Techno-economic Assessment for Bio-accelerated Weathering for Carbon Sequestration

Luke Plante[1]; Jacob D. Klug[2]; Stephanie Murillo Maikut[2]; Peter Wei[1]; Joseph J. Lee[1]; Alia Almansoori[1]; Gretchen Vengerova[1]; Enoch Nagelli[3]; Michael Charles[1]; Brian Richards[1]; Esteban Gazel[2‡]; Buz Barstow[1‡]; Hongyue Jin[4]

[1]Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

[2]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY 14853, USA

[3]Department of Chemical and Biological Sciences and Engineering, United States Military Academy, West Point, NY 10996, USA

[4]Department of Systems & Industrial Engineering, The University of Arizona, Tucson, AZ 85721, USA

[‡]Corresponding authors:

Buz Barstow, 228 Riley-Robb Hall, Cornell University, Ithaca, NY 14853, USA; bmb35@cornell.edu

Esteban Gazel, 4122 Snee Hall, Cornell University, Ithaca, NY 14853, USA; egazel@cornell.edu

Abstract

Significant efforts are required to remove CO_2 from the atmosphere to mitigate the worst effects of climate change. While several methods for CO_2 capture and storage have been proposed, weathering of silicate-rich rocks—which releases divalent cations like magnesium and iron for subsequent carbonation—has the highest potential removal capacity. However, natural weathering and carbonation rates are far too slow to prevent significant atmospheric warming. Bio-accelerated weathering aims to use microorganisms to accelerate these processes, but while it has been explored in laboratories, its economic viability at large scale remains unknown. Here we calculate the costs and revenues of bio-accelerated weathering of ultramafic mine tailings by the mineral-dissolving microbe *Gluconobacter oxydans*. Without tax credits and with unfavorable feedstock market prices, the cost for capturing and storing one tonne of CO_2 through bio-accelerated weathering could be as high as \$3,465. However, under favorable feedstock pricing, tax credits, and revenue from co-leached metals, a profit of \$3 per tonne of CO_2 captured and stored could be obtained. This study identifies microbial feedstock costs as the major cost driver, suggesting that process optimization, alternative feedstock development, and genetic engineering are the efforts most likely to maximize economic viability. Our results suggest that bio-accelerated weathering warrants further exploration as a climate change mitigation strategy.

Introduction

The trillion tonnes or so of excess CO_2 in the Earth's atmosphere and oceans creates a risk of serious climate disruption. The Intergovernmental Panel on Climate Change (IPCC) estimates that starting around 2070, 10 to 20 gigatonnes of CO_2 need to be removed from the atmosphere every year for several decades to prevent temperature increases greater than 1.5 °C above pre-industrial conditions[1]. Several simultaneous methods for CO_2 removal and storage are likely needed to solve this problem[2].

Natural weathering of ultramafic rocks rich in magnesium and iron[3] releases metal cations and subsequent mineralization that already captures and permanently stores about 0.45 gigatonnes of CO_2 per year in the form of carbonates[4-6], and will eventually clear the excess CO_2 introduced into the atmosphere since the start of the industrial revolution. In fact, if completely dissolved, the ultramafic rocks close enough to Earth's surface to mine could provide enough metal cations to capture and store 100-100,000 trillion tonnes of CO_2, which would account for well over 50 times the excess CO_2 emitted from fossil fuels since the beginning of the industrial revolution[7-10]. Ultramafic mine tailings alone—small-diameter waste products from traditional mining that are much easier to weather than rocks in nature—are produced at a sufficient rate to sequester over 60 megatonnes of CO_2 per year[11,12], while existing tailings could sequester up to 10 gigatonnes of CO_2[13]. However, both the natural weathering and mineralization processes are slow: they are likely to take thousands or tens of thousands of years to remove all excess CO_2, far slower than the century or so in which we need to address it[4,14,15].

Because natural weathering is so slow, numerous schemes to accelerate the weathering of ultramafic material have been proposed[16,17]. However, these schemes are either limited in ultimate CO_2 storage capacity, too expensive, or both[18]. Even the United States Department of Energy's target cost of \$100 per tonne of CO_2 captured and stored[19] is still high considering the quantity of CO_2 that needs to be addressed. Capturing and storing 20 gigatonnes of CO_2 per year would correspond to an annual cost of \$2 trillion (approximately equal to the world's defense budget[20]) at this target price, adding up to well over \$100 trillion USD to sequester all excess CO_2 in the atmosphere (approximately world GDP in 2025[21]).

Treating accelerated weathering as a mining problem could make large-scale CO_2 sequestration financially viable. In addition to mining magnesium and iron for CO_2 sequestration, the simultaneous extraction of other critical metals—those that are crucial for advanced technologies yet limited in supply and with vulnerable supply chains—from ultramafic rocks is also theoretically possible. Supplying critical metals (e.g., aluminum, chromium, manganese, cobalt, nickel, copper, zinc, and titanium) from ultramafic rocks in addition to magnesium and iron can help offset the costs of CO_2 sequestration[3,22,23]. However, the concentrations of these metals in ultramafic rocks are far lower than would normally be considered economically viable for traditional mining technologies. Biomining—the use of microorganisms to extract metals from rocks—is far better suited for mining from low-grade ores[24-28] and thus has the potential to liberate metals from ultramafic rocks. In fact, biomining already accounts for approximately 15% of copper and approximately 5% of gold production[28] from low-grade ores. Bio-accelerated weathering of ultramafic rocks has been proposed[29] and studied at the laboratory scale[8,16,30-33].

Gluconobacter oxydans is a genetically tractable mineral-dissolving microbe that is considered a leading candidate for biomining critical metals, including rare earth elements[34-37]. *G. oxydans* secretes a mineral-dissolving cocktail called a biolixiviant that is primarily composed of gluconic acid, but this biolixiviant is much more effective than gluconic acid alone[8,30,34]. We speculate that the biolixiviant can also alter the reduction-oxidation state of metals to increase their solubility (redoxolysis) or produce organic compounds that bind to specific elements and extract them (complexolysis)[34,35,37-47]. Recently, co-authors of this article demonstrated that *G. oxydans* can successfully bioleach magnesium and other metals from ultramafic rocks[8,30] and do so far more effectively than other well-known rock-dissolving microbes[8]. Genetic and process engineering may even make this biomining more efficient[36,37] and perhaps even profitable.

However, until now, no one has considered the costs of biomining ultramafic rocks for accelerated weathering and the supply of critical elements. Here we present a techno-economic assessment (TEA) using *G. oxydans* for bio-accelerated weathering. The proposed process included adding atmospheric air to provide CO_2 to biomined magnesium-rich liquid (leachate) to form magnesium carbonate (magnesite) for permanent CO_2 storage. The bioleaching process occurred through heap leaching of ultramafic rock mine tailings, where CO_2 was mineralized to magnesite, and the valuable co-leached metals provided revenue to offset costs while contributing to the sustainability of energy technologies—potentially even making this process profitable. Additionally, the process in this TEA can be applied in the future to the biomining of other rocks for other purposes and modified to meet various conditions.

Process Description

Ultramafic Rock Availability and Composition

Ultramafic rocks are characterized by high magnesium and iron content and less than 45% wt. SiO_2, and their availability is quite vast[7]. About 10 gigatonnes of ultramafic mine tailings (small-diameter waste products stored on-site at mines) are available globally[13], and about 100 megatonnes of ultramafic mine tailings are produced annually[48]. This study proposes to process about 2.7 megatonnes of ultramafic mine tailings per year – less than 1% of current ultramafic mine waste produced globally each year – to capture and store about 1 megatonne of CO_2 annually. While a minimum of 1.6 tonnes of pure forsterite (magnesium olivine) are required to mineralize one tonne of CO_2[12], the magnesium content of real ultramafic rocks is much lower. The largest geologically available sources of ultramafic material contain ≈ 26% Mg by weight (**Supporting Information Table 1**). Furthermore, we assumed that only 90% of magnesium in the rock could be leached leaching and that only 90% of this could be used for magnesite formation. While mining ultramafic rocks specifically for this proposed purpose is possible, this scenario is not considered here, but it will be addressed in an upcoming study.

While the composition of ultramafic rocks varies by deposit, several studies have been conducted to survey the content across regions, to include Mg and other metals content. We averaged ultramafic rock metal wt. % values from the world's largest and most accessible ultramafic rocks: ophiolites (Samail and Josephine Ophiolites), abyssal peridotite, and cratonic peridotite formations[49-52] as these are representative of tailings composition[53]. The average metal composition in the ultramafic rock tailings considered in this study is shown in the **Supporting Information Table 1**. Other rocks, including mafic rocks, sulfides, etc., may be considered in future work for CO_2 sequestration or for other purposes.

Process Flow Diagram & Material Requirements

The overall proposed process flow for this bio-accelerated weathering process is shown in **Figure 1**. This process assumes co-location with an ultramafic rock mine. Materials consumption, energy consumption, and costs are shown in **Table 1**. Price ranges are significant for glucose and yeast extract depending on geographical availability and market volatility of prices due to significant events in world politics economics, such as major changes in tariff policies.

Microbial growth of and biolixiviant production from *G. oxydans* occur at room temperature in aerated and mixed tanks. All tanks in all steps of this proposed plant are of 70,000 United States gal (~265,000L) capacity. Growth and biolixiviant production tanks are mixed and aerated for 3.75 days to account for 48 hours for growth and 42 hours for subsequent biolixiviant production[8,30,39,54]. An economical, minimal medium consists of industrial water of average price in the United States, 10% glucose weight per volume (w/v), and 0.5% w/v yeast extract[55-57]. The plant was assumed to operate 24 hours per day for 300 days per year, and 20% contingency cost was added for the fixed capital investment. Numbers of tanks and associated equipment (e.g., agitators, diffusors, air pumps, and liquid pumps) were determined for each processing step by calculating the required process volume per batch to meet the target processing capacity of 2.7 megatonnes of ultramafic mine tailings per year. A single clarifier was determined to be required given the plant's flow rate and clarifier capacity and operating parameters determined previously[58], though a second clarifier was added to account for maintenance requirements. Upon settling out microbes for disposal, the biolixiviant would then be applied to an ultramafic mine tailings heap via drippers. We calculated biolixiviant requirements assuming 60% pulp density (600 g rocks per 1 L biolixiviant) because 96% Mg recovery has been observed at this pulp density[30]. This is also similar in magnitude to an application rate of the biolixiviant of 0.012 m^3/m^2 surface area per hour if the heap were always at full capacity (a full year's worth of tailings production) despite dissolution and volume decreases from leaching[59]. Leaching efficiency was conservatively[30] assumed to be 90% in this study.

The heap consists of 2.706 megatonnes of ultramafic rock mine tailings (to sequester about 1 megatonne of CO_2) from a co-located ultramafic rock mine, and it occupies a 50,000 m^2 leaching pad. The assumed density of the mine tailings is 3 $g/(cm^3)$[60], and the conical heap is 60 m in height and 120 m in radius. An example formula of the magnesium-dissolving bioleaching is depicted in **Equation 1** using *G. oxydans* biolixiviant component gluconic acid and the ultramafic rock forsterite. This reaction will vary with the specific ultramafic rock leached.

$$Mg_2SiO_4 \text{ (forsterite)} + 4C_6H_{12}O_7 \text{ (gluconic acid)} \rightarrow 2Mg^{2+} + 4C_6H_{11}O_7^- + H_4SiO_4 \quad (1)$$

Sodium hydroxide was used to raise the pH of the leachate from 3-5 to 8-10 required for magnesite formation in agitated tanks. Atmospheric air containing CO_2 is then bubbled into the pH-adjusted leachate in the same tanks so that pH adjustment and magnesite formation tanks occurs in the same tanks. Magnesite formation was assumed to occur for 90% of leached magnesium at room temperature after heating to initiate nucleation, with mixing, and with aeration from atmospheric air continuously for 10 days based on previous modeling[61]. Magnesite formed is then geologically stored on site. **Equations 2** to **5** depict the process of CO_2 addition, carbonate formation, and magnesite formation,

$$H_2O+CO_{2\,(g)} \rightarrow H_2CO_3 \text{ (carbonic acid)}, \quad (2)$$

$$H_2CO_3 \rightarrow HCO_3^- \text{ (bicarbonate)} + H^+, \quad (3)$$

$$HCO_3^- \rightarrow CO_3^{2-} \text{ (carbonate)} + H^+, \quad (4)$$

$$Mg^{2+} + CO_3^{2-} \rightarrow MgCO_{3\,(s)} \text{ (magnesite)}. \quad (5)$$

In the best-case scenario, the magnesite is stored onsite geologically for a credit of \$180 per tonne of CO_2 captured and stored[62]. These credits are only available for the first 12 years of operation of a CO_2 sequestration plant. As this plant is assumed to have a 20-year lifespan, we reduced the annual credit from \$180[62] to \$108 per tonne of CO_2 captured and stored by dividing 12 years by 20 years (a factor of 0.6)[63]. Although not included in this study, carbon credit markets may offer additional revenue opportunities in the future.

We assumed that we could sell the metals recovered from bioleaching of ultramafic rocks for approximately 66% of their market value. We estimate the purification cost to be a fixed percentage of the market value of each metal (34%) (**Table 2**). We calculated this fixed percentage by subtracting the costs of acid leaching of nickel at trace concentrations in rock[64] from the market value[65]. We have used this method previously to estimate revenues generated from bioleaching rare earth elements[66].

An additional cost of \$6.95 per 1,000 US gallons (1 kgal) (equivalent to \$1.84 per m^3), the average national rate for US industrial wastewater treatment[67], was added for all scenarios. While these costs would generally be included in metals purification costs, the removal and disposal of microbes does incur costs, and these costs are conservatively represented by this wastewater treatment cost.

Electricity, Equipment, Labor, and Other Cost Estimation

Electricity requirements for agitators, air pumps, and liquid pumps were determined by multiplying the power needed per unit by hours of use, number of units, and the average electricity rate for US industrial customers. Equipment power requirements, parameters, and prices per unit were determined using modeling tools CheCalc[68] and Matche[69]. All values from the equipment pricing source were given in 2014 USD and were converted to 2025 USD by multiplying by 818/576.1 as estimated values for chemical engineering plant cost index (CEPCI)[70,71]. These values are summarized in **Table 3**. This calculation accounts for inflation in chemical engineering plant construction prices, and it is more specific to this process than is overall inflation in the US economy.

A total of 940 agitators were proposed. This corresponds to one agitator per tank for microbial growth and biolixiviant production as well as one per tank for pH adjustment and magnesite formation. Agitators were assumed to have a of capacity of 14.14 kW. Scale of agitation was 5 out of the possible 10, and volume was set at 70,000 gal, and power requirements were determined using **Equation 6** within CheCalc's agitator modeling software[68]. Here, P is power (W); Np is power number (1.370, derived from the Reynolds Number); ρ is fluid density (1,000 kg/m^3 here); N is agitator speed (24 rpm here); and D is agitator diameter (2.785 m here). Agitator type was Turbine, Top Entering, 14.14 kW, and carbon steel for a unit price of \$17,320[69],

$$P = Np\,\rho\,N^3\,D^5. \tag{6}$$

A total of 4,335 air pumps were proposed. This corresponds to one air pump per tank for microbial growth and biolixiviant production as well as six per tanks for magnesite formation. Air pump power was calculated using CheCalc blower and fan modeling software[68] using **Equation 7**. Q is air flow (70,000 cfm), SP is static pressure (3.50 in H_2O), and η is efficiency (67%). Air pumps were priced as blowers for 70,000 cfm and centrifugal, large, at $177,100 each[69].

$$P\ =\ Q\,SP/6{,}356\,\eta. \tag{7}$$

A total of 1,217 liquid pumps were proposed. This corresponds to two pumps per each growth and biolixiviant production tank (one influent and one effluent), 10 pumps leaving the operating clarifier, 10 pumps leaving the heap, and one pump leaving each magnesite formation tank. Pumps operated at 350 gallons per minute (gpm). Pumps were assumed to operate at a power (P) of 31.16 kW using CheCalc pump sizing modeling software[68], which used **Equation 8**. H is head (239.6 ft), Q is flow (350 gpm), and SG is specific gravity (1.0) at 50% pump efficiency. Pumps were priced for 350 gpm and 8 in pump diameter at $16,330 each[69] centrifugal pumps, and they were Horizontal, ANSI, 1-stage, Cast Iron & API-610 with Packing seal type.

$$P\ =\ H\,Q\,SG/3{,}960. \tag{8}$$

While magnesite has formed successfully at ambient temperatures in laboratory settings[72], most studies suggest that heating is typically required to initiate magnesite formation in short times[73]. Additionally, the initial nucleation of magnesite – not the continued magnesite crystal formation – has been observed to be limiting[74]. Heating energy requirements (Q) were estimated using **Equation 9**[75]. Mass (m) was estimated as 1,000 g per L of leachate. Specific heat capacity (C_p) was estimated by using water's heat capacity of 4.184 J/g °C[76]. Temperature change (ΔT) was calculated as 80 °C to heat leachate from roughly ambient temperature (20 °C) to boiling (100 °C). The heating efficiency (η) was assumed to be 60%[77]. Upon heating to boiling, nucleation of magnesite crystals is initiated, and magnesite is assumed to form without further heating.

$$Q\ =\ m\,C_p\,\Delta T/\eta. \tag{9}$$

Each operating tank and clarifier was assumed to require 0.5 operators, and the single heap was conservatively assumed to have as many operators as the growth and biolixiviant production tanks[78].

Fixed Capital Investment, Taxes, and Insurance

Table 4 summarizes fixed capital investment, taxes, and insurance cost estimates. Purchased equipment costs (PEC) included the sum of costs for tanks, agitators, diffusers, pumps, and the bioleaching pad for the heap to occupy. Total direct costs (TDC) were calculated as the sum of PEC, piping, instrumentation and control, electrical, buildings, service facilities, yard improvement, and land. Fixed capital investment (FCI) was calculated at 1.21 times the TDC[79]. Property tax and insurance were each calculated as yearly rates based on PEC, whereas PEC- and TDC-derived costs were discounted using the straight-line depreciation method and reported as annual costs assuming a 20-year plant operating life. During profitable scenarios, 21% federal income tax[80] and 7% state tax[81] would have been assessed; however, credits are not counted as revenues so these taxes were not assessed. Calculations for figures were derived from previous work[79].

Results and Discussion

Summary of Overall Costs

Table 5 summarizes the TEA results. All values are reported in 2025 USD per tonne of CO_2 captured and stored. The best-case scenario represented low input material costs (based on Chinese prices[82]) with metals sales and credits for CO_2 capture and storage (a profit of \$3 per tonne of CO_2 captured and stored), and the worst-case scenario represented high input costs (based on the US chemical prices[83]) with no metals sales and no CO_2 capture and storage credits (cost of \$3,465 per tonne of CO_2 captured and stored).

Major Costs

Figure 2 identifies the major cost driver as materials (more specifically, glucose and yeast extract) followed by equipment. Because glucose is the most variable input cost in this process, alternate and lower-cost sources should be explored to increase the economic viability of the proposed process.

Commercially available glucose's low-end costs were assumed to be \$450 per tonne as the price range found was between \$300 and \$600 per tonne. These were the bulk market prices found in China when this study started in 2024[82]. Significant world economic changes during this study prompted the consideration of US chemical prices, which were found to be \$4,885 per tonne in 2025[83]. Glucose requirements were significant in this process due to its need to generate a gluconic acid-based biolixiviant.

G. oxydans has the potential to convert much less-expensive sugar sources (organic wastes, wastewaters, etc.) to acids[8,30]. Cellulosic hydrolysate, a potentially abundant sugar source made from organic wastes like cardboard or nonrecyclable paper[54,84], or from biomass like corn stover[84] or eucalyptus plants[85], may decrease costs while also alleviating the potential impacts on US sugar supply. Additionally, the decrease in bioleaching performance with cellulosic hydrolysate as a feedstock instead of glucose is negligible[8,30]. While cellulosic hydrolysate is not yet available at scale, its development progress is promising[54,85,86]. Wastewater (e.g., potato wastewater) or food waste (e.g., orange peels) may also contribute significantly to low-cost, environmentally friendly nutrient or sugar sources needed for microbial growth or acid production[87].

Ultimately, the availability and cost of glucose (and other sugars) are limited by the low efficiency of photosynthesis. Electromicrobial production (EMP) — a nascent technology that aims to use electroactive microbes to convert CO_2 to complex molecules at much higher efficiency than photosynthesis — has potential to provide sugars in much greater supply and at lower cost than agriculturally produced glucose[29,88,89]. This glucose production method would not permanently capture and store CO_2 by itself as the organic acids produced would eventually oxidize back to CO_2, but it could help to solve the vast sugar requirement of bio-accelerated weathering while even decreasing costs. Additionally, if glucose production used renewable energy as the electron source for CO_2 reduction, global warming potentials for this sugar production would be dramatically decreased.

Genetic engineering has the potential to significantly increase efficiencies in this proposed process. Genetic engineering of *G. oxydans* allows it to more efficiently convert sugars to acids, to optimize conversion of specific alternative sugar sources to acids, and to more efficiently bioleach magnesium and other metals from ultramafic rocks[30,36].

Yeast extract is also a significant cost in this process. Yeast extract requirements are significant due to the magnitude of its demand for growth and its high market price. Genetic engineering for faster and more efficient microbial growth is a potential method for decreasing this cost. This decreased requirement for yeast extract would also lead to decreased requirements for equipment, electricity, and labor. Additionally, food wastes, wastewater, and processed recycled microbes could lead to significantly less expensive yeast extract alternatives.

The third major cost is equipment. Tanks are needed in significant numbers, and each tank requires agitators for mixing, air pumps and diffusors for aeration, and liquid pumps to transport liquid among processes. Powerful air pumps were the highest of these equipment costs. More efficient microbial growth, biolixiviant production, leaching, and magnesite formation process would decrease the need for each of the major pieces of equipment. Furthermore, if this process were scaled up to billions of tonnes of CO_2, then specialized equipment could be constructed whose cost could fall through learning by doing.

Revenue and Profit Estimation

Table 5 summarizes potential revenue from products sold and credits received in the best-case scenario. Prices are listed at about 66% of market value due to potential for metal impurities, so an approximately 34% decrease in metal prices was estimated to separate and purify for sales. This revenue estimation was approximated by subtracting the acid leaching costs for nickel production[64] from the market value for nickel[90]. Since the process this study proposes would account for the acid leaching portion of purification, its value is approximated at the acid leaching costs for metals. Silica accounts for a significant portion of average ultramafic rock content[49-52]. K also has a considerably high price, so this accounts for its relatively high revenue. Carbon credits at $180 per tonne of CO_2 captured and stored, though not technically revenue, make up the third highest source of offsetting costs or adding to overall profitability. These credits are averaged down to $108 per tonne because the credits are only valid for 12 of the plant's 20-year life. Ca revenue is fourth highest, and this is followed by several other energy critical metals. Profits are possible in the best-case scenario (**Table 5**). With low glucose and yeast extract costs and with both metals sales and credits, profits are $3 per tonne of CO_2 captured and stored.

Comparison of Capture and Storage Methods

Figure 3 provides a comparison of different CO_2 capture and storage methods based on this study and a previous comprehensive review[91]. Functions are listed as some only capture CO_2, other methods only store CO_2, and other methods capture and either temporarily or permanently store CO_2. Additionally, the cost range estimates are depicted, gigatonne sequestration potential range estimates are depicted, and technology readiness levels (TRL) are depicted. TRL definitions appear in **Supporting Information Table 2**.

The process proposed in this paper has a comparatively wide potential cost range compared with other methods. This process is not well explored or developed yet compared with others, and it is assessed to have a TRL of 3. This rating is assessed because bio-accelerated weathering of ultramafic rocks has been demonstrated in laboratory testing, but this process has not been proven in a pilot plant as of the time of this study. Additionally, a low TRL corresponds to a significant opportunity to explore, optimize, decrease costs, and iterate various process options.

The current uncertainties with this process – including costs and revenue generation at scale – are acknowledged limitations of this study. Implementing this process at scale, though, would certainly drive innovations in minimizing costs and maximizing revenues. Significant promise exists for bio-accelerated weathering, as it has the potential to capture and store more CO_2 than any other process.

Conclusion

The purpose of this study was to conduct a TEA of bio-accelerated weathering using *G. oxydans* for the bioleaching of ultramafic rock and large-scale sequestration of CO_2. The process proposed using atmospheric air as a source of CO_2, which reacted with the magnesium-rich leachate to form magnesite and enabled permanent CO_2 capture and storage. The bioleaching process included heap leaching of ultramafic rock mine tailings at the source cite, where CO_2 was mineralized into magnesite.

In addition to potential tax credits for CO_2 capture and storage, the co-leached metals present an opportunity for supplementary revenue to help offset process costs. Many of these metals – critical for clean energy technologies – are expected to grow in demand over the coming decades, which may further drive the development of efficient and cost-effective purification methods.

Under favorable market conditions for inputs such as glucose and yeast extract, and supported by tax credits incentives and metals sales, this process could potentially achieve or surpass the US Department of Energy's cost target of \$100 per tonne of CO_2 captured and stored. In fact, profitability may reach up to \$3 per tonne under optimal conditions. However, in less favorable market conditions – such as high costs or limited availability of microbe feedstocks and an absence of tax credits – expenses could rise substantially, up to \$3,465 per tonne.

Although these policy-dependent factors introduce uncertainty, they do not diminish the importance of pursuing sustainable carbon capture strategies. Further research is needed to optimize process parameters and enhance microbial efficiency. Incorporating organic waste as a low-cost feedstock and improving microbial performance through genetic engineering could significantly strengthen the economic viability of this CO_2 capture and storage approach.

End Notes

Data Availability

Data for figures have been deposited on GitHub at https://github.com/barstowlab/article-057-mt-scale-tea and archived on Zenodo.

Materials and Correspondence

Correspondence and material requests should be addressed to B.B. or E.G.

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Contributions

Conceptualization, L.P., B.R., E.G., B.B., and H.J.; Methodology, L.P., J.D.K, S.M.M., P.W., J.J.L., A.A., G.V., E.N., M.C., B.R., E.G., B.B., and H.J.; Investigation, L.P., B.R., H.J., and B.B.; Writing—Original draft, L.P.; Writing—Review and editing, L.P., B.R., E.G., B.B., and H.J.; Funding acquisition, E.G., and B.B.; Resources, E.G., B.B., and H.J.; Supervision, B.R., E.G., B.B., and H.J.; Data curation, L.P., B.R., B.B., and H.J.; Visualization, L.P., B.R., B.B., and H.J.; Formal analysis, L.P.

Competing Interests

B.B., E.G., A.A. and J.L. are co-founders of Gigatonne Bio which is developing engineered microbes for accelerated weathering and CO_2 sequestration.

Figures and Tables

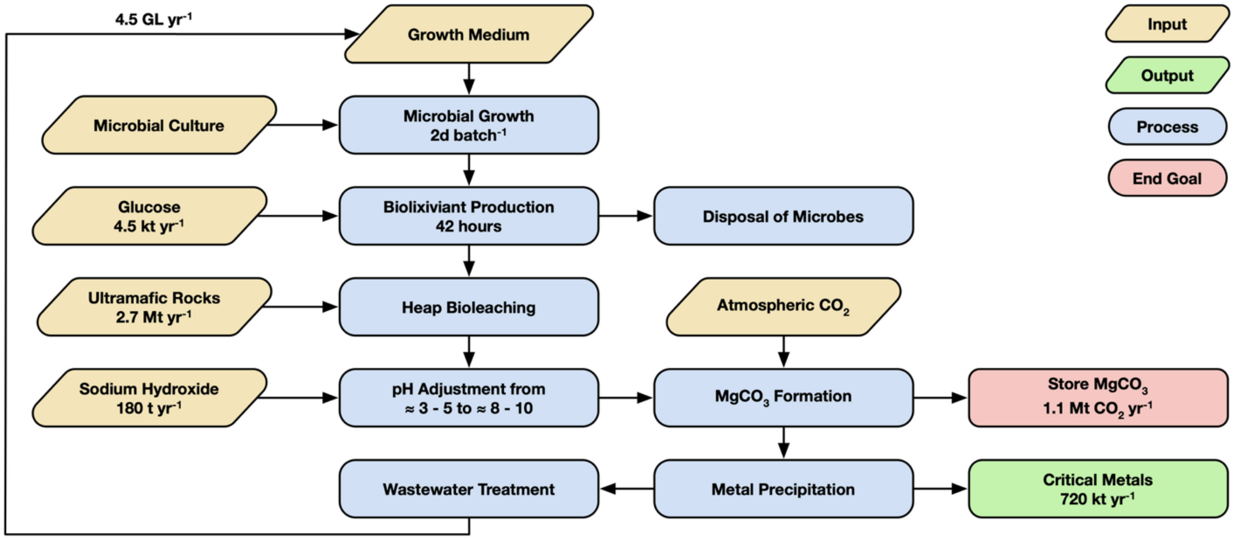


Figure 1. Overall bio-accelerated weathering and CO_2 sequestration process. Microbes are grown and produce an organic acid based biolixiviant for 3.75 days. This biolixiviant is then clarified to remove the microbes, and the biolixiviant is applied to ultramafic rock mine tailings through heap leaching to dissolve magnesium from the rocks. Sodium hydroxide is used to adjust the leachate's pH to favor magnesite formation, and CO_2 is supplied to the leachate from atmospheric air. Magnesite is precipitated and stored geologically on site at the mine. Co-leached metals are then separated, purified, and sold.

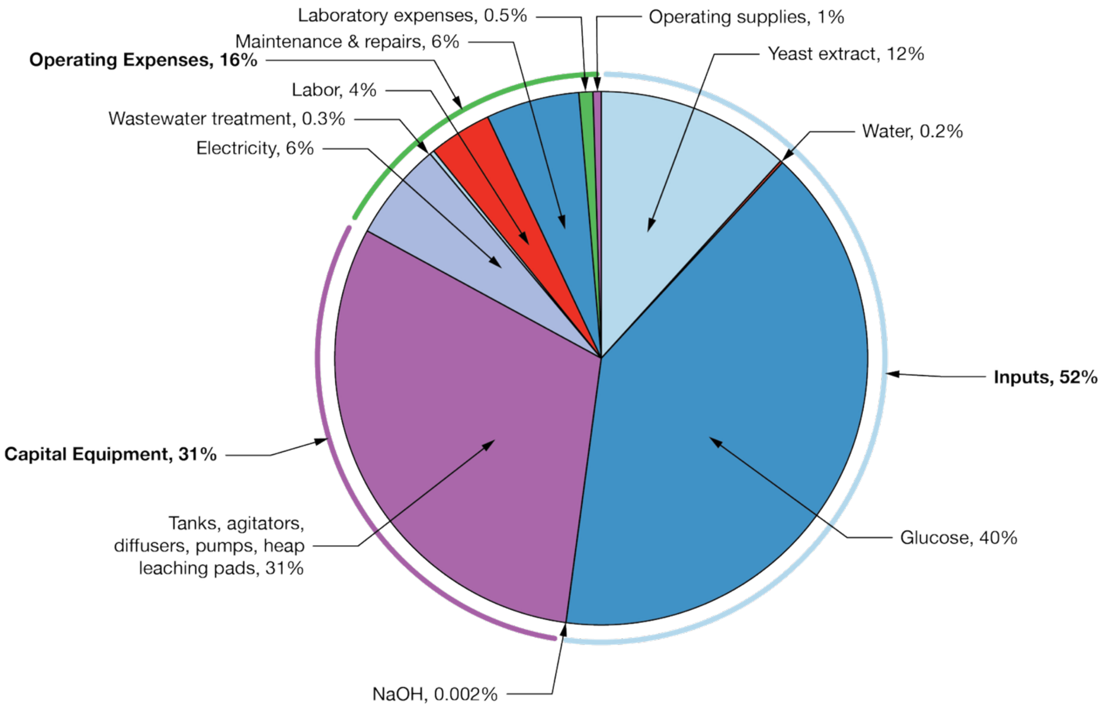
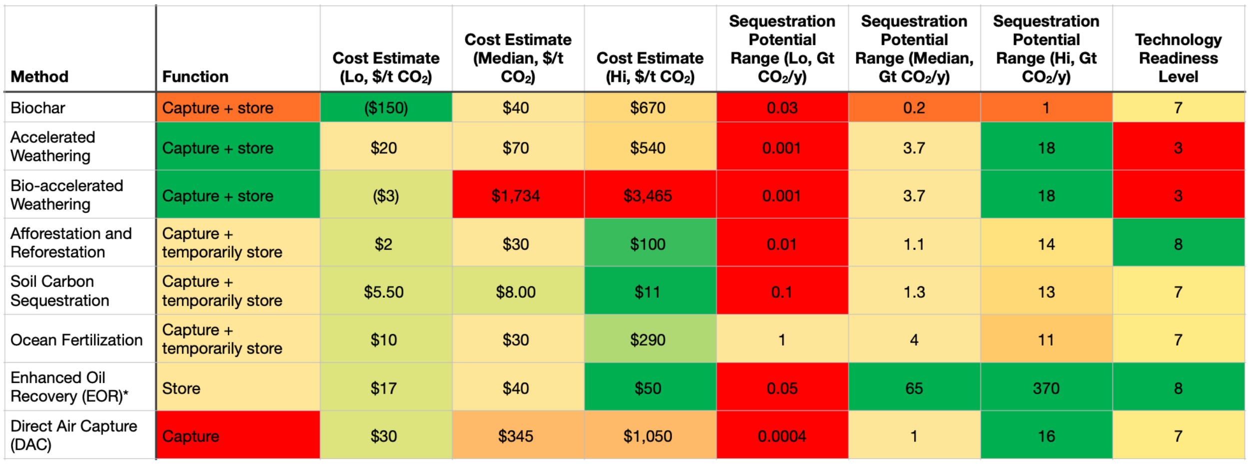


Figure 2. Glucose is the major cost in this process. This figure depicts cost fractions of various expenses. Chemical costs are averages of low and high prices.



Method	Function	Cost Estimate (Lo, $/t CO_2)	Cost Estimate (Median, $/t CO_2)	Cost Estimate (Hi, $/t CO_2)	Sequestration Potential Range (Lo, Gt CO_2/y)	Sequestration Potential Range (Median, Gt CO_2/y)	Sequestration Potential Range (Hi, Gt CO_2/y)	Technology Readiness Level
Biochar	Capture + store	($150)	$40	$670	0.03	0.2	1	7
Accelerated Weathering	Capture + store	$20	$70	$540	0.001	3.7	18	3
Bio-accelerated Weathering	Capture + store	($3)	$1,734	$3,465	0.001	3.7	18	3
Afforestation and Reforestation	Capture + temporarily store	$2	$30	$100	0.01	1.1	14	8
Soil Carbon Sequestration	Capture + temporarily store	$5.50	$8.00	$11	0.1	1.3	13	7
Ocean Fertilization	Capture + temporarily store	$10	$30	$290	1	4	11	7
Enhanced Oil Recovery (EOR)*	Store	$17	$40	$50	0.05	65	370	8
Direct Air Capture (DAC)	Capture	$30	$345	$1,050	0.0004	1	16	7

Figure 3. Bio-accelerated weathering compares favorably with other methods for CO_2 capture and storage. This figure compares various methods for carbon capture and storage. This study's focus is bio-accelerated weathering, which is at the lowest technology readiness level, but this proposed process represents a potentially profitable method of both capture and storage. Also of note is that EOR's potentials are total instead of annual.

Cost Category	Value (Low)	Value (High)	Requirement	Notes and Data Sources
Glucose	$450/t[92]	$4,885/t[93]	452,400 t/y	
Water	$3.86/kgal[67]	$3.86/kgal[67]	4,524,000 m^3/y	US industrial water rate
Yeast extract	$3,000/t[92]	$28,170/t[92]	22,620 t/y	
Sodium hydroxide	$280/t[94]	$495.60/t[95]	181 t/y	
Tanks	$119,600/tank	$119,600/tank	940 tanks	Tanks for growth and biolixiviant production, and magnesite formation. 70,000 gal, API, Cone Roof, Shop Fab; Carbon Steel & API; adjusted from 2014 USD ($84,200[69]) to 2025 USD by a CEPI factor of 818[70]/576.1[71].
Electricity	$0.0782/kWh[96]	$0.0782/kWh[96]	2,292,000,000 kWh/y	
Operating labor	$27.78/h[97]	$27.78/h[97]	3,589,000 operator-h/y	Assuming 0.5 operators per unit[78]

Table 1. Glucose price range is the most variable cost. This table depicts the unit prices and overall requirements of major material, capital, and operating costs. Best- and worst-case scenarios for material costs are included and depend on geographical availability and pricing as well as market volatility due to global economic environment changes.

Product	**Output (t/y)**	**Sale or Credit Price (per t)**	**Revenue (\$/y)**	**% of Revenue / Credits**
K	1,287	\$850,000[98]	\$725,900,000	66.63%
Mineralized CO_2 (within $MgCO_3$ - magnesite)	1,057,000	\$108[62]	\$114,100,000	10.47%
Ca	1,626	\$6,714[99]	\$97,090,000	8.912%
Ni	5,334	\$15,830[65]	\$56,010,000	5.141%
SiO_2	1,093,000	\$55.67[100]	\$40,340,000	3.703%
Al	16,560	\$2,386[65]	\$26,210,000	2.406%
Cr	274	\$9,343[101]	\$10,490,000	0.9629%
Fe	153,164	\$92[102]	\$9,347,000	0.8580%
Co	1,692	\$24,300[103]	\$4,414,000	0.4052%
Na	1,626	\$2,250[92]	\$2,427,000	0.2228%
Ti	569	\$6,182[103]	\$2,333,000	0.2141%
Mn	2,519	\$413[103]	\$690,300	0.06334%
P	297	\$300[104]	\$59,180	0.005432%
Total	**2,335,000**		**\$1,089,000,000**	**100%**

Table 2. Co-leached metals provide opportunities for revenue. In addition to credits for CO_2 captured and stored, this table depicts the metals co-leached and sold. Metal prices are decreased to 66% of their market values to account for the costs for separations and purifications.

Category	**Requirement**	**Unit Cost**	**% of Equipment Costs**
Microbial growth & biolixiviant production tanks (70,000 gal)	257	\$119,600	3.323%
Clarifier	2	\$174,000	0.03764%
Heap (\$32.29 per m^2; 50,000 m^2) (heap: conical; 60m height, 120m radius)	1	\$1,615,000	0.1746%
Magnesite formation tanks (70,000 gal)	683	\$119,600	8.832%
Agitators (200 hp)	940	\$26,410	1.761%
Diffusers (20/tank; 24" length)	18,800	\$130.00	0.2643%
Air Pumps (growth, biolixiviant production, magnesite formation; 70,000 cfm)	4,355	\$177,100	83.40%
Liquid Pumps (Horizontal, ANSI, 1-Stage Centrifugal Pump, 8 inch Discharge Pipe Diameter; Cast Iron & API-610)	1,217	\$16,330	2.203%
Total			**100%**

Table 3. Air pumps are the major equipment cost. This table depicts unit costs and requirements for direct fixed capital costs. Costs were converted to 2025 USD via a CEPCI conversion.

Category	Rate	Cost ($/y)	% of Fixed Costs
Direct costs			
Federal income tax (excludes tax credit from CO_2 capture and storage)	21%	$0	0%
State income tax	7%	$0	0%
Property tax	2% of FCI	$50,680,000	31.01%
Piping	31% of PEC	$12,830,000	7.851%
Instrumentation and control	18% of PEC	$7,450,000	4.559%
Electrical equipment and materials	10% of PEC	$4,139,000	2.532%
Buildings	38% of PEC	$15,730,000	9.624%
Service facilities	40% of PEC	$16,550,000	10.13%
Yard improvement	10% of PEC	$4,139,000	2.532%
Land	6% of PEC	$2,483,000	1.520%
Indirect costs			
Engineering and supervision	8% of TDC	$8,377,000	5.126%
Construction expenses	10% of TDC	$10,470,000	6.407%
Contractors fee	5% of TDC	$5,235,000	3.204%
Insurance	1% of FCI	$25,340,000	15.51%
Total		**$179,100,000**	**100%**

Table 4. Taxes and insurance are significant costs. This table depicts various additional costs beyond material, purchased equipment, and operating costs. Purchased equipment costs (PEC) included reactor tanks, agitators, liquid pumps, air pumps, diffusers, and the leaching pad. Total direct costs (TDC) were calculated as the sum of PEC, piping, instrumentation and control, electrical, buildings, service facilities, yard improvement, and land. Fixed capital investment (FCI) was calculated as 1.21 times TDC[79].

Category	Best-Case Scenario Costs	% of Total Costs (Best-Case Scenario)	Worst-Case Scenario Costs	% of Total Costs (Worst-Case Scenario)
Input Materials	\$261	25.42%	\$2,699	77.88%
Other Operating (Electricity, Wastewater Treatment, Labor, Overhead)	\$550	53.52%	\$550	15.87%
Equipment	\$44	4.257%	\$44	1.289%
Other Fixed Capital Investment, Taxes, and Insurance	\$173	16.81%	\$173	4.985%
Credits	\$(108)	(10.51)%	\$0	0%
Metals Sales	\$(923)	(89.80)%	\$0	0%
Overall Costs (No Credits or Metals Sales)	\$1,028	100%	\$3,465	100%
Overall Costs (With Credits)	\$920			
Overall Costs (With Credits & Metals Sales)	\$(3)			

Table 5. Favorable feedstock costs, tax credits, and revenue from metals sales may make bio-accelerated weathering profitable. This table depicts the overall costs for best- and worst-case scenarios. The best-case scenario included the lowest costs for glucose, yeast extract, and sodium hydroxide, tax credits for CO_2 captured and stored, and metals sales. The worst-case scenario included the highest material costs, no tax credits, and no metals sales. Values are listed per tonne of CO_2 captured and stored.

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