Mineral carbonation process of carbon dioxide using animal bone

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Abstract
Carbon dioxide has been identified as one of the greenhouse gases responsible for global warming. Several carbon capture and storage technologies have been developed to mitigate the large quantities of carbon dioxide released into the atmosphere, but these are quite expensive and not easy to implement. Thus, this research analyses the technical and economic feasibility of using calcium leached from cow bone to capture and store carbon dioxide through the mineral carbonation process. The capturing process of carbon dioxide was successful using the proposed technique of leaching calcium from cow shinbone (the tibia) in the presence of HCl by reacting the calcium solution with gaseous carbon dioxide. AAS and XRF analysis were used to determine the concentration of calcium in leached solutions and the composition of calcium in cow bone respectively. The best leaching conditions were found to be 4 mole/L HCl and leaching time of 6 h. Under these conditions, a leaching efficiency of 91% and a calcium conversion of 83% in the carbonation reaction were obtained. Other factors such as carbonation time, agitation rate, and carbonation reaction temperature had little effect on the yield. A preliminary cost analysis showed that the cost to capture 1 ton of CO$_2$ with the proposed technique is about US$ 268.32, which is in the acceptable range of the capturing process. However, the cost of material used and electricity should be reviewed to reduce the preliminary production cost.

Keywords
Sequestration, carbonation, carbon capture, and carbon storage, mineralization of carbon dioxide

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Introduction

Fossil fuels have been used as an energy source for many years. They supply about 80% of the global energy demand. The global energy demand continues to grow such that a 40% increase is expected by 2035 due to the increase in population and industrial development. Even with governments and policymakers trying to implement policies to mitigate greenhouse emissions, fossil fuels will still be the main source of energy contributing as much as 75% of global energy demand.\(^1\) Coal is expected to be the largest single source of energy. The main problem associated with this extensive use of fossil fuels is that a lot of carbon dioxide is emitted during their combustion process.

Carbon dioxide has been identified as one of the greenhouse gases responsible for global warming. Climate modeling suggests that temperature on the planet will increase until a point where glaciers start to melt and sea levels rise if nothing is done to reduce the CO\(_2\) emissions. Apart from causing global warming, carbon dioxide can cause the pH of water bodies to be acidic by reacting with water and forming weak carbonic acid which negatively affects marine life.\(^2\) Due to these concerns over the emission of carbon dioxide, research has been ongoing aimed at reducing carbon dioxide emissions. Several carbon capture and storage (CCS) technologies have been developed to mitigate the large quantities of carbon dioxide released from plants. Studies suggest that the use of CCS technology could reduce carbon dioxide discharge from power plants that use fossil fuels by up to 80%.\(^3\) This reduction in carbon dioxide emissions would have the same effect as planting 62 million trees and waiting for them to grow. Despite CCS technology is an ideal way to deal with carbon dioxide emissions, there are several problems associated with the existing CCS technology. The main problems are that the technology is quite expensive and not easy to implement.

The purpose of this research was to investigate whether animal bone can be used as a calcium source for carbon dioxide sequestration through mineral carbonation. It was motivated by the need to develop a low-cost CO\(_2\) sequestration procedure. Having a low-cost calcium source and sequestration procedure will promote the use of the CO\(_2\) sequestration and lead to a reduction in the emission of carbon dioxide into the atmosphere. Mineral carbonation is currently being done using calcium from limestone which requires large capital investments to mine. Other several carbon captures and storage techniques have been developed but their use has been very limited due to high costs, difficult to implement, or both. The technique applied in this research involved sequestration of CO\(_2\) using calcium that had been extracted from animal bone. In South Africa alone, it is estimated that roughly 3 million pigs, 2.5 million cows, and 6.3 million sheep and goats are slaughtered annually. Slaughter cows weigh 540 kg on average and the bones of a cow can contribute up to 32% of its weight. Slaughter pigs weigh up to 94 kg with bone contributing about 11% of the weight. Slaughter sheep and goats weigh up to 61 kg with bone contributing up to 20% of the weight. This amounts to roughly 539,880 tons of animal bone annually from the four-common livestock. This proves that animal bone is quite abundant. Bone contains about 27.9% calcium by weight, therefore
that equates to 150,626 tons of calcium. The abundance of animal bone ensures that animal bone can be a sustainable source of calcium. Animal bone is inexpensive and abundant hence this can have made the entire process cheaper and easier to implement. The applied technique involved leaching of calcium from the bone into solution using concentrated hydrochloric acid. The CO₂ was reacted with the calcium-rich solution to form thermodynamically stable calcium carbonate. The calcium carbonate produced is intended for energy use through thermochemical energy storage technology. It can be also used as an active ingredient in agricultural lime or help in soil firming up, allowing for the erection of bridges, homes, and towering edifices. The three main stages used in the experimental procedure were pre-treatment of bone to remove any chunks of flesh from the bones, leaching of calcium ion from the bone, and the carbonation reaction of the carbon dioxide and the calcium ions. The outcomes of the proposed method were used for preliminary cost analysis of this project.

**Materials and method**

**Materials**

The cow bone used in this project was the shinbone obtained from Alpha meat butchery (SA Pty Ltd). The cow bone was chosen as raw material because of its abundance as waste generated after the slaughtering of animals. The hydrochloric acid (HCl) used for leaching was analytical grade supplied by Sigma Aldrich (SA Pty ltd). Industrial grade CO₂ supplied by AFROX (SA Pty Ltd) was used for the carbonation reaction. The Sodium hydroxide (NaOH) used to vary the pH was the analytical grade supplied by ACE (SA Pty Ltd). The magnetic stirrers used for the leaching reaction and carbonation reaction are the Arex Velp Scientifica magnetic stirrer and Lasec 220V magnetic stirrer respectively. Atomic Absorption Spectrometry (AAS) analysis was done using an Agilent 240 FS machine supplied by Chemetrix (SA Pty Ltd).

**Pre-treatment of cow bone**

The pre-treatment step aimed to remove soft tissue and any fatty tissue that could interfere with the leaching process. The spongy parts and bone marrow were removed using an abrasive material. The bones were washed with warm distilled water to remove the blood and other loose material, thereafter dried in an oven at 70°C for 48 h. Finally, the dried bones were crushed into fine particles with a mean diameter of 852 microns using a ring and puck pulverizer.

**Leaching of calcium from cow bone**

Calcium was leached from the cow bone using the HCl solution. The weight of the bone was kept constant (30 g) for all the run. The acid concentration was varied from 1.5 to 4 M in increments of 0.5. The agitation was achieved by using a
magnetic stirrer, and the rate varied between 0 (no agitation), 1, 2, 3, 6, and 7 relative agitation speed. The leaching time was varied between 1, 2, 3, 4, 5, 6, and 8 h. The effect of leaching time, agitation rate, and concentration of HCl was investigated. One parameter was changed at a time while the other parameters were kept constant. For each run, a leachate sample was collected and tested for Ca\(^{2+}\) concentration using Atomic absorption spectrometry (AAS).

A total of 30 g of bone was leached in 60 mL of HCl solution at a desired stirring rate, and time. The leaching process was carried out at ambient temperature and pressure. Vacuum filtration was carried out to separate solids from the calcium-rich solution.

**Carbonation reaction**

The calcium solution from the leaching reaction was reacted with carbon dioxide in a three-neck flat bottom flask stirred by a magnetic stirrer. The Concentration of CO\(_2\) was controlled by feeding it at a constant pressure of 100 kPa for 10 s. The effects of temperature and reaction time were investigated for the carbonation reaction. A 4 M sodium hydroxide solution was used to increase the pH of the leached solution to about pH 13 so that CaCO\(_3\) could precipitate. The solid CaCO\(_3\) formed was then separated from the solution by vacuum filtration and dried in an oven.

**Sieve analysis**

A 210 g sample of dried and pulverized cow shinbone was used for sieve analysis. The aim was to determine the particle size distribution and mean particle size. A total of five sieves and a bottom plate were used. The plates used had aperture sizes of 2800, 2000, 1180, 800, and 600 µm. The sample was poured into the top sieve, and the sieve stack was shaken vigorously to allow the particles to fall. The mass of bones captured in each sieve was weighed using an analytical balance to determine the mass distribution in each size class. The data was recorded and used to determine a particle size distribution and mean particle diameter.

**Atomic absorption spectrometry**

A 0.5 mL sample of leachate solution was extracted using a graduated syringe. The extraction was done after the filtration of the leaching reactants. The 0.5 mL of calcium solution was diluted with 10 mL of distilled water to give a dilution ratio of 21. The dilution was done so that the concentration of samples would fall within the AAS detectable limits set using the available standard solutions. The estimated calcium concentration of the diluted samples ranged between 20 and 350 ppm, hence the standards were made to cover this range. The four standards used for calibration were 20, 100, 200, and 350 ppm.
X-ray fluorescence

Two bone samples were sent for XRF analysis to determine the bone calcium content. The first sample was of the cow shinbone used in this project, and the second sample was of cow bones from other random parts of the cow. The samples were prepared by completely drying the bones in an oven at 70°C for 48 h. The dry bones were then pulverized into a fine powder using a ring-roll pulverizer. The soil and mining methods were used for each sample.

Results and discussion

Particle size distribution of pulverized bone

The particle size distribution of the crushed bones was determined through the sieve analysis technique. Figure 1(a) and (b) represent the collected data as a cumulative frequency curve and the frequency curve respectively. By using the frequency distribution curve, the mean particle diameter was identified as the diameter that coincides with the peak point of the curve. The mean particle diameter was determined to be 850 μm. The graphical mean was calculated using the Folk and ward formula shown in equation (1) and data from the cumulative frequency curve.

$$ \text{Graphical mean} = \frac{D_{16\%} + D_{50\%} + D_{84\%}}{3} $$

Where $D_{16\%}, D_{50\%}, D_{84\%}$ = the particle diameter at cumulative frequencies of 16%, 50%, and 80%.

The graphical mean was determined to be 854 μm. The two mean diameter values determined through the two different methods only show a small difference of 0.40%. Using the two values, the mean particle diameter was calculated to be

![Figure 1. Particle size distribution of crushed bone: (a) cumulative frequency curve and (b) frequency curve.](image-url)
852 μm. The effect that particle size has on leaching depends on whether the leaching process in question is chemically-controlled or diffusion controlled. Equations (2) and (3) show the relationship between leaching efficiency and particle size for chemically controlled and diffusion controlled leaching reactions respectively. In both cases, there is an inverse relationship between leaching efficiency and particle size. The particle size will have a larger impact on leaching efficiency when the leaching is diffusion-controlled due to the effect on the thickness of mass transfer film.

\[
\text{leaching efficiency} \propto \frac{1}{\text{radius}} \tag{2}
\]

\[
\text{leaching efficiency} \propto \frac{1}{\text{radius}^2} \tag{3}
\]

**Carbonation reaction**

The carbonation reaction involved the reaction of bicarbonate ions formed from CO₂ reacting with water and calcium ions to form CaCO₃. The CaCO₃ is thermally stable over long periods thus; it can be safely stored without the risk of any of the reacted CO₂ leaking into the atmosphere. The mineral carbonation reaction to form calcium carbonate has multiple steps which occur simultaneously as shown in equations (4) to (6).

\[
\text{CO}_2(g) + \text{H}_2\text{O}(l) \rightleftharpoons \text{CO}_3^{H^+}(aq) + \text{HCO}_3^- \tag{4}
\]

\[
\text{Ca}^{2+}(aq) + \text{HCO}_3^-(aq) \rightleftharpoons \text{CaCO}_3(s) + \text{H}^+(aq) \tag{5}
\]

\[
\text{Ca}^{2+}(aq) + \text{CO}_2(g) + \text{H}_2\text{O}(l) \rightleftharpoons \text{aCO}_3(s) + 2\text{H}^+(aq) \tag{6}
\]

Equation (4) shows the reaction between water and carbon dioxide to form bicarbonate ions and hydrogen ions. The bicarbonate ions formed in first reaction go on to react with calcium ions obtained from the leaching process to form the desired calcium carbonate as shown in equation (5). Equation (6) shows the overall carbonation reaction which is an exothermic reaction. The presence of water was proven to significantly improve the reaction kinetics of the carbonation reaction.5

**Effect of varying agitation rate during leaching**

Leaching experiments were conducted in a batch system at different relative agitation speeds. The relative agitation speeds ranged between 0 and 7. The experiments were conducted in a fume hood at ambient temperature and pressure, where the ambient temperature ranged between 25°C and 27°C. The leaching time was kept constant and the other parameters were also kept constant throughout.

From Figure 2(a), CaCO₃ yield increases as relative agitation increase from 0 to 1 and remained constant until 2. After that, it was observed that the yield slightly
decreased with an increase in relative agitation. The increase in calcium leached and CaCO₃ yield can be explained by the fact that increasing the agitation rate (Figure 3(a)) reduces the thickness of the diffusion layer which in turn improves the mass transfer between the bones and the leaching reagent. A higher agitation rate also ensures that the bone particles remain suspended in the leaching reagent hence increasing the contact surface area between the two phases. This results in more calcium being leached from the bone which in turn increases the yield of calcium carbonate. The increase in CaCO₃ yield between relative agitation rate of 0 and 1 suggests that the leaching is diffusion-controlled up to this point. This means that

Figure 2. Effect of various parameters on carbonation reaction: (a) effect of agitation rate, (b) effect of leaching time, (c) effect of temperature in carbonation reaction, (d) effect of HCl concentration, and (e) effect of carbonation reaction time.
The diffusion rate is slower than the reaction rate which implies that the diffusion rate is the determining step in the leaching process. There is no further increase in CaCO₃ yield when the relative agitation rate exceeds one because at this point the diffusion layer has become so thin that the diffusion rate becomes faster than the reaction rate. When the diffusion rate becomes faster than the reaction rate, and the reaction rate becomes the rate-determining step. At this point, any increase in the agitation rate will not improve the leaching rate. Multiple researchers such as Ahmed et al.⁸ observed a similar trend during their leaching tests. Therefore, the optimum agitation rate during these experiments was at the relative speed of one on the Arex Velp Scientifica magnetic stirrer.

Figure 3. Effect of various parameters on leaching process: (a) effect of agitation rate, (b) effect of leaching time, (c) effect of temperature in carbonation reaction, (d) effect of HCl concentration, and (e) effect of carbonation reaction time.
Effect of varying HCl concentration in the leaching step

The effect of HCl concentration during leaching was investigated by varying the HCl concentration between 1.5 and 4 M (Figure 3(d)). The observation from Figure 2(d) is that the yield of CaCO₃ increases with the increase in the concentration of leaching solvent. The mass of CaCO₃ increases significantly from 1.97 to 12.5 g as the concentration was increased from 1.5 to 4 M. The increase in yield of CaCO₃ is as a result of the increase in the amount of leached calcium (Figure 3(d)). The increase in the amount of calcium leached can be explained using the collision theory model. Zelichenko et al.⁹ conducted similar experiments of leaching calcium-phosphorus compounds from cow bones and the results obtained show a similar trend to those obtained in this investigation. The only difference between the two sets of results is that Zelichenko’s results suggest that there is a sharp decline in yield as concentration surpasses 3.5 M while results from this research show that the yield continues to increase past the 3.5 M concentration. The increase in the yield of calcium carbonate is also a result of the higher acid concentration promoting the carbonation reaction by increasing ionization of reacting molecules. The more ionized the reacting molecules, the faster the reaction occurs. The only setback during this research was that leaching with an HCl concentration of 4 M yielded an oily sludge as the bones began to disintegrate due to this high concentration. This made the process of separating the leachate and solids quite difficult, hence no experiments were carried out with concentrations higher than 4 M.

Effect of varying leaching time

From Figure 2(b), the observation is that the yield of CaCO₃ increases as gradually as the leaching time is increased between 2 to 8 h. This increase in CaCO₃ yield can be attributed to the increase in the amount of calcium leached from the bone (Figure 3(b)). Increasing the leaching time from 2 to 6 h resulted in the concentration of leached calcium increasing by 2%. The increase in leaching time improves leaching because there is more time for the calcium ions to transfer from the bone into the acid solution. This observation can be supported by equation (7) which applies to both chemical-controlled and diffusion-controlled reactions.

\[ x = 1 - e^{-kt} \]  

Where \( x \) = leached fraction  
\( k \) = reaction constant in (1/min)  
\( t \) = residence time (min)

As the value of time increases, the value exponential function becomes smaller hence the value of leached fraction increases. After the 6-h mark, a plateau can be observed and this indicates that there is no further leaching occurring beyond this point. This is a very common trend observed in different leaching experiments. For example, Rao et al.¹⁰ observed a similar trend when leaching uranium from Indian ore.
Effect of varying reaction time in carbonation reaction

From Figure 2(e), the observation is that the curve for the mass of CaCO₃ plotted against carbonation reaction time is almost a horizontal line. This shows that the carbonation reaction is very fast and reaches completion in as little as 5 min. The fast reaction can be attributed to the fact CO₂ quickly ionizes to form the bicarbonate ion as represented by equation (5). The bicarbonate ions formed then quickly form new bonds with the calcium ions. The fast completion of ionic reactions can also be attributed to the fact that there are no steric hindrances to slow down the reaction such as in non-ionic reactions.

Effect of varying temperature in carbonation reaction

The temperature was varied from 5°C to 80°C to determine the effect on carbonation efficiency. All leaching parameters were kept constant. The temperature of 5°C was achieved by carrying out the reaction in a water bath filled with ice and the higher temperatures were achieved by carrying out the reaction in a heated water bath. The temperature fluctuated throughout the reaction hence an average value was obtained by taking a reading at the beginning and the end of the reaction. The results shown in Figure 2(c) indicate that varying temperature within the specified range had little effect on the yield of calcium carbonate. Another observation is that initially, the yield decreases as temperature is increased from 5°C to 57°C. However, the yield starts to increase after 57°C. The explanation for these unusual observations is that an increase in temperature has contradicting effects on the yield of CaCO₃. Firstly, an increase in temperature increases the rate of reaction by increasing the kinetic energy of reacting molecules as explained by the collision theory (temperature effect). On the other hand, an increase in temperature also reduces the solubility of CO₂ into solution hence reducing the concentration of HCO₃⁻ available for reaction with Ca²⁺. Furthermore, the carbonation reaction is exothermic hence an increase in temperature will favor the reverse reaction which means less CaCO₃ formed. At the low temperature of 5°C, the solubility of CO₂ would be very high hence the carbonation efficiency is relatively high. This is despite the low reaction kinetics caused by the low temperature. As the temperature increases to 35°C, the carbonation efficiency slightly decreases because the solubility of CO₂ has decreased. The positive effect of an increase in kinetics is less than the negative effect of a decrease in solubility. Upon a further increase in temperature, it can be observed that there is an increase in carbonation efficiency. This is because, at the higher temperature, the positive effect of increased kinetic becomes greater than the negative effect of reduced solubility. Due to the contradicting effects of temperature, there is very little effect of temperature increase on carbonation efficiency within the temperature range of 5°C to 80°C. This observation is similar to the observation made by Ji et al. However, the work by Ramezani et al. showed that changing the temperature between 600°C and 800°C significantly changed the carbonation yield. This suggests that carbonation efficiency is
significantly affected by temperature change only when the temperatures are very high.

*Conversion and yield of Ca$^{2+}$ in carbonation reaction*

Figure 2 shows that the mass of CaCO$_3$ obtained ranges between 1.97 and 12.59 g. Acid concentration is the factor that greatly influences the mass of CaCO$_3$ obtained. This is because a higher acid concentration increases the amount of calcium leached and also improves the carbonation reaction due to an increased rate of ionization (Figure 3(d)). Using acid with a concentration of four molars, 12.59 g of calcium carbonate was formed, and this corresponds to 83% conversion as indicated in Figure 3(b). The lowest yield of CaCO$_3$ was 1.97 g which correspond to 1.5 M acid and 16% conversion of calcium. The other factors such as agitation rate, carbonation temperature, leaching time, and carbonation reaction rate had a very small effect on the CaCO$_3$ yield. The CaCO$_3$ yield with these factors ranged between 5 and 6 g and the calcium conversion ranged from 33% to 49% which shows how insignificant their effect was on the process. The technique used during this research can produce a relatively high conversion of calcium under ambient temperature and pressure, which means reduced energy costs.

*Leaching efficiency*

The leaching efficiency for the different runs was determined using XRF data and data obtained from the lab experiments. Leaching efficiency was calculated using equation (8).

\[
\text{Efficiency\%} = \frac{\text{Mass Calcium leached (g)}}{\text{Mass of bone (g)*calcium content in bone (\%)}} \times 100 \tag{8}
\]

The leaching efficiencies obtained ranged from 73% to 91% which is quite high. A concentration of 4 M gave the highest leaching efficiency of 91% as seen in Figure 4. The agitation rate in the leaching reactor had the least effect on leaching efficiency. The leaching process was found to be reaction limited at an agitation rate above 1, which also explain the low effect that agitation rate has on the leaching efficiency.

*XRF analysis of cow bone*

XRF analysis was done to determine the elemental composition of the cow bone used for the experimental work during this research. A total of two-cow bone samples were analyzed through XRF, one sample consisted of the shinbone and the other had a mix of bones from different parts of the cow. Each sample was analyzed using the mining analysis method and the soil analysis method. Figure 5(a) and (b) show the results of the analysis. The soil analysis method showed that shinbone has a calcium content of 22.1 wt.% while the calcium content in the other
sample of bones was 20.2 wt.%. This is a small difference of 8.6% and this can be attributed to the presence of bone marrow in the other sample.

The mining analysis showed that the shinbone has a calcium concentration of up to 220,000 ppm while the other bone had a concentration of about 193,500 ppm. The calcium content obtained from the mining analysis method corresponds to the data obtained by Buddhachat et al.14

**Figure 4.** Effect of various parameters on leaching efficiency of Ca$^{2+}$: (a) effect of agitation rate, (b) effect of leaching time, (c) effect of temperature in carbonation reaction, (d) effect of HCl concentration, and (e) effect of carbonation reaction time.
One of the major factors that have been limiting the implementation of several CCS technologies is the high costs per ton of CO₂ sequestered. CO₂ sequestration by mineral carbonation is generally more expensive relative to other sequestration methods because of the additional investment costs for equipment. No commercially viable procedure for mineral carbonation has been identified, hence it is very difficult to come up with a detailed cost estimate. Using data from pilot plants, it is approximated that the cost of mineral carbonation is between $50 and $300 per ton of carbon dioxide captured. These high costs arise mainly due to high energy costs and material handling costs. Comparing costs from different reports is complicated because of the difference in boundary conditions for each cost analysis report. The applicability of the CCS technique proposed in this research is highly influenced by the costs involved. The cost of sequestration calculated in this investigation represents costs incurred from the point where raw materials are fed into the process to the point where solid CaCO₃ is obtained. The desired outcome would be to have the cost per ton be lower than that of existing mineral carbonation techniques. Therefore, a preliminary economic evaluation on operating costs of the proposed mineral carbonation technique was done to obtain a rough estimate of sequestration costs. Several assumptions were made while performing economic analysis. The major assumptions were:

- All raw materials are available on site, therefore, no transport costs involved.
- CO₂ is already pre-treated therefore the costs of capture and pre-treatment were ignored.
- Fixed capital investment is ignored.
- The cost of labor and administration is ignored.
- Bones used are “waste” hence they are acquired for free.
**Mass balance**

A mass balance was done to determine the amount of raw materials required to sequestrate 1 ton of carbon dioxide. The raw materials and their respective quantities are shown in Table 1. The main raw materials fed into the process are fresh HCl which has a concentration of 32% and purity of 99.8% which is the analytical grade. Freshwater is also important for dilution of the fresh HCl to the desired concentration of 4 M and also for making NaOH solution from the pellets. The bones are the source of the calcium and they are required in the largest quantities compared to the other raw materials. The ratio of bones to CO₂ is about 12.

**Raw material and utility cost**

For the purposes of calculations, the exchange rate of Rand to USD used was R14.60/US$1\textsuperscript{17} taken as at 1 January 2019. The total cost of sequestrating one-ton CO₂ was calculated to be US$268.32 and the breakdown of this total is shown in Table 2. The largest energy use in this process is by the drying kiln. The kiln specifications are shown in Table 3 and the power usage was calculated using equation (9).

\[
\text{Energy usage (KWh)} = \frac{V \times I \times t}{1000}
\]  

(9)

Where

\( V = \) voltage in volts  
\( I = \) electrical current in Amps  
\( t = \) time in hours

The cost of NaOH contributed the greatest amount to the total cost, contributing 54% to the total cost.

**Table 1. Raw materials required.**

| Raw material       | Quantity (kg/h) |
|--------------------|-----------------|
| Fresh HCl          | 228.1           |
| Freshwater         | 3438.7          |
| NaOH pellets       | 584.2           |
| Bones              | 12,079.5        |

**Table 2. Cost of raw materials and utilities.**

| Material          | Unit cost (ZAR) | Unit cost (USD) | Cost per ton CO₂ (USD) | Reference       |
|-------------------|-----------------|-----------------|-------------------------|-----------------|
| Water/(kL)        | 32.27           | 2.21            | 7.60                    |                 |
| HCl/(ton)         | 150.00          | 34.22           |                         | Alibaba.com\textsuperscript{18} |
| NaOH/(ton)        | 250.00          | 146.04          |                         | Alibaba.com\textsuperscript{19} |
| Electricity/(kW h)| 1.70            | 0.12            | 80.48                   |                 |
| Total             |                 |                 | 268.32                  |                 |
Conclusion

The main aims of this project were to determine the technical and economic feasibility of sequestrating CO₂ using calcium from animal bone. The other objectives included determining the effects of certain parameters on the yield of CaCO₃ or the amount of CO₂ captured. The technique that was proposed in this project successfully captured CO₂ using calcium from animal bone which means that the objective of technical feasibility was achieved. A leaching efficiency of 91% and calcium conversion of 83% were achieved with a concentration of HCl at 4 M. This is a great concept because we are basically using “waste” bone to alleviate the problem of CO₂ being released into the atmosphere. The results went on to show that the concentration of HCl was the most important parameter in the proposed technique because a higher concentration improves leaching efficiency and improves the carbonation reaction due to an increased degree of ionization. The preliminary economic evaluation gave an estimated cost of sequestration to be $268 per ton of CO₂ captured and stored. The cost of NaOH pellets and electricity used were identified to be the largest contributing factor to the sequestration cost. Hence, cheaper alternative material and energy source could be investigated in order to achieve the desired process efficiency. Further pilot investigation needs to be carried out before this technique can fully be implemented.

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Table 3. Drying kiln specifications.

| Specification       | Value |
|---------------------|-------|
| Voltage (V)         | 240   |
| Current (A)         | 60    |
| Power (kW)          | 14.4  |
| Operating time (h)  | 48    |
| Usage (kW h)        | 691.2 |
References

1. Shafiee S and Topal E. When will fossil fuel reserves be diminished? *Energy Policy* 2009; 37: 181–189.
2. Fivelstad S, Waagbø R, Zeitz SF, et al. A major water quality problem in smolt farms: combined effects of carbon dioxide, reduced pH and aluminium on Atlantic salmon (Salmo salar L.) smolts; physiology and growth. *Aquaculture* 2003; 215: 339–357.
3. Rahman FA, Aziz MMA, Saidur R, et al. Pollution to solution: capture and sequestration of carbon dioxide (CO₂) and its utilization as a renewable energy source for a sustainable future. *Renew Sustain Energy Rev* 2017; 71: 112–126.
4. Folk RL and Ward WC. Brazos River bar [Texas]; a study in the significance of grain size parameters. *J Sediment Res* 1957; 27: 3–26.
5. Huijgen WJJ and Comans RNJ. *Carbon dioxide sequestration by mineral carbonation*. Thesis. Energy research Centre of the Netherlands ECN, The Netherlands, 2003.
6. Sheu FC and Chen KS. The effect of temperature, agitation and content of gold on the thickness of electroplated gold at various current densities. *J Chinese Chem Soc* 1978; 25: 9–16.
7. Venugopal R, Sharma T, Saxena V, et al. Mineral processing technology. In: *International seminar on mineral processing technology (MPT-2005)*. New Delhi: Tata McGraw-Hill Pub. Co., 2005.
8. Ahmed I, Nayl A and Daoud J. Leaching and recovery of zinc and copper from brass slag by sulfuric acid. *J Saudi Chem Soc* 2016; 20: S280–S285.
9. Zelichenko E, Guzeev V, Rogulina A, et al. Investigation of the properties of hydroxyapatite extracted from the bone tissue of agricultural animals. *Chem Sustain Dev* 2012; 20: 491–496.
10. Rao KA, Sreenivas T, Vinjamur M, et al. Continuous leaching of uranium from an Indian ore: residence time scale up and heat effects. *Hydrometallurgy* 2014; 146: 119–127.
11. Servio P and Englezos P. Effect of temperature and pressure on the solubility of carbon dioxide in water in the presence of gas hydrate. *Fluid Phase Equilib* 2001; 190: 127–134.
12. Ji L, Yu H, Wang X, et al. CO₂ sequestration by direct mineralisation using fly ash from Chinese Shenfu coal. *Fuel Process Technol* 2017; 156: 429–437.
13. Ramezani M, Tremain P, Doroodchi E, et al. Determination of carbonation/calcination reaction kinetics of a limestone sorbent in low CO₂ partial pressures using TGA experiments. *Energy Procedia* 2017; 114: 259–270.
14. Buddhachat K, Klinhom S, Siengdee P, et al. Elemental analysis of bone, teeth, horn and antler in different animal species using non-invasive handheld X-ray fluorescence. *PLoS One* 2016; 11: e0155458.
15. Herzog H. *Carbon sequestration via mineral carbonation: overview and assessment*. MIT Laboratory for Energy and Environment, 2002.
16. Sanna A, Uibu M, Caramanna G, et al. A review of mineral carbonation technologies to sequester CO₂. *Chem Soc Rev* 2014; 43: 8049–8080.
17. USD/ZAR XC. www.xe.com/currencyconverter/convert/?Amount=1From=USDTo=ZAR, 2019. (accessed 1 January 2019).
18. Alibaba.com. https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=hydrochloric+acid+32&viewtype=&tab=
19. Alibaba.com. https://www.alibaba.com/trade/search?fsb=y&IndexArea=product_en&CatId=&SearchText=sodium+hydroxide&viewtype=&tab=
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