sustainability

MDPI

Article

Carbon Dioxide-Based Neutralization of High-Density Sludge Effluents as a Sustainable Climate and Water Quality Alternative to the Use of Strong Mineral Acids

Julio C. Gastañadui-Cruz [1], Iván A. Reyes-Lopez [1], Agusberto Cortijo-Garcia [1], Hans R. Portilla-Rodriguez [1], John A. Bush [2], Johan Vanneste [2] and Pablo A. Garcia-Chevesich [2,3,*]

[1] Centro para Investigación en Recursos Sostenibles, Universidad Nacional de Trujillo, Trujillo 13011, Peru; endercgsac@gmail.com (J.C.G.-C.); ireyes@unitru.edu.pe (I.A.R.-L.); hportilla@unitru.edu.pe (H.R.P.-R.)
[2] Colorado School of Mines, Center for Research in Sustainable Resources, Golden, CO 80401, USA; jobush@mines.edu (J.A.B.); vanneste@mines.edu (J.V.)
[3] Intergovernmental Hydrological Programme, United Nations Educational, Scientific, and Cultural Organization (UNESCO), Montevideo 11800, Uruguay
* Correspondence: pablogarcia@mines.edu

Abstract: The neutralization of high-density sludge (HDS) effluent is a required process involved in the treatment of acid mine drainage (AMD). In their last treatment stage, effluents with high pH values are acidified to reach legal standards before being released to the environment using hydrochloric or sulfuric acid. In this investigation, CO_2 was tested as an alternative way to decrease the pH of the HDS effluent, together with an economic analysis comparing the results with the use of strong mineral acids, considering a full-scale 300 m^3/h plant. HDS samples were collected from a PAN American Silver operation in Cajamarca, northern Peru. Four acidification tests were carried out on 20 L containers, with a subsequent evaluation of reaction time and CO_2 consumption to regulate the final pH of the treated solution. The results suggest that by adding CO_2 (0.5 L/min) to the solution, the pH was successfully decreased from 10–10.5 to 6.5–7.5 (which falls within the legal limits) in a matter of minutes. An average of 130 g of CO_2 was sequestrated per m^3 of solution to decrease the pH within legal limits, representing around USD 0.031/m^3 in terms of treatment cost for a full-scale plant. While this is more expensive than using other acids, with a CO_2 credit of USD 100/ton, sequestrated CO_2 neutralization is 12% cheaper and only 6% more expensive than using H_2SO_4 and HCl, respectively. Moreover, in terms of the costs per ton of avoided CO_2 of USD 133 and USD 262 for replacing hydrochloric and sulfuric acid, respectively, it is markedly lower than the cost of other CO_2 abatement technologies, like, for instance, solar photovoltaic panels (PV) that can cost between USD 368 and USD 684/ton of avoided CO_2 in Peru and require substantial capital investments. Moreover, the use of CO_2 implicates a series of additional safety, operational, and environmental advantages that should be considered. Therefore, the use of CO_2 to decrease HDS effluent's pH should be further explored in Peru and elsewhere as a sustainable alternative.

Keywords: sulfates; carbon dioxide; pH; operating costs; acid mine drainage; Peru

check for updates

Citation: Gastañadui-Cruz, J.C.; Reyes-Lopez, I.A.; Cortijo-Garcia, A.; Portilla-Rodriguez, H.R.; Bush, J.A.; Vanneste, J.; Garcia-Chevesich, P.A. Carbon Dioxide-Based Neutralization of High-Density Sludge Effluents as a Sustainable Climate and Water Quality Alternative to the Use of Strong Mineral Acids. *Sustainability* **2024**, *16*, 10363. https://doi.org/10.3390/su162310363

Academic Editors: Agostina Chiavola and Andrea G. Capodaglio

Received: 11 September 2024
Revised: 13 November 2024
Accepted: 21 November 2024
Published: 27 November 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Water pollution from acid mine drainage (AMD) is a global concern. Surface or groundwater contamination from untreated (or not properly treated) AMD has been reported in countless geographical areas around the world, including India [1], Spain [2], Indonesia [3], Slovakia [4], Portugal [5], Brazil [6], and the United States [7]. Moreover, Peru (the home of this investigation) is not an exception; scientists such as Grande et al. [8], Sevink et al. [9], and Vriens et al. [10], among many others, have reported water contamination from AMD in this South American country.

AMD remediation costs can vary widely depending on several factors, including the scale of the affected area, the severity of contamination, and the chosen remediation techniques [11]; however, AMD treatment cost is known to be high and has been the focus of interest of researchers with the purpose of finding an economic way to improve the quality of those toxic effluents. For example, AMD can be treated using microbes [12], membranes [13], or wetlands [14]. Furthermore, the latter is often considered the most cost-effective treatment method [15]; for example, in a comprehensive study in Pennsylvania, wetlands were found to amount to USD 5700/per km of affected stream per year [16]. However, when it comes to semi-arid regions like parts of Peru, those toxic effluents are commonly treated with hydrated lime ($Ca(OH)_2$) in a high-density sludge (HDS) system to increase the pH until around 9.5 to 10.5, depending on the metal type and concentration, as basic fluids can maximize the metal precipitation process [17]. However, the resulting cleaner water cannot be released into the environment because it is too basic, so hydrochloric or sulfuric acid (HCl and H_2SO_4, respectively) is commonly used to decrease the pH of the effluent [18]. Moreover, this process adds chloride or sulfate ions to the fluid, which can cause adverse effects at higher concentrations in people [19], downstream water transportation structures [20,21], and the environment [22]. While many sulfate removal technologies exist such as chemical-, electrical-, biological-, and membrane-based approaches, among many others [23–27], these technologies are generally not implemented, as they add significant costs to the process of AMD treatment, and sulfate ion regulations are commonly not very stringent due to the moderate toxicity of the sulfate ion.

It is long known that when CO_2 is dissolved into a fluid, it reacts with water molecules, becoming carbonic acid (H_2CO_3) and making water more acidic [28]. Hence, AMD's pH can be lowered by simply adding carbon dioxide (CO_2) into the fluid [29], which is what motivated this investigation. Moreover, the use of CO_2 can contribute to decreasing carbon emissions from mining operations and, therefore, mitigate global warming [30].

The use of CO_2 in AMD treatment is not novel. For example, the authors that used CO_2 on AMD highlight the work by Vaziri Hassas et al. [31], who used CO_2 mineralization to produce rare elements' precipitation in AMD in Pennsylvania (USA). Similarly, Masindi et al. [32] applied CO_2 bubbling (among other techniques) to treat AMD waters and generate gypsum and limestone in South Africa. However, not much has been done in terms of CO_2 sequestration in the process of HDS effluent's pH decrease, other than the work by Lee et al. [33], who performed a feasibility study using CO_2 injection after applying hydrated lime to increase the pH of AMD from an abandoned coal mine in Germany. The authors injected CO_2 into the AMD neutralization process to generate calcium carbonate ($CaCO_3$), noting that estimating the optimum CO_2 injection volume and concluding that CO_2 sequestration using the neutralization process can be considered a sustainable option. However, an economic analysis of CO_2 injection compared to hydrochloric and sulfuric acid for acidification of AMD is highly needed for further decision-making and environmental policies. Moreover, Lee et al. [33] applied CO_2 injection to HDS effluent with a pH of 12. This pH is much higher than a typical HDS effluent's pH and may have led to an overestimated CO_2 sequestration potential as well as a prohibitively high cost of acidification. Therefore, in this investigation, CO_2 injection was applied to bring the pH of a typical HDS effluent of 10 down to legal disposable levels (following the Peruvian environmental standard DS 010-2010-MINAM), complementing an economic evaluation of the process. The main objective of our research was to determine the influence of CO_2 injection on the reduction of pH and, at the same time, assess the amount of CO_2 that can be sequestered as well as the avoided CO_2 emissions from not using other mineral acids. The second objective was to assess the operating costs of using CO_2 as opposed to hydrochloric or sulfuric acid at a future 300 m^3/h AMD treatment plant at the Shahuindo Mining Unit operation in Peru.

2. Materials and Methods

The investigation took place at the Choloque subdrainage of a pilot plant, with AMD samples provided by Pan American Silver (PAS) in the Shahuindo Mining Unit operation

in Peru (coordinates 9158986N-808891E). This open-pit gold and silver operation is able to produce over 36 thousand tons per day of minerals. The operation, which is considered large-scale, i.e., above 5000 tons of minerals processed per day per Peruvian law, is located in the District of Cachaci, Province of Cajabamba, Department of Cajamarca in northern Peru (blue dot in Figure 1).



Figure 1. Map of Peru (red color in South America) and the location of the study site (blue dot) within the Department of Cajamarca. Source: Wikipedia under Creative Commons License (Genérica de Atribución/Compartir-Igual 3.0). Available at: https://es.m.wikipedia.org/wiki/Archivo:Peru_location_map.svg (accessed on 12 October 2024).

The objective of the pilot plant is to determine optimal design parameters for the full-scale 300 m^3/h AMD treatment plant. The pilot plant's operating process (Figure 2) consists of the following stages: reagent preparation; contact between the acid solution and the alkalis; alkalization; flocculation; sedimentation; acidification; and filtration. For this, ten tanks are used in the pilot plant, as well as a bag filter and a filter press. The reagent preparation is subdivided into two types of reagents, alkalis (lime milk) and flocculant, for which there are two tanks of approximately 120 L for each reagent (preparation and dosing tank). The lime milk is prepared at 15% solids and the flocculant at a concentration of 0.1% (1000 ppm). The acid solution and the lime milk are mixed in a 500-L contact tank. Acid water is fed using a centrifugal pump from the acid water receiving tank (provided by PAS-Shahuindo) to the contact tank and the lime milk is fed by a peristaltic pump from the lime milk dosing tank. The mixture made in the contact tank is then transferred by a centrifugal pump to an adjacent alkalization tank, which has a capacity of 2 m^3. In this tank, the mix spends a certain residence time to react and reduce the metals contained in the initial solution, bringing the pH to levels of approximately 10.5 at the tank outlet. The solution is then transferred to the flocculation tank by overflow, where it comes into contact with the flocculant, transported by a peristaltic pump from the flocculant dosing tank, forming floccules, which are essential for the solid–liquid separation stage. Flocculation takes place in a 250 L tank that also receives the recirculation of sludge from a later stage. Once the mixture is flocculated, it is transferred to the 5 m^3 clarifier reactor using a centrifugal pump. The reactor has two products: (1) an underflow that is partially recirculated, while the remainder is stored for later tests; and (2) an overflow that is transferred to the holding tank of the bag filter which, using a centrifugal pump, filters the last solid residues present in the clarifier overflow solution, which is then transported to a 250 L tank where it undergoes an acidification period using CO_2 (the focus of this study). All tanks have individual frequency

converters and agitators that allow the agitator rotation speed to be regulated. Additionally, the pump's inlet flow is regulated using the rotameter and the pump outlet valves.

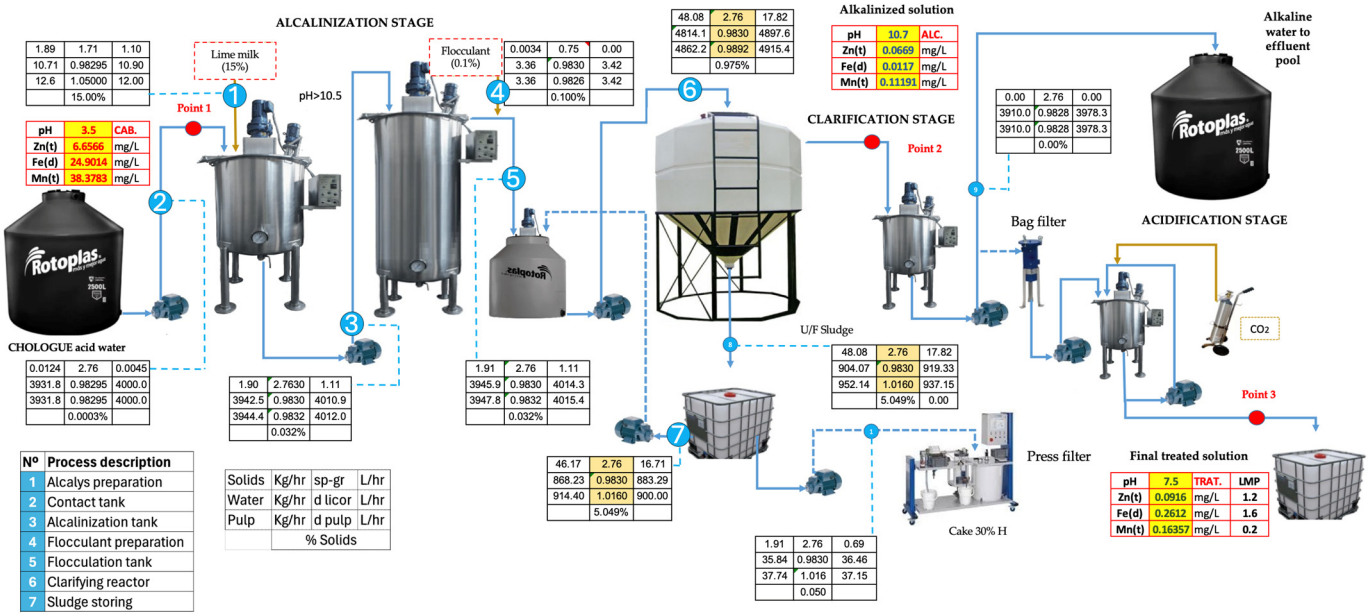


Figure 2. Mass balance of the operation (courtesy of Julio César Gastañadui-Cruz, co-author).

The lime was prepared at 15% solids by mass, named "Bendiciones de Dios" (65% CaO and 42% -m200 particle size) in 120 L tanks with the lime milk preparation for 30 min, with constant agitation to prevent segregation of suspended particles. Moreover, the flocculant used was MT-6506 at a concentration of 0.1% (weight) and a contact time of one hour under constant agitation. The operating conditions for the execution of the pilot tests developed in the Shahuindo Mining Unit—Choloque Platform and the quality of the final overflow to be treated are shown in Appendix A, while physicochemical analyses of four samples (from the feed water to be treated) are detailed in Appendix B. The consumption ratio of lime to reach pH of 10.4, 10.5, 10.6, 10.7, and 10.8 according to treatment flows were 0.43, 0.45, 0.47, 0.49, 0.51 kg/m^3, considering a density of 1.11 kg/L of 15% lime milk, respectively. No preliminary screening of the coarse fractions of lime was performed in the preparation of lime milk. Needless to say, those pH values violate Peruvian environmental standards.

Four acidification tests were carried out on 20 L containers after filtering using a 15-micrometer screen due to surface total suspended solid (TSS) contents removing the slimes that are passed to the clarifier overflow to avoid the redissolution of solids when regulating the pH of the overflow solution. A subsequent evaluation of reaction time and CO_2 consumption to regulate the final pH of the treated solution to a target 6.5–8.5 range (to make sure legal limits are not violated) was performed. For each test, exact weight, CO_2 flow set with a rotameter, and reaction time were documented. Similarly, CO_2 consumption was determined by measuring the exact weight of the gas cylinder before and after the test, also documenting the residence time. Obviously, initial and final pH values were precisely measured.

3. Results

The results from the four tests are shown in Table 1, while the water quality levels of samples alkalinized using lime and samples from further acidified water using CO_2 are detailed in Appendices C and D, respectively. The evolution of pH over time is detailed in Appendix E and water quality analysis methods in Appendix F. By adding CO_2 (0.5 L/min) to the solution, the pH was successfully decreased from 10–10.5 to 6.5–7.5 (which falls within the legal limits), in 5–10 min. An average CO_2 consumption of 130 g per m^3 of solution was required to decrease the pH within legal limits.

Table 1. Acidification test conditions for the four neutralized solutions tested.

Sample ID	Solution Weight (kg)	Initial pH	CO_2 Flow (L/min)	Reaction Time (min.)	Initial CO_2 Tank Weight (kg)	Final CO_2 Tank Weight (kg)	CO_2 Consumption (g/m^3)	Residence Time (min.)	Final pH	pH Drop
S1	13.82	10.43	0.5	1.2	8.632	8.63	144.7	10	6.63	3.80
S2	16.11	10.39	0.5	0.8	8.612	8.61	124.18	5.3	7.76	2.63
S3	15.08	10.16	0.5	0.55	8.608	8.606	132.59	10	7.40	2.76
S4	17.05	10.42	0.5	0.9	8.612	8.61	117.32	10	7.50	2.92

A comparison between the economic cost of acidification with CO_2 to the benchmark with HCl or H_2SO_4 is shown in Table 2. Slightly less H_2SO_4 is required for acidification [28]. Carbon dioxide and especially HCl and H_2SO_4 costs have exhibited a sharp spike since the pandemic in 2020 [29]. Therefore, the cost was calculated considering (1) an average global CO_2 price from 2020 to July 2024 of USD 0.236/kg, as well as a minimum and maximum price of USD 0.223/kg and USD 0.259/kg, respectively; (2) an average HCl price in Latin America of USD 0.18/kg, as well as a minimum and maximum price of USD 0.13/kg and USD 0.26/kg, respectively; and (3) an average global H_2SO_4 price of USD 0.161/kg, as well as a minimum and maximum price of USD 0.101/kg and USD 0.298/kg, respectively. Considering this, Table 3 summarizes the average yearly cost for the full-scale 300 m^3/h AMD treatment plant, assuming no downtime. Table 3 also lists the amount of CO_2 that can be sequestered per year for the full-scale plant. Unfortunately, most Latin American countries currently do not have a functioning carbon emission credit market, with a resulting average carbon tax of only USD 5/ton CO_2 compared to more than USD 100/ton CO_2 in some European countries [34]. However, this may change in the future, leading to extra costs for using hydrochloric or sulfuric acid and hence an added advantage of acidification with CO_2. Therefore, an acidification cost including USD 100/ton of CO_2 sequestrated was included in Table 3 as well.

Table 2. Comparison of acidification cost with carbon dioxide, hydrochloric acid, and sulfuric acid.

Sample ID	CO_2 Consumption (g/m^3)	CO_2 Cost (USD/m^3)			HCl Equivalent (g/m^3)	HCl Cost (USD/m^3)			H_2SO_4 Equivalent (g/m^3)	H_2SO_4 Cost (USD/m^3)		
		Ave.	Min.	Max.		Ave.	Min.	Max.		Ave.	Min.	Max.
S1	144.7	0.03	0.03	0.04	102.9	0.02	0.01	0.03	138.3	0.02	0.02	0.04
S2	124.2	0.03	0.03	0.03	88.3	0.02	0.01	0.02	118.7	0.02	0.01	0.04
S3	132.6	0.03	0.03	0.03	94.3	0.02	0.01	0.03	126.7	0.02	0.01	0.04
S4	117.3	0.03	0.03	0.03	83.5	0.02	0.01	0.02	112.2	0.02	0.01	0.03

Table 3. Average acidification cost and CO_2 sequestrated for a full-scale 300 m^3/h AMD treatment plant.

Sample ID	CO_2 Consumption (g/m^3)	CO_2 300 m^3/h (Ton/Year)	Average CO_2 Cost (USD/m^3)	Average CO_2 Cost with USD 100/Ton CO_2 Credit (USD/m^3)	Cost 300 m^3/h (USD/Year)	Cost 300 m^3/h with USD 100/Ton CO_2 Credit (USD/Year)	HCl Equivalent (g/m^3)	Average HCl Cost (USD/m^3)	Cost 300 m^3/h (USD/Year)	H_2SO_4 Equivalent (g/m^3)	Average H_2SO_4 Cost (USD/m^3)	Cost 300 m^3/h (USD/Year)
S1	144.7	380.3	0.034	0.020	89,744	51,717	102.926	0.019	48,688	138.3	0.022	58,527
S2	124.2	326.3	0.029	0.017	77,017	44,383	88.330	0.016	41,783	118.7	0.019	50,227
S3	132.6	348.4	0.031	0.018	82,233	47,389	94.312	0.017	44,613	126.7	0.020	53,629
S4	117.3	308.3	0.028	0.016	72,763	41,931	83.450	0.015	39,475	112.2	0.018	47,452
Average	129.7	340.8	0.031	0.018	80,439	46,355	92.254	0.017	43,640	124.0	0.020	52,459

However, by not using the other acids, the embedded CO_2 emissions incurred during the production of those acids could also potentially be avoided. The CO_2 emission factor for the production of liquid carbon dioxide is 0.82 CO_2 equivalents per kg compared to hydrochloric and sulfuric acid, which have 0.89 and 0.14 kg CO_2 equivalents per kg of acid, respectively [35]. With these emission factors, the total avoided CO_2 emissions per m^3 of HDS effluent, including the CO_2 sequestrated, can be calculated (Table 4). Lastly, taking into account the difference in cost of using CO_2 instead of the other acids, a cost per ton of avoided CO_2 can be calculated and compared with the CO_2 abatement cost of other technologies like solar photovoltaic (PV). Based on the range of the cost of utility-scale solar PV in Peru [36], the carbon-intensity of the Peruvian grid [37], and the carbon-intensity of utility-scale solar PV [38], a CO_2 abatement cost range of PV can be calculated in Peru (Table 5).

Table 4. Average cost of avoided CO_2 emissions by using CO_2 instead of hydrochloric or sulfuric acid.

HCl Avoided Emissions (g CO_2/m^3)	Avoided CO_2 300 m^3/h (Ton/Year)	Avoided + Sequestered CO_2 (g CO_2/m^3)	Additional Cost of Using CO_2 Over HCl (USD/m^3)	Cost Avoided CO_2 HCl (USD/Ton CO_2)	H_2SO_4 Avoided CO_2 Emissions (gCO_2/m^3)	Avoided CO_2 300 m3/h (Ton/Year)	Avoided + Sequestered CO_2 (g CO_2/m^3)	Additional Cost of Using CO_2 Over H_2SO_4 (USD/m^3)	Cost Avoided CO_2 H_2SO_4 (USD/Ton CO_2)
−24	−64	105	0.014	133	−89	−234	41	0.011	262

Table 5. Cost range of avoided CO_2 emissions for utility-scale solar PV in Peru.

Minimum PV Cost (USD/kWh)	Maximum PV Cost (USD/kWh)	Emission Factor PV (Ton CO_2/kWh)	Emission Factor Electricity Grid (Ton CO_2/kWh)	Minimum Cost Avoided CO_2 PV (USD/Ton CO_2)	Maximum Cost Avoided CO_2 PV (USD/Ton CO_2)
0.07	0.13	23	213	368	684

4. Discussion

Carbon dioxide has been successfully used in AMD treatment [38]. The use of this greenhouse gas to lower the pH of treated AMD is promising. Lee et al. [33] were able to sequestrate 0.54 g CO_2 per kg of AMD. Our results showed that for this particular HDS effluent, about four times less CO_2 can be sequestrated, i.e., between 0.12–0.15 g CO_2 per kg of effluent (see Table 1). This still translates into 341 tons of CO_2 sequestrated/year for the full-scale 300 m^3/h AMD plant. The main reason for the significantly lower CO_2 sequestration in this study, compared to the results by Lee et al. [33], is that the pH of the HDS effluent was around 10 instead of 12.5 in that study. HDS systems typically operate at a pH of 9.5–10.5, since at that pH, most metals such as iron, zinc, copper, and lead exhibit the lowest solubility [39]. Only to remove nickel and cadmium is a higher pH of 10.5–11 necessary. Operating at a pH of 12.5 is likely cost-prohibitive, and metal solubility increases again above pH 11. The CO_2 sequestration potential obtained in this study at an HDS effluent pH of 10 can therefore be considered more realistic. The fact that the total pH drop has a significant impact on CO_2 sequestration is confirmed by the largest pH drop of 3.8, with S1 having by far the largest CO_2 consumption. Further investigations should focus on how to increase the efficiency of this approach, including an optimization of the variables involved; as Lee et al. [33] recommended, reaching an optimum CO_2 injection volume is important. Unfortunately, Lee et al. [33] did not report the alkalinity of the water after alkalinization, which is another important variable to assess CO_2 sequestration potential besides pH. However, in this study, no clear trend could be discerned. S3 and S4 had very similar pH drops, but for S4, quite a bit more alkalinity was added, while it had a lower CO_2 consumption. This is a testament to the complexity of the process and the need for experimental validation.

Therefore, this investigation should be replicated in other mining operations within Peru and elsewhere to evaluate the results under other site conditions. Considering the large volumes of acid mine drainage in the world, even small specific sequestration quantities (around 130 g/m^3 of AMD, according to our results) can add up to significant total CO_2 sequestration volumes. Unfortunately, there does not seem to be a good estimate available in the literature on global acid mine drainage generation, let alone average water quality characteristics to quantify the potential.

Lee et al. [33] did not include an economic analysis in their study, but considering the four times larger CO_2 consumption, it may be cost-prohibitive in their case. For the AMD in this study, USD 0.031/m^3 seems reasonable, which would amount to nearly USD 80 thousand/year for the full-scale 300 m^3/h plant (Table 3). Currently, using CO_2 to decrease the pH in HDS effluent is still about 55% and 82% more expensive than using sulfuric or hydrochloric acid, respectively. However, the cost of CO_2 is still decreasing from a peak during the past COVID-19 pandemic. Moreover, if a credit of USD 100/ton of CO_2 sequestrated is taken into account, using CO_2 is only 6% more expensive than using HCl and 12% cheaper than using H_2SO_4. Unfortunately, the emission factor for the production of liquid CO_2 is quite high because the main production method is as a waste product from the Haber–Bosch ammonia fertilizer process that is very energy- and emission-intensive [40]. This leads to the fact that higher CO_2 consumption compared to the other acids also leads to higher embedded CO_2 emissions, hence the negative values for avoided CO_2 emissions shown in Table 4. Nevertheless, the cost per ton of CO_2 avoided, taking into account both the sequestrated CO_2 and the higher embedded emissions, of USD 133 and USD 262/ton CO_2 for replacing HCl and H_2SO_4, respectively, is actually significantly lower than other CO_2 abatement technologies (see Tables 4 and 5). One of the most popular CO_2 abatement technologies, namely solar photovoltaic panels, can cost between USD 368 and USD 684/ton of avoided CO_2 in Peru and require substantial capital investments. The high CO_2 abatement costs of PV in Peru (in the US, the range is USD 60 to USD 300/ton of CO_2 [41]), are mainly due to the already low carbon-intensity of the electrical grid because of the large contribution of hydropower [42]. However, additional PV will likely not replace hydropower, but gas-fired power plants with a typical emission factor of 490 tons of CO_2/GWh [43]. In this case, the range of CO_2 abatement costs drops to USD 150 to USD 278/ton CO_2, quite similar to the cost of CO_2 neutralization.

Dosing CO_2 also requires much fewer safety measures, like the secondary containment and personnel protective equipment necessary for handling strong mineral acids, and hence could lead to additional cost benefits and a less hazardous work environment for operators. Similarly, AMD treatment represents only a small fraction of the entire mining process during active operation, meaning that increasing acidification costs by less than half will not dramatically change the operation's economic balance. However, this new practice could result in a better public image and a significant contribution to a better planet.

In addition to the above, using CO_2 also has several water quality benefits. For this AMD, the addition of 0.08–0.10 g/m^3 of chlorides and 0.11–0.14 g/m^3 of sulfates can be avoided, which improves water quality [44]. Adding CO_2 also buffers the water, leading to a more stable pH [45]. Similarly, dosing CO_2 is much less corrosive than dosing strong mineral acids, minimizing the release of metals through downstream pipes into receiving surface waters [46]. Most importantly, storing CO_2 in the mining process effluents, especially if it can be captured from on-site sources, could result in more sustainable mineral extraction worldwide.

The long-term advantages and potential financial incentives for CO_2 sequestration within the mining sector can be systematically classified into environmental, economic, regulatory, and reputational dimensions (e.g., [47,48]). Notably, the principal environmental benefits include the reduction of greenhouse gas emissions, along with enhancements in water quality and ecosystem health, as previously mentioned. Furthermore, economic advantages are reflected in cost reduction associated with remediation, long-term liability mitigation, and the prospective generation of revenue through carbon credits. CO_2

sequestration initiatives are capable of producing carbon credits that can be traded in carbon markets for revenue generation. Depending on the prevailing regulatory framework, mining companies have the opportunity to capitalize on their CO_2 reductions, thereby transforming a sequestration cost into a potential revenue source. Additionally, mining companies can utilize carbon credits derived from carbon capture and sequestration (CCS) to counterbalance their own direct emissions, facilitating the achievement of their internal emission reduction goals or ensuring compliance with external emissions reduction mandates.

Regarding regulatory benefits and compliance, numerous countries and regions are progressively adopting carbon pricing mechanisms, such as carbon taxes or cap-and-trade programs (e.g., [49]). CCS offers mining companies a mechanism to offset their CO_2 emissions, thereby diminishing their liability to taxes or penalties. Likewise, governments frequently extend financial incentives to entities that invest in carbon sequestration technologies. Such incentives may comprise tax credits, grants, and additional forms of financial support designed to expedite the adoption of CCS technologies. Notably, some examples of subsidy programs and incentives include the US 45Q Tax Credit [50], the Carbon Utilization Procurement Grants [51], and the EU Funding Programs (e.g., [52]). Furthermore, mining companies that implement CCS for environmental reasons may find themselves better equipped to comply with stringent environmental standards established by national or international regulatory authorities. This compliance could alleviate the risk of incurring fines or penalties for non-adherence to environmental regulations, particularly in jurisdictions with rigorous environmental protection legislation.

Equally important is that mining corporations may accrue reputational and corporate social responsibility advantages through the reduction of CO_2 emissions (e.g., [53]). Mining entities that practice environmentally responsible measures and adopt proactive approaches to diminish their carbon footprint and neutralize environmental contaminants, such as acid mine drainage, can enhance their public image. This may exert a direct influence on their marketability, attract investors with environmental inclinations, and foster robust relationships with customers and stakeholders. Furthermore, mining companies that invest in CO_2 sequestration technologies and exhibit a reduced environmental impact have the capacity to produce comprehensive sustainability reports. These reports are of increasing importance to investors, consumers, and regulators who concentrate on environmental, social, and governance criteria. This could elevate the likelihood of obtaining green investments and diminish community opposition.

5. Conclusions

The results indicate that adding CO_2 to HDS effluent resulted in disposable AMD with pH levels that fall within the Peruvian environmental standards. The carbon dioxide addition decreased the pH from 10–10.5 to 6.5–7.5 within minutes. While the 130 g CO_2/m^3 is lower than a previous study that started at a rather unrealistic pH above 12, when calculating for a 300 m^3/h full-scale treatment plant, this still amounts to 341 tons of CO_2 sequestered per year.

When compared to traditional HCl- and H_2SO_4-based approaches to decrease pH in AMD, the CO_2-based approach seems to be more expensive in the current economic environment (around 82% and 55% more expensive than using HCl and H_2SO_4, respectively). However, when taking into account a CO_2 credit of USD 100/ton, CO_2 neutralization is 12% less expensive than using sulfuric acid and only 6% more expensive than using hydrochloric acid. Moreover, the calculated cost per ton of avoided CO_2 of USD 133 and USD 262 for replacing HCl and H_2SO_4, respectively, is cost-competitive with the CO_2 abatement cost of solar photovoltaic panels in the Peruvian context. The advent of higher carbon taxes and cheaper carbon capture technologies that could recover CO_2 from mining operations on-site should reduce this cost dramatically in the future. Moreover, using CO_2 has numerous other benefits compared to strong mineral acids like improved water quality, a less hazardous work environment, and the decreased corrosion of downstream pipes.

Therefore, this new approach should be further explored as it represents a valuable option for more sustainable mining operations overall.

Author Contributions: Conceptualization, J.C.G.-C., J.A.B. and J.V.; methodology, J.C.G.-C., I.A.R.-L., A.C.-G., H.R.P.-R., J.A.B. and J.V.; formal analysis, J.C.G.-C.; investigation, J.C.G.-C., J.V. and P.A.G.-C.; resources, J.V. and I.A.R.-L.; data curation, J.C.G.-C., J.V. and P.A.G.-C.; writing—original draft preparation, J.C.G.-C., J.V. and P.A.G.-C.; writing—review and editing, J.C.G.-C., I.A.R.-L., A.C.-G., H.R.P.-R. and J.A.B.; visualization, P.A.G.-C., I.A.R.-L., A.C.-G. and H.R.P.-R.; supervision, J.V., I.A.R.-L. and P.A.G.-C.; project administration, J.V., I.A.R.-L., A.C.-G. and H.R.P.-R.; funding acquisition, J.V. and I.A.R.-L. All authors have read and agreed to the published version of the manuscript.

Funding: Please add: This research was supported by the Center for Research in Sustainable Resources (Grant Nº470189).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors sincerely thank Pan American Silver (PAS) in the Shahuindo Mining Unit operation in Peru for its support towards this investigation. Similarly, the authors deeply appreciate the help provided by the Center for Research in Sustainable Resources, a joint effort from the Colorado School of Mines and Universidad Nacional de Trujillo.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Pilot test operating conditions, by batch. NTU: Nephelometric turbidity units.

Choloque Subdrainage (Feeding)			Alcalinization (Lime Milk)			Flocculation (Floc. MT-6506)		Overflow	
Flow (m^3/h)	pH	NTU	mL/min	pH	Kg/m^3	mL/min	g/m^3	pH	NTU
3	5.78	61.2	130	10.4	0.434	50	0.99	10	14.2
4	5.1	59.9	150	10.6	0.376	57	0.84	10.25	17.64
3.5	4.17	74.7	200	10.6	0.573	57	0.96	10.17	11.3
4	3.8	70.2	190	10.55	0.476	57	0.84	10.09	13.33
4	3.71	98.7	142	10.48	0.356	55	0.81	10.2	16.9
5	3.48	111.5	200	10.45	0.401	57	0.68	10.41	11.47
4	3.65	90.4	200	10.87	0.501	57	0.84	10.4	17.72
4	3.62	90.2	200	10.75	0.501	57	0.84	10.72	17.00

Appendix B

Table A2. Feeding water quality samples (before lime addition for alkalinization). MPL: Maximum permissible limit. Bold numbers indicate MPL violation. ECA-3: Irrigation water standard. HCL-P1-02 through 04: Sample codes. V: Valence value.

Parameter	V	Unit	MPL	ECA-3	HLC-P1-02	HLC-P1-04	HLC-P1-05	HLC-P1-07
pH		-	6–9	6.5–8.5	**5.1**	**3.8**	**3.7**	**3.7**
Alkalinity		mg/L $CaCO_3$			<1.0	<1.0	<1.0	<1.0
Bicarbonate		mg/L HCO_3			<1.2	<1.2	<1.2	<1.2
Carbonate		mg/L CO_3			<0.6	<0.6	<0.6	<0.6
TSS		mg/L	25	-	50	63	46	52
Cr (VI)	2	mg/L	0.08	-	<0.005	<0.005	<0.005	<0.005
AG		mg/L	16	5	<0.4	0.4	<0.4	<0.4
Total CN		mg/L	0.8	-	<0.0008	<0.0008	<0.0008	<0.0008

Table A2. *Cont.*

Parameter	V	Unit	MPL	ECA-3	HLC-P1-02	HLC-P1-04	HLC-P1-05	HLC-P1-07
CN WAD		mg/L	-	0.1	<0.0008	<0.0008	<0.0008	<0.0008
Total Al	3	mg/L	-	5	1.93	1.831	0.747	1.307
Total As		mg/L	0.08	0.1	0.00301	0.02279	0.01936	0.02172
Total Cd		mg/L	0.04	0.01	0.00024	0.00906	0.00083	0.00981
Total Cu	2, 1	mg/L	0.4	0.2	0.02375	0.02859	0.02511	0.02393
Total Hg		mg/L	0.0016	0.001	0.00015	0.00032	0.00026	0.00039
Total Mn	7, 4, 2	mg/L	-	0.2	**37.496**	**38.388**	**37.762**	**32.411**
Total Pb		mg/L	0.16	0.05	0.0064	0.0053	0.0041	0.0076
Total Zn	2	mg/L	1.2	2	**7.791**	**6.631**	**6.455**	**6.580**
Diss. Fe		mg/L	1.6	-	**28.670**	**21.057**	**23.516**	**32.946**

Appendix C

Table A3. Results of chemical analysis of lime-based alkalinized solution. MPL: Maximum permissible limit. Bold numbers indicate MPL violation. ECA-3: Irrigation water standard. HCL-P2-02 through 04: Sample codes. V: Valence value.

Parameter	V	Unit	MPL	ECA-3	HLC-P2-02	HLC-P2-04	HLC-P2-05	HLC-P2-07
pH		-	6 to 9	6.5–8.5	**10**	**10.2**	**10.1**	**10.4**
Alkalinity		mg/L $CaCO_3$			16.1	7.3	14.6	9.8
Bicarbonate		mg/L HCO_3			19.7	8.9	17.8	12
Carbonate		mg/L CO_3			1.6	5	5	1.2
TSS		mg/L	25	518	6	22	17	17
Cr(VI)	2	mg/L	0.08	-	<0.005	<0.005	<0.005	<0.005
AG		mg/L	16	-	<0.4	<0.4	<0.4	<0.4
CN total		mg/L	0.8	5	<0.0008	<0.0008	<0.0008	<0.0008
CN WAD		mg/L	-	-	<0.0008	<0.0008	<0.0008	<0.0008
Total Al	3	mg/L	-	0.1	0.075	0.18	0.216	0.111
Total As		mg/L	0.08	5	0.00075	0.00215	0.00141	0.00301
Total Cd		mg/L	0.04	0.1	0.00021	0.00046	0.00052	0.00071
Total Cu	2, 1	mg/L	0.4	0.01	0.00377	0.00391	0.00403	0.00341
Total Hg		mg/L	0.0016	0.2	0.00019	0.00025	0.00032	0.00039
Total Mn	7, 4, 2	mg/L	-	0.001	**2.60498**	**1.55266**	**1.65068**	**0.91863**
Total Pb		mg/L	0.16	0.2	0.0006	0.0006	0.0006	0.0012
Total Zn	2	mg/L	1.2	0.05	0.0587	0.2205	0.2613	0.2156
Diss. Fe		mg/L	1.6	2	0.3036	0.8695	1.4928	1.0198

Appendix D

Table A4. Water quality analysis (samples) on acidified solution using CO_2. MPL: Maximum permissible limit. Bold numbers indicate MPL violation. ECA-3: Irrigation water standard. HCL-P3-02 through 04: Sample codes. V: Valence value.

Parameter	V	Unit	MPL	ECA-3	HLC-P3-02	HLC-P3-04	HLC-P3-05	HLC-P3-07
pH		pH	6 to 9	6.5–8.5	6.6	7.8	7.4	7.5
Alkalinity		mg/L $CaCO_3$			26.6	18.8	21.9	34.0
Bicarbonate		mg/L HCO_3			32.4	22.9	26.7	41.5
Carbonate		mg/L CO_3			<0.6	<0.6	<0.6	<0.6
TSS		mg/L	25	-	<3	<3	<3	<3
Cr(VI)	2	mg/L	0.08	-	<0.005	<0.005	<0.005	<0.005
Oils and fats		Mg/L	16	5	<0.4	<0.4	<0.4	<0.4

Table A4. *Cont.*

Parameter	V	Unit	MPL	ECA-3	HLC-P3-02	HLC-P3-04	HLC-P3-05	HLC-P3-07
Total CN		mg/L	0.8	-	<0.0008	<0.0008	<0.0008	<0.0008
CN WAD		mg/L	-	0.1	<0.0008	<0.0008	<0.0008	<0.0008
Total Al	3	mg/L	-	5	0.134	0.122	0.104	0.081
Total As		mg/L	0.08	0.1	0.00045	0.00339	0.00106	0.00105
Total Cd		mg/L	0.04	0.01	0.00018	0.00034	0.00026	0.00049
Total Cu	2, 1	mg/L	0.4	0.2	0.01583	0.00882	0.00508	0.01506
Total Hg		mg/L	0.0016	0.001	0.00024	0.0003	0.00032	0.00034
Total Mn	7, 4, 2	mg/L	-	**0.2**	**0.60192**	**0.57469**	**0.5936**	0.16357
Total Pb		mg/L	0.16	0.05	0.0008	0.0006	0.0007	0.001
Total Zn	2	mg/L	1.2	2	0.092	0.1034	0.0916	0.0802
Diss. Fe		mg/L	1.6	-	0.2881	0.3965	0.305	0.2612
Bicarbonates		mg/L	-	518	24.1	22.9	26.7	41.5
Clorides		mg/L	-	500	4.78	4.764	5.132	2.851
Conductivity		uS/cm	-	2500	796	753	766	697
Fluorides		mg/L	-	1	0.018	0.112	0.112	0.158
Nitrates		mg/L	-	10	<0.006	<0.006	<0.006	<0.006
Nitrites + nitrates		mg/L	-	100	<0.0062	<0.0062	<0.0062	0.434
Sulfates		mg/L	-	1000	893.31	819.13	537.5	702.24
Total Ba		mg/L	-	0.7	0.0226	0.0249	0.0225	0.0163
Total Be	2	mg/L	-	0.1	0.000019	0.00017	0.00013	<0.00006
Total B	3	mg/L	-	1	0.091	0.059	0.055	0.066
Total Li	1	mg/L	-	2.5	0.0201	0.0222	0.0218	0.0208
Total Mg	2	mg/L	-	250	28.305	23.916	23.37	18.01
Total Ni	2	mg/L	-	0.2	0.0023	0.0038	0.0038	0.0013
Total Se		mg/L	-	0.02	<0.0013	0.0021	0.0014	0.0025
Phosphates		mg/L		1	<0.038	<0.038	0.601	<0.038

Appendix E

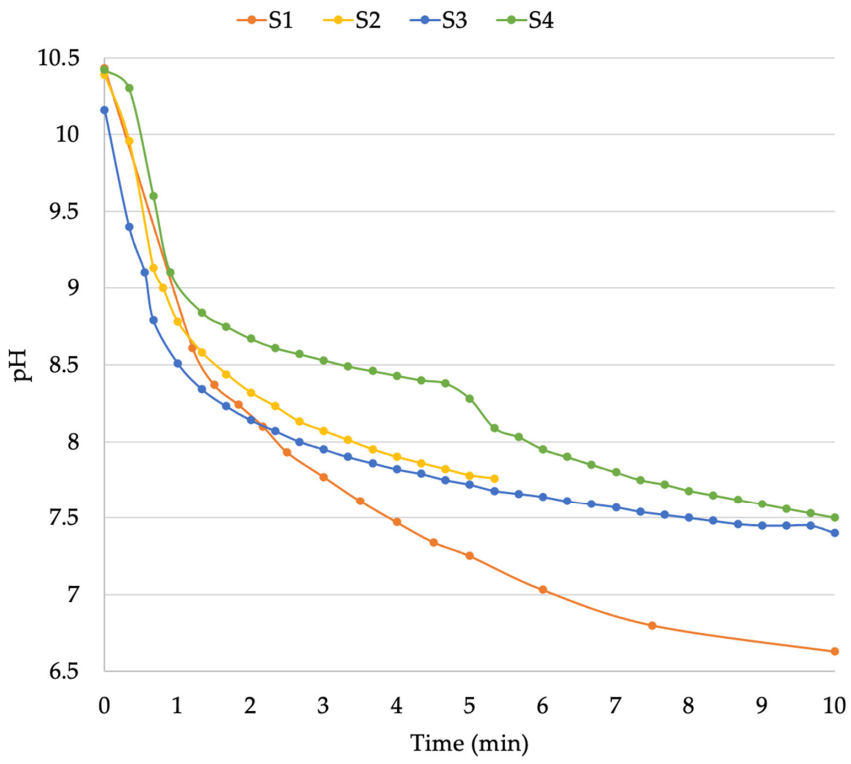


Figure A1. Graphical representation of the four tests to lower AMD's pH over time using CO_2, with S1, S2, S3, and S4 collected water samples.

Appendix F

Table A5. Water quality analysis methods.

Parameter	Method of Analysis
Alkalinity	SMEWW-APHA-AWWA-WEF Part 2320 B, 24th Ed., 2023. Alkalinity Titration Method.
pH	APERA PH850 portable pH, accuracy +/− 0.01 pH
Weight	A&D Weighing GXK model GX-12K, max 12 Kg, 0.1 g accuracy
TSS	SMEWW-APHA-AWWA-WEF Part 2540-D: 23rd: 2017. Solids: Total Suspended Solids dried at 103–105 °C.
Cr(VI)	SMEWW-APHA-AWWA-WEF Part 3500-Cr-B, 23rd Ed., 2017. Chromium. Colorimetric Method.
Oils and fats	ASTM D3921—96 (Reapproved 2011).Standard Test Method for Oil and Grease and Petroleum Hydrocarbons in Water.
Total CN	ASTM D7511-12 (Reapproved 2017) E01. Standard Test Method for Total Cyanide by Segmented Flow Injection Analysis, In-Line Ultraviolet Digestion and Amperometric Detection
CN WAD	EPA Method OIA-1677-09:2010, Avaliable Cyanide by Ligand Exchange and Flow Injection Analysis (FIA)
Total Metals	EPA-Method 200.8 Rev. 5.4, 1994. Determination of trace elements in water and wastes by Inductively Coupled Plasma-Mass spectrometry. 2015
Clorides	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.
Fluorides	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.
Nitrates	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.
Nitrites + nitrates	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.
Sulfates	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.
Phosphates	EPA 300.0. Rev. 2.1:1993. Determination of Inorganic Anions by Ion Chromatography.

References

1. Equeenuddin, S.M.; Tripathy, S.; Sahoo, P.K.; Panigrahi, M.K. Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. *J. Geochem. Explor.* **2010**, *105*, 75–82. [CrossRef]
2. Córdoba, F.; Luís, A.T.; Leiva, M.; Sarmiento, A.M.; Santisteban, M.; Fortes, J.C.; Dávila, J.M.; Álvarez-Bajo, O.; Grande, J.A. Biogeochemical indicators (waters/diatoms) of acid mine drainage pollution in the Odiel river (Iberian Pyritic Belt, SW Spain). *Environ. Sci. Pollut. Res. Int.* **2022**, *29*, 31749–31760. [CrossRef] [PubMed]
3. Indra, T.L.; Amalia, R.P.; Damayanti, A. GIS and RS-Based Analysis of Water Pollution Potential Caused by Acid Mine Drainage in Samarinda, Indonesia. *J. Settl. Spat. Plan.* **2021**, *9*, 5–13. [CrossRef]
4. Singovszka, E.; Balintova, M.; Demcak, S.; Pavlikova, P. Metal Pollution Indices of Bottom Sediment and Surface Water Affected by Acid Mine Drainage. *Metals* **2017**, *7*, 284. [CrossRef]
5. Candeias, C.; Avila, P.F.; Ferreira da Silva, E.; Ferreira, A.; Salgueiro, A.R.; Teixeira, J.P. Acid mine drainage from the Panasqueira Mine and its influence on Zezere River (central Portugal). *J. Afr. Earth Sci.* **2014**, *99*, 705–712. [CrossRef]
6. Galhardi, J.A.; Bonotto, D.M. Hydrogeochemical features of surface water and groundwater contaminated with acid mine drainage (AMD) in coal mining areas: A case study in southern Brazil. *Environ. Sci. Pollut. Res. Int.* **2016**, *23*, 18911–18927. [CrossRef]
7. Herbst, D.B.; Medhurst, R.B.; Black, N.J.P. Long-term effects and recovery of streams from acid mine drainage and evaluation of toxic metal threshold ranges for macroinvertebrate community reassembly. *Environ. Toxicol. Chem.* **2018**, *37*, 2575–2592. [CrossRef]
8. Grande, J.A.; Loayza-Muro, R.; Alonso-Chaves, F.M.; Fortes, J.C.; Willems, B.; Sarmiento, A.M.; Santisteban, M.; Dávila, J.M.; de la Torre, M.L.; Durães, N.; et al. The Negro River (Ancash-Peru): A unique case of water pollution, three environmental scenarios and an unresolved issue. *Sci. Total Environ.* **2019**, *648*, 398–407. [CrossRef]
9. Sevink, J.; Verstraten, J.M.; Kooijman, A.M.; Loayza-Muro, R.A.; Hoitinga, L.; Palomino, E.J.; Jansen, B. Rare Moss-Built Microterraces in a High-Altitude, Acid Mine Drainage-Polluted Stream (Cordillera Negra, Peru). *Water Air Soil Pollut.* **2015**, *226*, 201–220. [CrossRef]
10. Vriens, B.; Peterson, H.; Laurenzi, L.; Smith, L.; Aranda, C.; Mayer, K.U.; Beckie, R.D. Long-term monitoring of waste-rock weathering at the Antamina mine, Peru. *Chemosphere* **2019**, *215*, 858–869. [CrossRef]
11. Mosai, A.K.; Ndlovu, G.; Tutu, H. Improving acid mine drainage treatment by combining treatment technologies: A review. *Sci. Total Environ.* **2024**, *919*, 170806. [CrossRef] [PubMed]
12. He, W.; Li, H.; Xu, Y.; Zhong, F.; Dong, H.; Wang, M. Enhanced Microbial Oxidation-Neutralization Treatment of Acid Mine Drainage Rich in Ferrous Ions (Fe^{2+}). *Int. J. Environ. Res. Public Health* **2022**, *19*, 6543. [CrossRef] [PubMed]
13. Ryu, S.; Naidu, G.; Hasan Johir, M.A.; Choi, Y.; Jeong, S.; Vigneswaran, S. Acid mine drainage treatment by integrated submerged membrane distillation–sorption system. *Chemosphere* **2019**, *218*, 955–965. [CrossRef] [PubMed]
14. Pat-Espadas, A.; Loredo Portales, R.; Amabilis-Sosa, L.; Gómez, G.; Vidal, G. Review of Constructed Wetlands for Acid Mine Drainage Treatment. *Water* **2018**, *10*, 1685. [CrossRef]

15. Environmental Protection Agency. Cost of Remediation at Mine Sites. Available online: https://archive.epa.gov/epawaste/hazard/web/pdf/costs.pdf (accessed on 6 October 2024).
16. Black, K.J.; Weber, J.G. Treating abandoned mine drainage can protect streams cost effectively and benefit vulnerable communities. *Commun. Earth Environ.* **2024**, *5*, 508. [CrossRef]
17. Seo, E.Y.; Cheong, Y.W.; Yim, G.J.; Min, K.W.; Geroni, J.N. Recovery of Fe, Al and Mn in acid coal mine drainage by sequential selective precipitation with control of pH. *Catena* **2017**, *148*, 11–16. [CrossRef]
18. Abd Al-Hussein, A.S. Using sulfuric acid (H_2SO_4) for pH adjustment in water treatment. *J. Pet. Res. Stud.* **2021**, *11*, 19–27. [CrossRef]
19. Perutz, M.F.; Shih, D.T.; Williamson, D. The Chloride Effect in Human Haemoglobin: A New Kind of Allosteric Mechanism. *J. Mol. Biol.* **1994**, *239*, 555–560. [CrossRef]
20. Quraishi, M.A.; Nayak, D.K.; Kumar, R.; Kumar, V. Corrosion of reinforced steel in concrete and its control: An overview. *J. Steel Struct. Constr.* **2017**, *2*, 124. [CrossRef]
21. Rahmania, H.; Asbaghb, Y.I. Effects of sulphate ions on the corrosion resistance of Montmorillonite-modified dense concretes. *Aust. J. Struct. Eng.* **2018**, *19*, 248–255. [CrossRef]
22. Lomba, L.; Errazquin, D.; Garralaga, P.; López, N.; Giner, B. Ecotoxicological study of glucose:choline chloride and sorbitol:choline chloride at different contents of water. *Environ. Sci. Pollut. Res. Int.* **2023**, *30*, 46427–46434. [CrossRef] [PubMed]
23. Mukwevho, M.; Chirwa, E.; Maharajh, D. The effect of pH and temperature on biological sulphate reduction. *Chem. Eng. Trans.* **2019**, *74*, 517–522.
24. Kartic, D.N.; Narayana, B.C.h.A.; Arivazhagan, M. Removal of high concentration of sulfate from pigment industry effluent by chemical precipitation using barium chloride: RSM and ANN modeling approach. *J. Environ. Manag.* **2018**, *206*, 69–76. [CrossRef] [PubMed]
25. Oztemur, G.; Basaran, S.T.; Tayran, Z.; Sahinkaya, E. Fluidized bed membrame bioreactor achieves high sulphate reduction and filtration performances at moderate temperatures. *Chemosphere* **2020**, *252*, 126587. [CrossRef] [PubMed]
26. van Rooyen, M.; van Staden, P.J.; du Preez, K.A. Sulphate removal technologies for the treatment of mine-impacted water. *J. S. Afr. Inst. Min. Metall.* **2021**, *1221*, 523–529. [CrossRef]
27. Uddin, M.K. A review on the adsorption of heavy metals by clay minerals, with special focus on the past decade. *Chem. Eng. J.* **2017**, *308*, 438–462. [CrossRef]
28. Olson, A.R.; Youle, P.V. The Strength of Carbonic Acid. The Rate. of Reaction of Carbon Dioxide with Water and Hydroxyl Ion. *J. Am. Chem. Soc.* **1940**, *62*, 1027. [CrossRef]
29. Pastrana-Martínez, L.M.; Silva, A.M.T.; Fonseca, N.N.C.; Vaz, J.R.; Figueiredo, J.L.; Faria, J.L. Photocatalytic Reduction of CO_2 with Water into Methanol and Ethanol Using Graphene Derivative–TiO_2 Composites: Effect of pH and Copper(I) Oxide. *Top. Catal.* **2016**, *59*, 1279–1291. [CrossRef]
30. Yang, B.; Bai, Z.; Zhang, J. Environmental impact of mining-associated carbon emissions and analysis of cleaner production strategies in China. *Environ. Sci. Pollut. Res.* **2021**, *28*, 13649–13659. [CrossRef]
31. Vaziri Hassas, B.; Rezaee, M.; Pisupati, S.V. Precipitation of rare earth elements from acid mine drainage by CO_2 mineralization process. *Chem. Eng. J.* **2020**, *399*, 125716. [CrossRef]
32. Masindi, V.; Madzivire, G.; Tekere, M. Reclamation of water and the synthesis of gypsum and limestone from acid mine drainage treatment process using a combination of pre-treated magnesite nanosheets, lime, and CO_2 bubbling. *Water Resour. Ind.* **2018**, *20*, 1–14. [CrossRef]
33. Lee, H.C.; Min, K.W.; Seo, E.Y. A feasibility study on CO_2 sequestration using the neutralization process of acid mine drainage. *Geosystem Eng.* **2016**, *19*, 293–301. [CrossRef]
34. Praxair. Case Study: Cost and Maintenance Reduction with CO_2 to Replace Sulfuric Acid for pH Control at Steel Dynamics, Inc. (Butler, IN). 3 p. 2015. Available online: https://www.tpomag.com/uploads/downloads/P-40-4099_CO%C2%B2_replaces_Sulfuric_for_pH_control_at_SDI_180119_134148.pdf (accessed on 3 September 2024).
35. Veolia. WSTP South End Plant Process Selection Report. Appendix H: CO_2 Emission Factors Database. Winnipeg. Available online: https://legacy.winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_appendix_h-wstp_south_end_plant_process_selection_report/appendix%207.pdf (accessed on 6 October 2024).
36. Global Solar Atlas. Global Photovoltaic Power Potential. Country Factsheet Peru. Available online: https://globalsolaratlas.info/global-pv-potential-study (accessed on 8 October 2024).
37. International Renewable Energy Agency. Energy Profile Peru. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/South%20America/Peru_South%20America_RE_SP.pdf (accessed on 8 October 2024).
38. Smith, B.L.; Sekar, A.; Mirletz, H.; Heath, G.; Margolis, R. An Updated Lifecycle Assessment of Utility-Scale Solar Photovoltaic Systems Installed in the United States. National Renewable Energy Laboratory. Available online: https://www.nrel.gov/docs/fy24osti/87372.pdf (accessed on 8 October 2024).
39. Business Analitiq. All Comodities Index. 2024. Available online: https://businessanalytiq.com/procurementanalytics/index/all-commodities-index/ (accessed on 3 September 2024).
40. Environmental Protection Agency. Carbon Dioxide Supply Chain. Executive Summary. Available online: https://www.epa.gov/system/files/documents/2023-03/Carbon%20Dioxide%20Supply%20Chain%20Profile.pdf (accessed on 7 October 2024).

41. Friedman, J.; Fan, Z.; Byrum, Z.; Ochu, E.; Bhardwaj, A.; Sheerazi, H. Levelized Cost of Carbon Abatement: An Improved Cost-Assessment Methodology for a Net-Zero Emission World. 2020. Available online: https://www.energypolicy.columbia.edu/publications/levelized-cost-carbon-abatement-improved-cost-assessment-methodology-net-zero-emissions-world/ (accessed on 7 October 2024).
42. Chen, S.; Lu, X.; Nielsen, C.P.; McElroy, M.B.; He, G.; Zhang, S.; He, K.; Yang, X.; Zhang, F.; Hao, J. Deploying solar photovoltaic energy first in carbon-intensive regions brings gigatons more carbon mitigations to 2060. *Commun. Earth Environ.* **2023**, *4*, 369. [CrossRef]
43. IPCC 5th Assessment Report. Annex III. Technology Specific Cost and Performance Parameters (PDF). Available online: https://archive.ipcc.ch/pdf/assessment-report/ar5/wg3/drafts/fgd/ipcc_wg3_ar5_final-draft_fgd_annex-iii.pdf (accessed on 8 October 2024).
44. Unger-Lindig, Y.; Merkel, B.; Schipek, M. Carbon dioxide treatment of low-density sludge: A new remediation strategy for acidic mining lakes? *Environ. Earth Sci.* **2010**, *60*, 1711–1722. [CrossRef]
45. de Vries, A.; Goloviznina, K.; Reiter, M.; Salanne, M.; Lukatskaya, M.R. Solvation-Tuned Photoacid as a Stable Light-Driven pH Switch for CO_2 Capture and Release. *Chem. Mater.* **2024**, *36*, 1308–1317. [CrossRef]
46. Campbell, K.M.; Alpers, C.N.; Nordstrom, D.K. Formation and prevention of pipe scale from acid mine drainage at Iron Mountain and Leviathan Mines, California, USA. *Appl. Geochem.* **2020**, *115*, 104521. [CrossRef]
47. International Energy Agency (IEA). CCS in the Mining Sector: A Pathway to Decarbonization. 2021. Available online: https://www.iea.org (accessed on 12 November 2024).
48. Global CCS Institute. Global Status of CCS 2021. 2021. Available online: https://www.globalccsinstitute.com (accessed on 12 November 2024).
49. Carbon Pricing Leadership Coalition (CPLC). The Role of Carbon Pricing in Achieving Net Zero Emissions. 2020. Available online: https://www.carbonpricingleadership.org (accessed on 12 November 2024).
50. U.S. Department of Energy. 45Q Tax Credit for Carbon Capture. 2021. Available online: https://www.energy.gov (accessed on 12 November 2024).
51. Department of Energy. Carbon Utilization Procurement Grants. 2024. Available online: https://www.energy.gov/fecm/funding-notice-bipartisan-infrastructure-law-carbon-utilization-procurement-grants#:~:text=The%20Carbon%20Utilization%20Procurement%20Grants,dioxide%20and%20carbon%20monoxide%20emissions (accessed on 12 November 2024).
52. European Commission. The Innovation Fund. 2020. Available online: https://ec.europa.eu (accessed on 12 November 2024).
53. Institute for Energy, Economics, and Financial Analysis. Carbon Capture Is About Reputation, Not Economics. 2020. Available online: https://ieefa.org/wp-content/uploads/2020/07/CCS-Is-About-Reputation-Not-Economics_July-2020.pdf (accessed on 12 November 2024).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.