September 2020).
5. Park, I.; Tabelin, C.B.; Jeon, S.; Li, X.; Seno, K.; Ito, M.; Hiroyoshi, N. A review of recent strategies for acid mine drainage prevention and mine tailings recycling. *Chemosphere* **2019**, *219*, 588–606.
6. Igarashi, T.; Salgado, P.H.; Uchiyama, H.; Miyamae, H.; Iyatomi, N.; Hashimoto, K.; Tabelin, C.B. The two-step neutralization ferrite-formation process for sustainable acid mine drainage treatment: Removal of copper, zinc and arsenic, and the influence of coexisting ions on ferritization. *Sci. Total Environ.* **2020**, *715*, 136877.
7. Tabelin, C.B.; Corpuz, R.D.; Igarashi, T.; Villacorte-Tabelin, M.; Alorro, R.D.; Yoo, K.; Raval, S.; Ito, M.; Hiroyoshi, N. Acid mine drainage formation and arsenic mobility under strongly acidic conditions: Importance of soluble phases, iron oxyhydroxides/oxides and nature of oxidation layer on pyrite. *J. Hazard. Mater.* **2020**, *399*, 122844.
8. Longos, A.; Tigue, A.A.; Dollente, I.J.; Malenab, R.A.; Bernardo-Arugay, I.; Hinode, H.; Kurniawan, W.; Promentilla, M.A. Optimization of the mix formulation of geopolymer using nickel-laterite mine waste and coal fly ash. *Minerals* **2020**, *10*, 1144.
9. Wu, J.; Li, J.; Rao, F.; Yin, W. Characterization of slag reprocessing tailings-based geopolymers in marine environment. *Minerals* **2020**, *10*, 832.
10. Opiso, E.M.; Tabelin, C.B.; Maestre, C.V.; Aseniero, J.P.J.; Park, I.; Villacorte-Tabelin, M. Synthesis and characterization of coal fly ash and palm oil fuel ash modified artisanal and small-scale gold mine (ASGM) tailings based geopolymer using sugar mill lime sludge as Ca-based activator. *Heliyon* **2021**, *7*, e06654.
11. Aseniero, J.P.J.; Opiso, E.M.; Banda, M.H.T.; Tabelin, C.B. Potential utilization of artisanal gold-mine tailings as geopolymeric source material: Preliminary investigation. *SN Appl. Sci.* **2019**, *1*, 35.
12. Cao, S.; Yilmaz, E.; Song, W. Evaluation of viscosity, strength and microstructural properties of cemented tailings backfill. *Minerals* **2018**, *8*, 352.
13. Lam, E.J.; Carle, R.; González, R.; Montofré, Í.L.; Veloso, E.A.; Bernardo, A.; Cánovas, M.; Álvarez, F.A. A Methodology Based on Magnetic Susceptibility to Characterize Copper Mine Tailings. *Minerals* **2020**, *10*, 939.
14. Jung, M.Y.; Park, J.H.; Yoo, K. Effects of Ferrous Sulfate Addition on the Selective Flotation of Scheelite over Calcite and Fluorite. *Minerals* **2020**, *10*, 864.

15. Lazo, P.; Lazo, A. Assessment of Native and Endemic Chilean Plants for Removal of Cu, Mo and Pb from Mine Tailings. *Minerals* **2020**, *10*, 1020.
16. Yamaguchi, K.; Tomiyama, S.; Igarashi, T.; Yamagata, S.; Ebato, M.; Sakoda, M. Effects of Backfilling Excavated Underground Space on Reducing Acid Mine Drainage in an Abandoned Mine. *Minerals* **2020**, *10*, 777.
17. Tangviroon, P.; Noto, K.; Igarashi, T.; Kawashima, T.; Ito, M.; Sato, T.; Mufalo, W.; Chirwa, M.; Nyambe, I.; Nakata, H.; et al. Immobilization of lead and zinc leached from mining residual materials in Kabwe, Zambia: Possibility of Chemical Immobilization by Dolomite, Calcined Dolomite, and Magnesium Oxide. *Minerals* **2020**, *10*, 763.
18. Keller, V.; Stopić, S.; Xakalashe, B.; Ma, Y.; Ndlovu, S.; Mwewa, B.; Simate, G.S.; Friedrich, B. Effectiveness of Fly Ash and Red Mud as Strategies for Sustainable Acid Mine Drainage Management. *Minerals* **2020**, *10*, 707.
19. Ran, Z.; Pan, Y.; Liu, W. Co-Disposal of Coal Gangue and Red Mud for Prevention of Acid Mine Drainage Generation from Self-Heating Gangue Dumps. *Minerals* **2020**, *10*, 1081.
20. Retka, J.; Rzepa, G.; Bajda, T.; Drewniak, L. The Use of Mining Waste Materials for the Treatment of Acid and Alkaline Mine Wastewater. *Minerals* **2020**, *10*, 1061.
21. Turingan, C.O.A.; Singson, G.B.; Melchor, B.T.; Alorro, R.D.; Beltran, A.B.; Orbecido, A.H. Evaluation of Efficiencies of Locally Available Neutralizing Agents for Passive Treatment of Acid Mine Drainage. *Minerals* **2020**, *10*, 845.
22. Bortnikova, S.; Gaskova, O.; Yurkevich, N.; Saeva, O.; Abrosimova, N. Chemical treatment of highly toxic acid mine drainage at a gold mining site in Southwestern Siberia, Russia. *Minerals* **2020**, *10*, 867.
23. Aghaei, E.; Wang, Z.; Tadesse, B.; Tabelin, C.B.; Quadir, Z.; Alorro, R.D. Performance Evaluation of Fe-Al Bimetallic Particles for the Removal of Potentially Toxic Elements from Combined Acid Mine Drainage-Effluents from Refractory Gold Ore Processing. *Minerals* **2021**, *11*, 590.
24. Tabelin, C.B.; Resabal, V.J.T.; Park, I.; Villanueva, M.G.B.; Choi, S.; Ebio, R.; Cabural, P.J.; Villacorte-Tabelin, M.; Orbecido, A.; Alorro, R.D.; et al. Repurposing of aluminum scrap into magnetic Al0/ZVI bimetallic materials: Two-stage mechanical-chemical synthesis and characterization of products. *J. Clean. Prod.* **2021**, *317*, 128285.
25. Ai, C.; Yan, Z.; Hou, S.; Zheng, X.; Zeng, Z.; Amanze, C.; Dai, Z.; Chai, L.; Qiu, G.; Zeng, W. Effective treatment of acid mine drainage with microbial fuel cells: An emphasis on typical energy substrates. *Minerals* **2020**, *10*, 443.
26. Chen, J.; Liu, Y.; Diep, P.; Mahadevan, R. Genomic analysis of a newly isolated Acidithiobacillus ferridurans JAGS strain reveals its adaptation to acid mine drainage. *Minerals* **2021**, *11*, 74.
27. Mun, Y.; Strmić Palinkaš, S.; Kullerud, K. The Role of Mineral Assemblages in the Environmental Impact of Cu-Sulfide Deposits: A Case Study from Norway. *Minerals* **2021**, *11*, 627.
28. Vriens, B.; Plante, B.; Seigneur, N.; Jamieson, H. Mine waste rock: Insights for sustainable hydrogeochemical management. *Minerals* **2020**, *10*, 728.
29. Tokoro, C.; Fukaki, K.; Kadokura, M.; Fuchida, S. Forecast of AMD quantity by a series tank model in three stages: Case studies in two closed Japanese mines. *Minerals* **2020**, *10*, 430.