

## Sustainable System for CO<sub>2</sub> Capturing with Multiple Products

Kenji Sorimachi<sup>1\*</sup> and Hossam A. Gabbar<sup>2\*</sup>

<sup>1</sup>Bioscience Laboratory, Environmental Engineering, Co., Ltd., Takasaki, Gunma, Japan

<sup>2</sup>Department of Energy and Nuclear Engineering, Faculty of Engineering and Applied Science, Ontario Tech University, Canada

### \*Corresponding Author

Kenji Sorimachi, Bioscience Laboratory, Environmental Engineering, Co., Ltd., Takasaki, Gunma, Japan.

Hossam A Gabbar, Department of Energy and Nuclear Engineering, Faculty of Engineering and Applied Science, Ontario Tech University, Canada.

Submitted: 2023, June 01; Accepted: 2023, June 11; Published: 2023, June 20

**Citation:** Sorimachi, K., Gabbar, H. A. (2023). Sustainable System for CO<sub>2</sub> Capturing with Multiple Products. *Petro Chem Indus Intern*, 6(3), 187-197.

### Abstract

Currently, we are facing several serious issues, including diseases, climate change, economics, and wars. Among them, which needs to be resolved imminently to protect the future generations. Recently, we developed an innovative CO<sub>2</sub> fixation and storage method based on the use of chemical compounds such as NaOH and CaCl<sub>2</sub>, to prevent the climate crisis. Herein, the electrolysis of a NaCl solution or seawater was performed to make the resultant NaOH react with CO<sub>2</sub>. Amines that react with CO<sub>2</sub> were also examined. Moreover, seawater was used to produce CaCO<sub>3</sub> rather than the CaCl<sub>2</sub> solution. Although amines are currently used to capture CO<sub>2</sub> from exhaust gases, the thermal treatment of the amine-CO<sub>2</sub> complex solution is necessary to release CO<sub>2</sub>. Thermal treatment requires energy that eventually produces CO<sub>2</sub> and induces the degradation of organic amines. However, the CO<sub>2</sub> captured in the amine or NaOH solution was released easily by acidifying the CO<sub>2</sub>-containing solutions. Moreover, HCl could release CO<sub>2</sub> from hydro carbonates, Ca(OH)<sub>2</sub>, Mg(OH)<sub>2</sub>, and mMgCO<sub>3</sub>·Mg(OH)<sub>2</sub>·nH<sub>2</sub>O, as well as from mineral carbonates, CaCO<sub>3</sub> and MgCO<sub>3</sub>. This simple method of releasing the captured CO<sub>2</sub> from the amine-CO<sub>2</sub> complexes, hydro carbonates, and mineral carbonates is crucial to obtain pure CO<sub>2</sub> for additional usage as an original material.

**Keywords:** CO<sub>2</sub>, Climate Crisis, SDGs, DAC, CCS, Limestone, CaCO<sub>3</sub>, Seawater

### 1. Introduction

Post the Industrial Revolution, the increase in the CO<sub>2</sub> levels in the atmosphere has led to a climate crisis and an increase in the global temperature [1]. On July 4, 2023, the British Broadcasting Corporation reported that at least seven people had been killed after being caught in an avalanche initiated by the collapse of the Marmolada Glacier in the Italian Alps. Similarly, on July 23, 2023, NHK (Japan Broadcasting Corporation) reported extremely high temperatures in over 40 European countries such as the UK, France, Spain, and Portugal. Over 1,300 people died in Spain and Portugal, and thunderbolts caused by unexpectedly high temperatures led to severe mountain fires in Spain. These incidents indicate that the accumulated CO<sub>2</sub> in the atmosphere should be reduced immediately through global cooperation to prevent the Earth from irreversible ruin [2]. CO<sub>2</sub> can be captured from ambient air or flue gas using several methods, such as absorption, adsorption [3-9], and membrane separation [10,11]. However, achieving a carbon-neutral society by 2050 is unlikely. Practically, based on their nucleophilic characteristics, amine solutions have been used to capture CO<sub>2</sub> [12-14]. Therefore, we evaluated practical methods for reducing atmospheric CO<sub>2</sub> using amines. We recently developed an innovative method for CO<sub>2</sub> fixation and storage using low concentrations of NaOH and CaCl<sub>2</sub> [16-19]. Certain improvements in our CO<sub>2</sub> fixation

method would contribute to the prevention of the climate crisis.

Although renewable energy sources, including solar radiation and wind, can reduce CO<sub>2</sub> emissions, these alternative systems require energy expenditure and may involve CO<sub>2</sub> production. Furthermore, they do not remove the accumulated CO<sub>2</sub> in the atmosphere or address the ongoing problem of CO<sub>2</sub> generation from exhaust gases and industrial sources. Thus, even if a carbon-neutral society could be immediately realized, the accumulated CO<sub>2</sub> in the atmosphere remains to be a problem. Therefore, it is important to develop immediate methods to reduce the current CO<sub>2</sub> level in the Earth's atmosphere. Geosequestration by injecting CO<sub>2</sub> into underground geological formations, such as oil fields, gas fields, and saline formations, has potential for CO<sub>2</sub> storage [20,21].

However, these methods are projects for the future.

### 2. Materials and Methods

#### 2.1. Chemicals

Reagent grade NaOH, CaCl<sub>2</sub>, ethanolamine, and MgCl<sub>2</sub> were purchased from Fujifilm Wako Pure Chemical Corp. (Osaka, Japan). Gaseous CO<sub>2</sub> was purchased from Keni's (Osaka, Japan).

## 2.2 Electrolysis

The electrolysis of the NaCl solution or seawater was performed using an electric current converter (SKY Top power) from Shines Tenakee Degen Co. Ltd. (Shines, China).

## 2.3. CO<sub>2</sub> Concentration Measurements

CO<sub>2</sub> was captured and released in polyethylene terephthalate (PET) bottles. Small volumes (5–10 mL) of solutions such as NaOH, seawater, and electrolyzed NaCl and seawater were poured into the PET bottles (300–600 mL). Subsequently, the CO<sub>2</sub> concentration within the bottles was measured under various conditions using CO<sub>2</sub> analysers, CX-6000 ((for high concentration; Riken Keiki, Co. Ltd. (Tokyo, Japan)), and XP-3140 ((for low concentration; Cosmo, Co., Ltd. (Tokyo, Japan))).

## 2.4. Precipitate Measurement

A small portion (1.5 mL) of the resulting solutions was poured into microcentrifuge tubes and centrifuged at 6200 rpm for 1 min to separate the precipitates. The weight of the wet precipitates was obtained by measuring the difference in the centrifuge tube

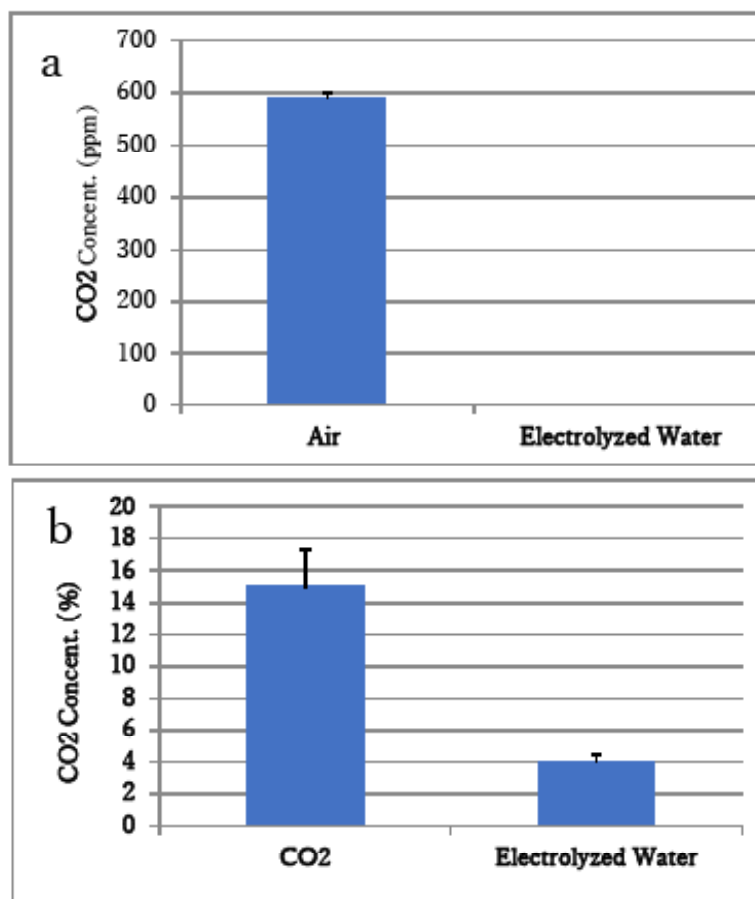
weight before and after centrifugation [16].

## 3. Results

### 3.1. Electrolysis of NaCl

Electrolysis converts H<sub>2</sub>O into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>) [16,17,22]. Herein, the NaCl solution was electrolyzed, and NaOH was eventually produced. The produced NaOH easily reacted with CO<sub>2</sub> in the solution and formed Na<sub>2</sub>CO<sub>3</sub> and NaHCO<sub>3</sub>. The carbonate ions, CO<sub>3</sub><sup>2-</sup> and HCO<sub>3</sub><sup>-</sup>, react with Ca<sup>2+</sup> and form CaCO<sub>3</sub> precipitates, existing as limestone in nature. Interestingly, CaCO<sub>3</sub> is a component of corals.

When the electrolyzed NaCl solution was treated with air bubbles in the vinyl chloride pipe, CO<sub>2</sub> (~600 ppm) in the atmosphere was completely captured in the solution (Fig. 1a). The air containing 12%–18% CO<sub>2</sub> in the same system reduced the CO<sub>2</sub> concentration to 4% when passed through the electrolyzed solution (Fig. 1b). These results demonstrate that the electrolyzed NaCl solution is extremely effective in capturing CO<sub>2</sub> in the air.



**Figure 1:** CO<sub>2</sub> absorption by electrolyzed NaCl solution. A 200 mL solution of the electrolyzed NaCl solution was poured into the vinyl chloride pipe (40-mm diameter), and air (a) or CO<sub>2</sub>-added air (b) was bubbled from the bottom of the pipe through the bubble former. The presented value is the mean of three to five experiments.

### 3.2. Electrolysis of Seawater

Seawater that contains many minerals, such as Na, Mg, and Ca, is preferred for electrolysis rather than a NaCl solution. Electrolyzing seawater yielded white precipitates because a large amount of  $Mg^{2+}$  readily formed magnesium hydrate,  $Mg(OH)_2$ , under alkaline conditions. In fact, 1.5 g of wet precipitate was obtained in 40 mL of electrolyzed solution. Bubbling  $CO_2$  in the supernatants after centrifuging the solution yielded no white precipitates. However, the addition of  $CaCl_2$  before bubbling  $CO_2$  yielded white precipitates of  $CaCO_3$ , suggesting that  $CaCO_3$  precipitation might have occurred during the electrolysis of seawater.

### 3.3. $Mg(OH)_2$ and $Ca(OH)_2$ Precipitations

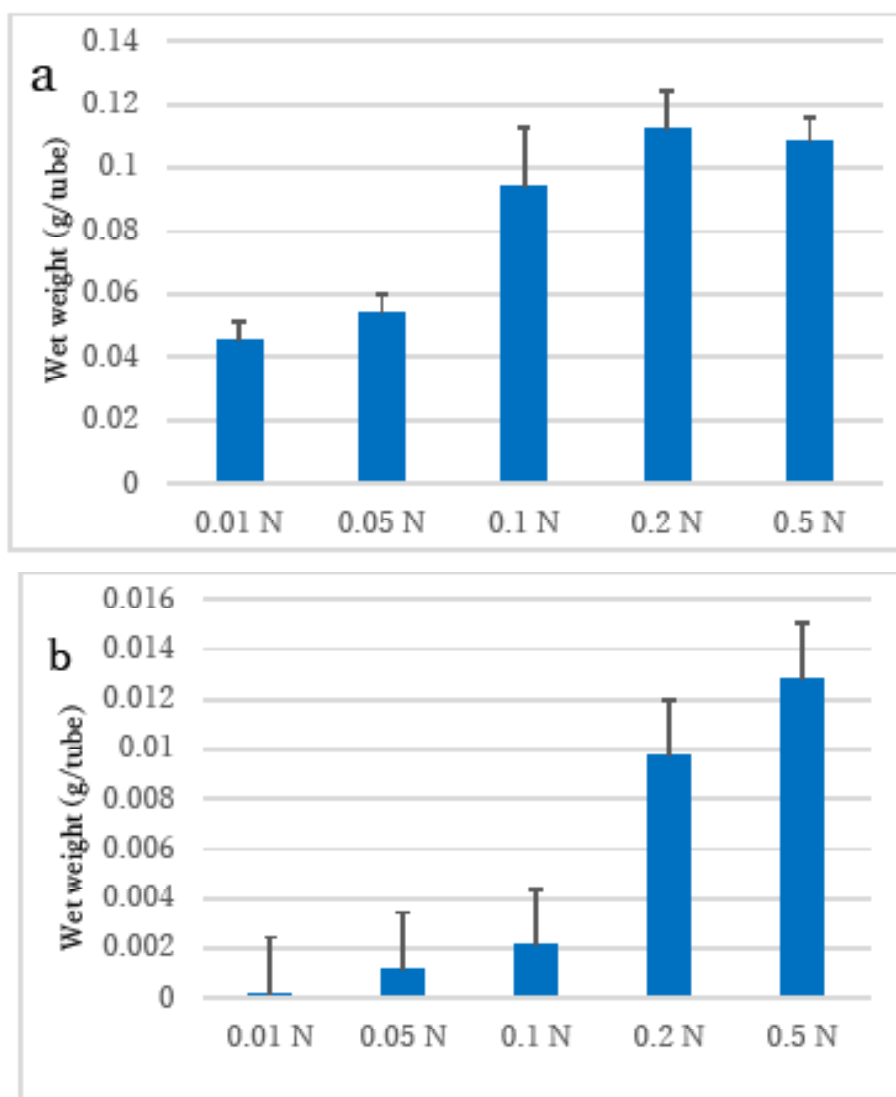
A  $MgCl_2$  solution was mixed with the NaOH solution to vary the pH levels. A small amount of  $Mg(OH)_2$  precipitates, which are semi-transparent white colloids, appeared at low NaOH concentrations of 0.01–0.05 M, while clear precipitates were observed at concentrations of  $>0.1$  M NaOH (Fig. 2).  $Mg(OH)_2$

precipitate formation plateaued at 0.1 M NaOH.

When  $CaCl_2$  and NaOH solutions were mixed to form varying pH levels, a clear white precipitate,  $Ca(OH)_2$ , was observed at a concentration of  $>0.2$  M NaOH (Fig. 2b). Apparently, the solution of concentration below 0.1 M NaOH did not show any precipitate because of  $Ca(OH)_2$ . This result is consistent with our previous results [16]. The critical concentration at which hydrate precipitation occurs differs for  $Mg^{2+}$  and  $Ca^{2+}$  (Fig. 2).

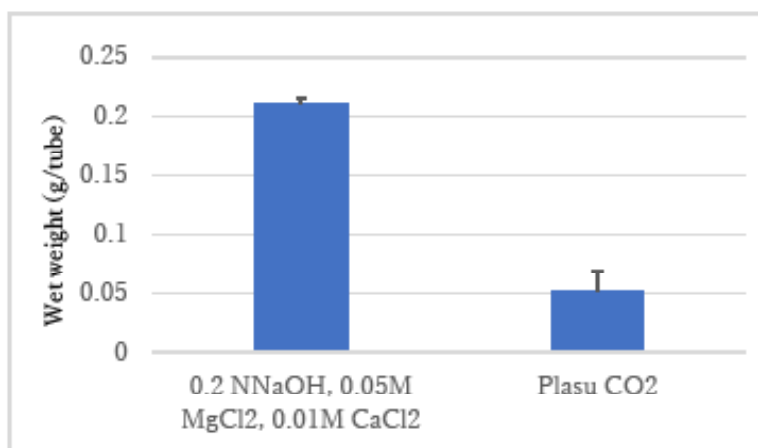
### 3.4. $CO_2$ Treatment of Authentic Seawater

The characterized mineral concentrations in seawater for  $Na^+$ ,  $Mg^{2+}$ , and  $Ca^{2+}$  are known to be 0.3, 0.05, and 0.01 M, respectively. Herein, their concentrations were 0.2, 0.05 and 0.01 M, respectively. At 0.2 M NaOH solution,  $Mg^{2+}$  was precipitated by its hydrate formation,  $Mg(OH)_2$ , as shown in Fig. 3. The precipitate was isolated by centrifuging at 3,000 rpm for 10 min. It was found that the precipitate was dominantly  $Mg(OH)_2$  with a small amount of  $Ca(OH)_2$  (Fig. 2b).



**Figure 2:**  $Mg(OH)_2$  and  $Ca(OH)_2$  precipitations at different NaOH concentrations. 0.5 M  $MgCl_2$  (a) or 0.5 M  $CaCl_2$  (b) was mixed with NaOH at different concentrations. The precipitates were separated via centrifugation at 6,200 rpm for 1 min. The weight of the wet precipitates is the mean of four to five experiments.

When the supernatant was treated with bubbling  $\text{CO}_2$ ,  $\text{Ca}^{2+}$  was precipitated as  $\text{CaCO}_3$  in the solution (Fig. 3). The  $\text{CaCO}_3$  precipitate could be observed clearly and was separated via centrifugation. However, the  $\text{CaCO}_3$  precipitate amount was considerably lesser than that of  $\text{MgCO}_3$  (Fig. 3). This result is reasonable based on their initial concentrations.



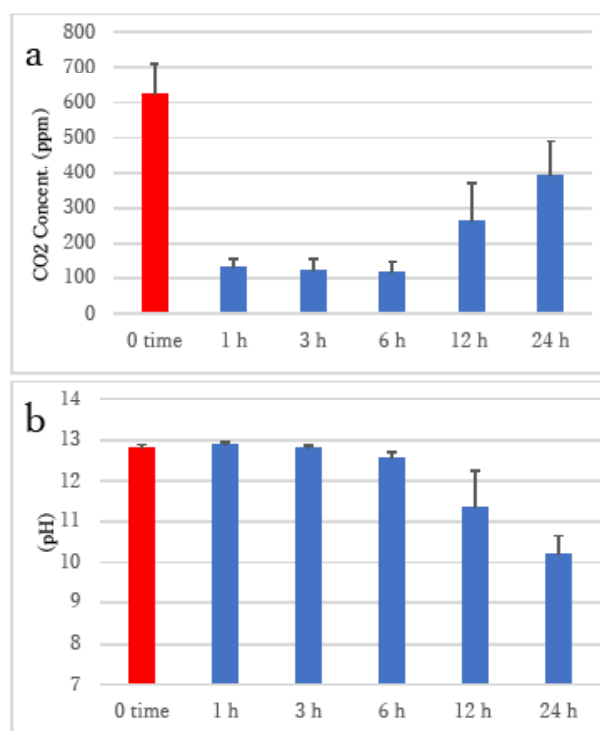
**Figure 3:**  $\text{Mg}(\text{OH})_2$  precipitation and further  $\text{CaCO}_3$  precipitation by  $\text{CO}_2$  bubbling. Authentic seawater comprising 0.2 M NaOH, 0.05 M  $\text{MgCl}_2$ , and 0.01 M  $\text{CaCl}_2$  was prepared, and the obtained  $\text{Mg}(\text{OH})_2$  precipitate was first separated via centrifugation at 6,200 rpm for 1 min. After separating  $\text{Mg}(\text{OH})_2$ ,  $\text{CO}_2$  gas was bubbled into the supernatant and the weight of the wet  $\text{CaCO}_3$  precipitate was measured. The presented value is the mean for five experiments.

### 3.5. $\text{CO}_2$ Treatment of Seawater

Seawater was alkalinized by adding solid NaOH to prepare a 0.2 M NaOH solution. Air was bubbled using a microbubble former stone at the bottom of the vinyl chloride pipe. The  $\text{CO}_2$  concentration in the air at the upper part of the pipe was measured at different times (Fig. 4a). The  $\text{CO}_2$  concentration decreased considerably from 630 to 120 ppm within 1 h. This reduction occurred in 5 min. The effect of the alkaline solution on  $\text{CO}_2$  capture continued until 6 h, and a slight effect persisted

even after 24 h (Fig. 4a).

The seawater pH value was changed at different  $\text{CO}_2$  bubbling times (Fig. 4b). The pH value was almost constant for 6 h of bubbling and then gradually decreased along with decreasing bubbling time. This pH change period correlated with the  $\text{CO}_2$  capture ability of the alkaline seawater (Fig. 4). Thus, the result indicates that  $\text{CO}_2$  capture depends on the solution pH.

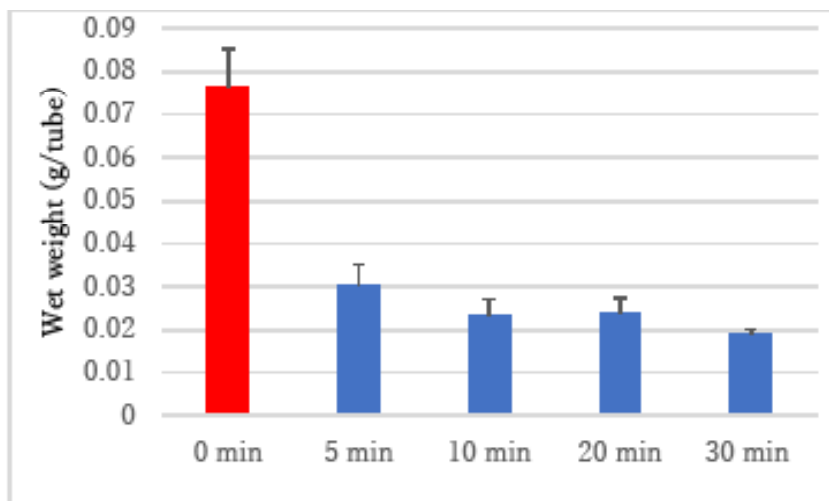


**Figure 4:**  $\text{CO}_2$  absorption by alkalinized seawater. Solid NaOH (1.6 g) was dissolved into 200 mL seawater in a 300 mL PET bottle. Air was bubbled from the PET bottle bottom, and  $\text{CO}_2$  concentration in the upper space of the bottle at different times (a) and the pH value (b) in the solution were measured. The presented value is the mean of four to five experiments.

### 3.6. Mg(OH)<sub>2</sub> Reacts with CO<sub>2</sub>

The reaction of Mg(OH)<sub>2</sub> with CO<sub>2</sub> is well characterized [22]. When Mg(OH)<sub>2</sub> is treated with CO<sub>2</sub> in an aqueous solution, mMgCO<sub>3</sub> Mg(OH)<sub>2</sub> nH<sub>2</sub>O is formed. Mg(OH)<sub>2</sub> was formed at 0.2 M NaOH in 0.05 M MgCl<sub>2</sub> solution, followed by CO<sub>2</sub>

bubbling for 30 s. The solution was centrifuged to separate the precipitates at different times. After 5 min, the precipitate amount considerably reduced and a slight reduction continued until 30 min (Fig. 5).

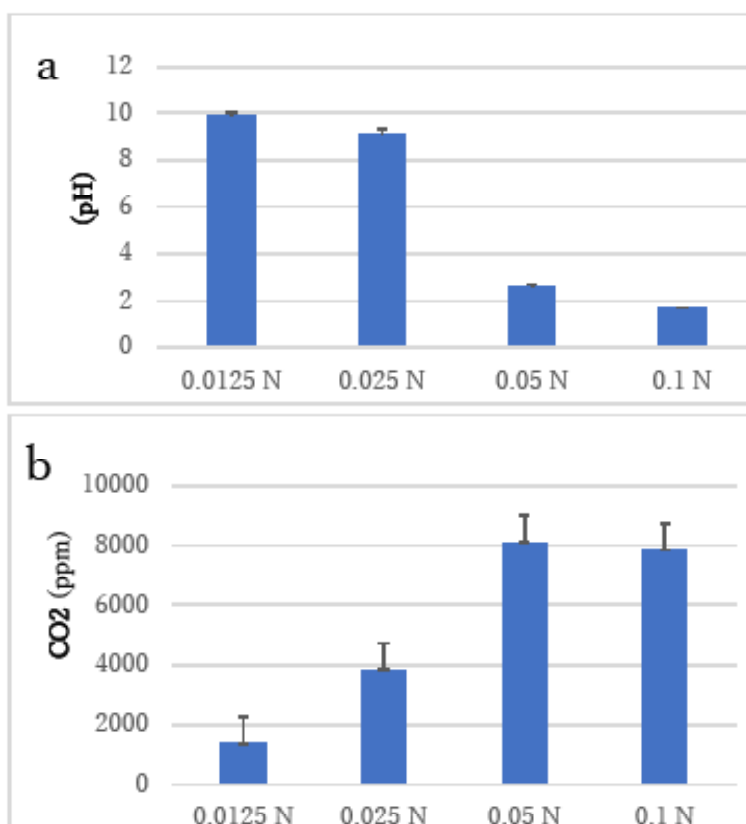


**Figure 5:** Reaction of Mg(OH)<sub>2</sub> with CO<sub>2</sub>. CO<sub>2</sub> gas was bubbled into 0.05 M Mg(OH)<sub>2</sub> solution for 30 s, and then the weight of the wet precipitates was measured. The presented value is the mean of four experiments.

### 3.7. Release of the Captured CO<sub>2</sub>

When 0.05 M NaOH solution bubbled with air was acidified by HCl addition, its pH reduced from 10.0 to 1.5 with increasing HCl addition (Fig. 6a). However, the CO<sub>2</sub> release from the bubbled

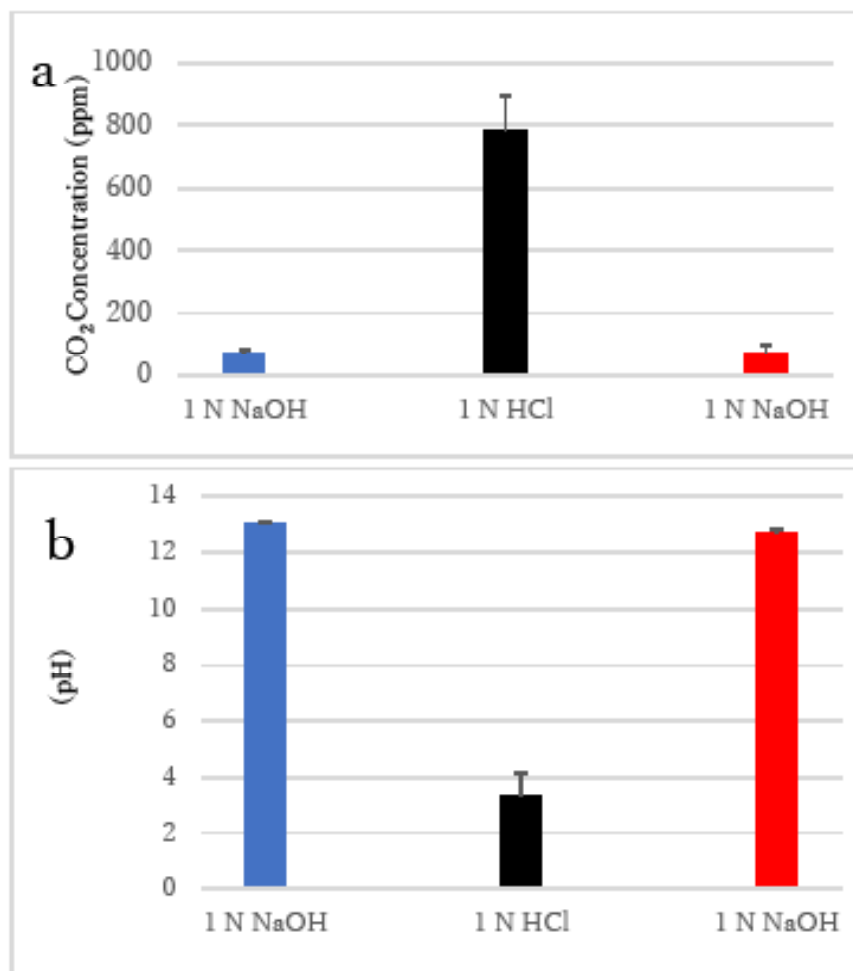
solution increased from 1,500 to 8,000 ppm with increasing HCl addition (Fig. 6b). Drastic CO<sub>2</sub> release was observed below pH 3.0. It plateaued at 0.05 M NaOH, indicating the pH and CO<sub>2</sub> release were inversely related.



**Figure 6:** Change of pH and CO<sub>2</sub> release by HCl addition. Air was bubbled into 200 mL of 0.05 M NaOH solution for 6 h, followed by adding different volumes of HCl to the bubbled solution. CO<sub>2</sub> concentration was measured after 5 min of HCl addition. The presented value is the mean of five experiments.

Mixing 0.1 N NaOH solution with CO<sub>2</sub> vigorously in a PET bottle reduced the CO<sub>2</sub> concentration to 75 ppm (Fig. 7a). This result was consistent with other studies [16]. Acidifying the CO<sub>2</sub>-treated solution by adding HCl released CO<sub>2</sub> and increased its concentration to 780 ppm in the bottle. Further, alkalizing the solution by NaOH addition reduced the CO<sub>2</sub> concentration to 75 ppm. In the first step, OH<sup>-</sup> and CO<sub>2</sub> formed CO<sub>3</sub><sup>2-</sup>, which was

subsequently converted to CO<sub>2</sub> and H<sub>2</sub>O by adding HCl in the second step. Finally, alkalizing with NaOH led to CO<sub>2</sub> capture by the solution. Adding CaCl<sub>2</sub> to the solution in the first step caused Ca<sup>2+</sup> and CO<sub>3</sub><sup>2-</sup> to react and precipitate CaCO<sub>3</sub>. Although CaCl<sub>2</sub> addition occurred at higher NaOH concentration of >0.2 N, Ca(OH)<sub>2</sub> precipitates were formed [17]. The pH values were 13.06, 3.38, and 12.76 at the three steps, respectively (Fig. 7b).

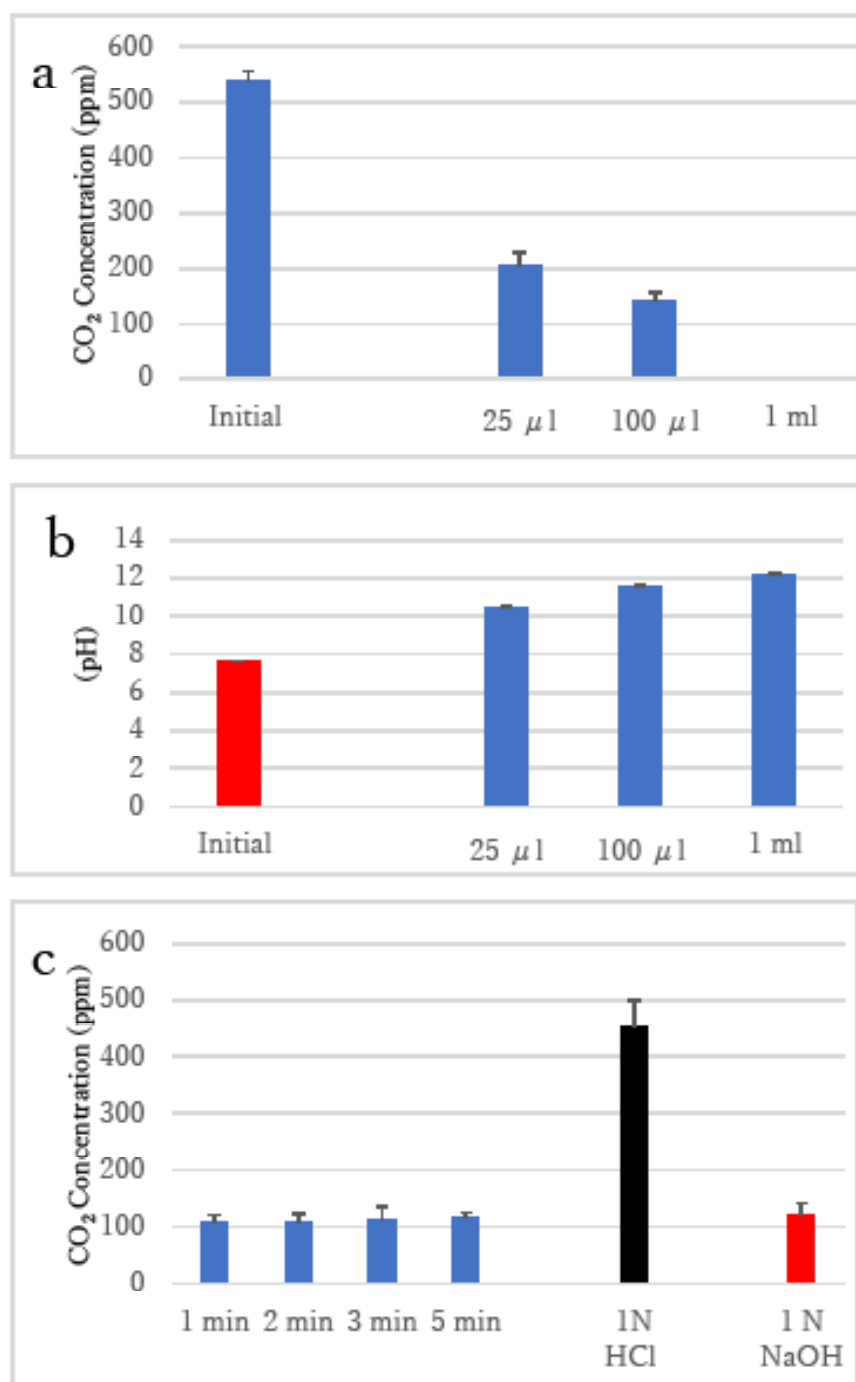


**Figure 7:** CO<sub>2</sub> capture, release, and recapture. 0.1 M (10 mL) NaOH solution was placed in the PET bottle. First, 0.5 mL of 1 N HCl followed by 0.5 mL of 1 N NaOH were added to the solution. CO<sub>2</sub> concentration in the PET bottle (a) and pH values (b).

### 3.8. CO<sub>2</sub> Capture by Ethanolamine and Release of Captured CO<sub>2</sub> by HCl.

Ethanolamine is a liquid compound that can capture CO<sub>2</sub> because of its fundamental characteristics [12-15]. The atmospheric CO<sub>2</sub> in the PET bottle was captured with different aqueous ethanolamine solution concentrations (0.25%, 1.0%, and 10% v/v). The initial CO<sub>2</sub> concentration was 504 ppm, which increased with increases in ethanolamine concentrations to 205, 140, and 0 ppm, respectively (Fig. 8a). The pH values of these solutions were 7.58, 10.43, 11.56, and 12.20, respectively (Fig. 8b). Once the ethanolamine solution was treated with CO<sub>2</sub>, CaCO<sub>3</sub> precipitation was observed with CaCl<sub>2</sub> addition (data not shown).

Atmospheric CO<sub>2</sub> was captured by the ethanolamine–water solution in a PET bottle, and the solution was acidified by adding HCl. The first ethanolamine treatment reduced the CO<sub>2</sub> concentration from 480 to 110–117 ppm (Fig. 8c). Acidifying the CO<sub>2</sub>-containing ethanolamine solution with HCl increased the CO<sub>2</sub> concentration to 453.3 ppm in the PET bottle. However, alkalizing the solution with NaOH reduced the CO<sub>2</sub> concentration to 120 ppm (Fig. 8c). This indicates that the interaction between CO<sub>2</sub> and ethanolamine is reversible and pH-based. The result regarding CO<sub>2</sub> capture and CO<sub>2</sub> release by HCl addition was consistent with results obtained from other amines, such as 2-amino-1-phenylethanol and polyethyleneimine (data not shown).

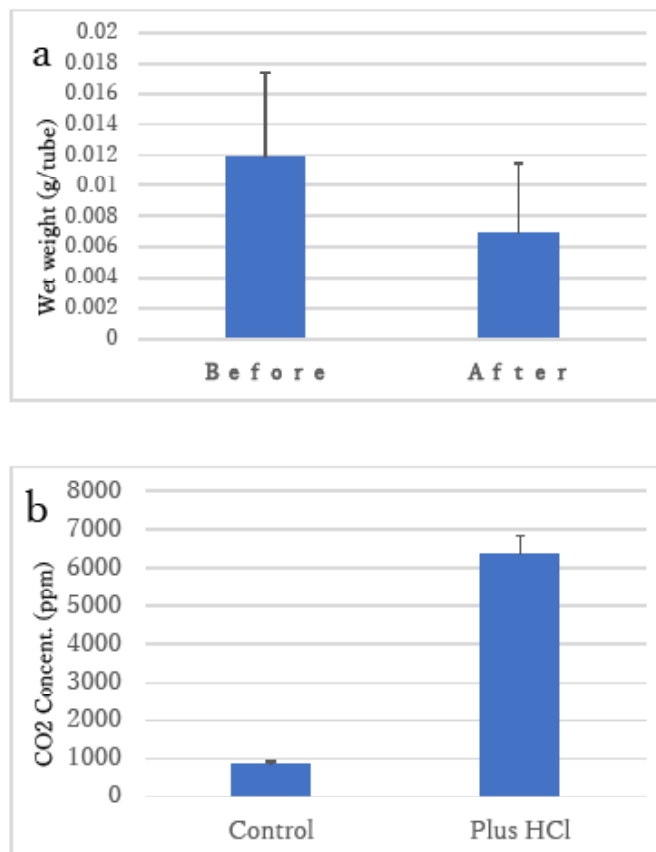


**Figure 8:** Atmospheric CO<sub>2</sub> capture by aqueous ethanolamine solution in the PET bottle. The ethanolamine concentrations were 25, 100, and 1,000 μL/10 mL H<sub>2</sub>O (a) the pH values at different ethanolamine concentrations (b) CO<sub>2</sub> captured by ethanolamine and then released by adding 4 mL of 1 N HCl, followed by the addition of 4 mL of 1 N NaOH (c).

### 3.9. Release of CO<sub>2</sub> from Electrolyzed Seawater

When seawater was alkalinized via electrolysis, Mg(OH)<sub>2</sub> precipitates were formed by the newly produced NaOH. This study demonstrated that the weight of the wet Mg(OH)<sub>2</sub> precipitates was reduced by treating the solution with CO<sub>2</sub> based on the formation of mMgCO<sub>3</sub> Mg(OH)<sub>2</sub> nH<sub>2</sub>O (Fig. 5). The same phenomenon was observed in case of electrolyzed seawater (Fig. 9a). The phenomenon of CO<sub>2</sub> bubbling of the electrolyzed seawater reduced the weight of the wet precipitates. This result is

also observed in case of authentic (Fig. 5) and natural seawaters (Fig. 9a). After the CO<sub>2</sub> bubbling of the electrolyzed seawater, the solution was acidified via HCl addition. The CO<sub>2</sub> captured in the electrolyzed seawater rapidly released into the air (Fig. 9b), indicating that CO<sub>2</sub> was released from CaCO<sub>3</sub> as well as from mMgCO<sub>3</sub> Mg(OH)<sub>2</sub> nH<sub>2</sub>O. The other precipitates, such as Ca(OH)<sub>2</sub> and MgCO<sub>3</sub>, might have converted into CO<sub>2</sub> and metal ions.

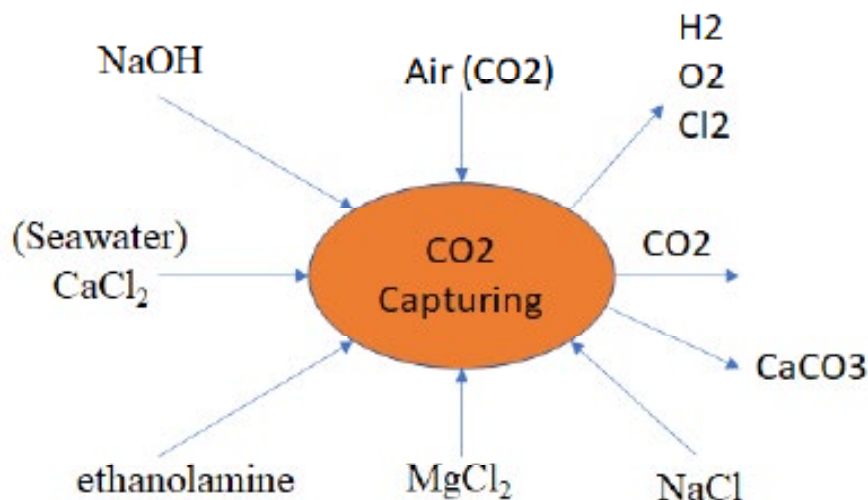


**Figure 9:**  $Mg(OH)_2$  precipitate and its  $CO_2$  complex in seawater and  $CO_2$  release by HCl addition. Solid NaOH (1.6 g) was dissolved into 200 mL of seawater, and then the weight of wet  $Mg(OH)_2$  precipitate was measured (a). Furthermore, the air was bubbled in the seawater for 3 h, and the wet weight of  $mMgCO_3 \cdot Mg(OH)_2 \cdot nH_2O$  was measured. After bubbling air into the solution, HCl was added to release  $CO_2$ .

#### 4. Applications of $CO_2$ Capturing in Waste Treatment Facility

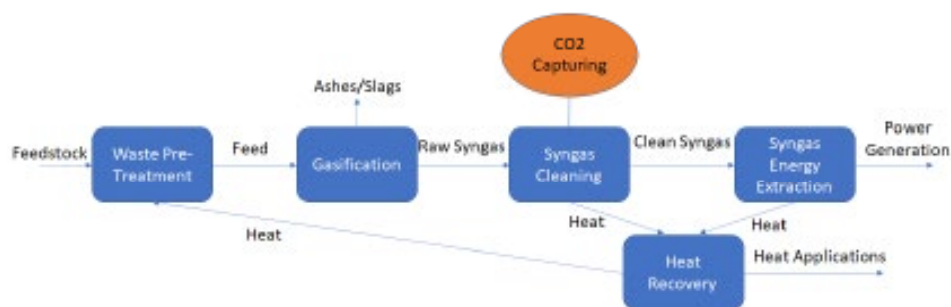
The proposed  $CO_2$  capturing technology will have potential deployment strategies in industrial and transportation applications and community infrastructures to support reduction of  $CO_2$  hence climate change. The proposed  $CO_2$  capturing technology is shown in Fig. 10, where input and output materials

are shown with benefits of multiple output products. One potential application is the integration within waste treatment facility. The proposed technology could be implemented as a standalone  $CO_2$  capturing unit with multiple products or as integrated with waste-to-energy gasification process where it will clean the syngas by removing  $CO_2$  for improved clean fuel and energy generation, as shown in Fig. 11.



**Figure 10:**  $CO_2$  Capturing Technology Conceptual Design





**Figure 11:** Waste-to-Energy Process Integration with CO<sub>2</sub> Capturing.

## 5. Discussion

Primitive life is considered to have appeared 3.6 billion years ago on the Earth. After a long biological evolution period, human beings became the most evolved organism based on genomic evolution and the five-fingernail functional cooperation [23]. Organisms developed a respiratory system, including the lung organ, in which CO<sub>2</sub> easily penetrates through tissue membranes, based on CO<sub>2</sub> characteristics. The diffusion force of CO<sub>2</sub> gas through plastic polymer membranes and bio membranes, including cellulose membranes, was considerably greater than that of O<sub>2</sub> or N<sub>2</sub> because of concentration differences [17,24]. Interestingly, the extensive use of fossil fuels, such as coal, oil, and natural gas, by the developing human civilization has induced the present climate change.

Charles Darwin made a statement based on his natural selection theory that “It is not the strongest of the species that survives, nor the most intelligent that survives. Rather, the one that is most adaptable to changes.” However, some humans believe in “the law of the jungle” and that humans are ranked at the top among all the organisms on the Earth. Humans are majorly responsible for the climate crisis. Therefore, our moral duty is to address the situation through global cooperation to protect our beautiful blue planet for future generations and other organisms that are not responsible for this climate crisis.

As mentioned above, amine solutions capture CO<sub>2</sub> from exhaust fumes [12-15]. Except for their pharmacological effects in vivo, the behaviour of amines is relatively obscure, although our body comprises amino derivatives, including polymers and monomers. The reason that CO<sub>2</sub> produced through the glucose metabolism is not captured in vitro and in vivo remains unknown. Industrial high-temperature treatments release the CO<sub>2</sub> captured by amine solutions. This study demonstrated that the neutralization of the amine–CO<sub>2</sub> solution could easily release CO<sub>2</sub> without thermal treatment. As our body does not accumulate CO<sub>2</sub>, our body fluids maintain a neutral pH. The CO<sub>2</sub> fixation and storage method converted CO<sub>2</sub> into CaCO<sub>3</sub>, limestone, and coral using low concentrations of NaOH and CaCl<sub>2</sub> [16]. This method converts NaHCO<sub>3</sub> and Na<sub>2</sub>CO<sub>3</sub>, the first compounds formed after the CO<sub>2</sub> and NaOH reaction, secondarily to CaCO<sub>3</sub> by CaCl<sub>2</sub> addition [16-19]. Therefore, this suggests that neutralizing or acidifying the NaHCO<sub>3</sub> and Na<sub>2</sub>CO<sub>3</sub> solutions can release pure CO<sub>2</sub> without thermal addition.

Space and artificial technology, including computer science,

have considerably developed during the present half-century. These technologies visualized natural phenomena, such as ozone-hole formation, glacier and polar ice reduction, and artificial reduction in rain forests by commercial tree cutting and agricultural land. Moreover, computer simulations can predict future climate changes based on various abovementioned phenomena. However, these modern technologies cannot capture the accumulated CO<sub>2</sub> in air; therefore, climate change remains unresolved. Thus, the most reliable method to practically improve climate change is capturing the accumulated CO<sub>2</sub> in the air. Furthermore, this method must be simple and cost-effective to develop practical plants worldwide.

NaCl solution or seawater electrolysis requires electric power to produce NaOH while producing H<sub>2</sub> and Cl<sub>2</sub>. Therefore, the generated H<sub>2</sub> can be used in the fuel battery to supply electric power and as a clean energy source [25,26]. Cl<sub>2</sub> can be used as reaction materials for other chemical compounds. Moreover, the final products are CaCO<sub>3</sub>, a component of limestone, and NaCl via Na<sub>2</sub>CO<sub>3</sub> and NaHCO<sub>3</sub> solutions. NaCl can be used as a starting material for electrolysis. This fact shows that sequential reactions form a whole cycle. It confirms that the system based on NaCl or seawater electrolysis capturing the accumulated CO<sub>2</sub> in the air can help mitigate climate change. Therefore, this system can achieve the sustainable development goals (SDGs).

Only the method that uses amines has been established to capture CO<sub>2</sub> from the exhaust gases [12-15]. Toxic organic solvents are a major reason why this amine method is not used worldwide. Furthermore, thermal treatment is necessary to release the captured CO<sub>2</sub> from the amine–CO<sub>2</sub> complexes. This process eventually induces amine degradation, which requires regeneration for further use. However, our developed method is based on the use of NaOH and CaCl<sub>2</sub>, which are inorganic, water soluble, and heat stable [16]. Both compounds are cost-effective, although a high concentration of NaOH is extremely toxic. In the developed method, however, low NaOH concentrations of <0.2 M should be used to prevent CaCO<sub>3</sub> formation from Ca(OH)<sub>2</sub> formation [16]. Under this condition, only CaCO<sub>3</sub>, which is harmless, is produced. Eventually, this method can convert CO<sub>2</sub> to naturally stable and harmless CaCO<sub>3</sub> limestone without requiring complex and expensive constructions. The fact that a large amount of pure CO<sub>2</sub> can be concentrated in the air in which CO<sub>2</sub> concentration is extremely low by our developed CO<sub>2</sub> fixation and storage method is crucial for future CO<sub>2</sub> usage. Further, CO<sub>2</sub> is a source of other chemical compounds

[27,28]. Conversely, direct air capture (DAC) technologies are challenging to improve in three areas, contactor, sorbent, and regeneration, to drive down the cost [29].

## 6. Conclusions

The electrolysis of NaCl or seawater produces NaOH, which reacts with CO<sub>2</sub> and yields carbonate compounds with metal ions such as Ca<sup>2+</sup> and Mg<sup>2+</sup>. CaCO<sub>3</sub>, a limestone component, was produced by adding CaCl<sub>2</sub> to the electrolyzed NaCl solution via CO<sub>2</sub> bubbling. Furthermore, using seawater rather than NaCl solution, CaCO<sub>3</sub> could be produced without adding CaCl<sub>2</sub>. Thus, the system for CO<sub>2</sub> fixation based on NaCl or seawater electrolysis fits the SDGs.

## Acknowledgments

The authors thank Rd. Kazumi Akimoto of Dokdo Medical University, Tochigi, Japan, for his arrangement of experimental apparatuses, Mr. Studio Saroya of Union Shokai, Gunma, Japan, for his arrangement of experimental apparatuses, and Ena go (<https://www.enago.jp>) for editing a draft of this manuscript. The authors thank lab members in the Smart Energy Systems Lab (SESL) at Ontario Tech University, Canada.

## Author Contributions

K.S. conceived, designed, and conducted the study and wrote the manuscript.

H.G. analysed, defined energy and process models, validated, and edited manuscript.

## Competing Financial Interests

The author declares that the present data have been used to support an application to the Japan

Patent Office (JP2022-199049, JP2023-7321 and PCT/JP2023/021554)

## References

1. Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., ... & Foley, J. A. (2009). A safe operating space for humanity. *nature*, 461(7263), 472-475.
2. Sorimachi, K. (2022). Human and earth evolution through CO<sub>2</sub>: Perspective for climate crisis. *J. Biomed. Res*, 3, 11-7.
3. Lv, B., Guo, B., Zhou, Z., & Jing, G. (2015). Mechanisms of CO<sub>2</sub> capture into monoethanolamine solution with different CO<sub>2</sub> loading during the absorption/desorption processes. *Environmental science & technology*, 49(17), 10728-10735.
4. Choi, S., Drese, J. H., & Jones, C. W. (2009). Adsorbent materials for carbon dioxide capture from large anthropogenic point sources. *ChemSusChem: Chemistry & Sustainability Energy & Materials*, 2(9), 796-854.
5. Jones, C. W. (2011). CO<sub>2</sub> capture from dilute gases as a component of modern global carbon management. *Annual review of chemical and biomolecular engineering*, 2, 31-52.
6. Nandi, M., Okada, K., Dutta, A., Bhaumik, A., Maruyama, J., Derks, D., & Uyama, H. (2012). Unprecedented CO<sub>2</sub> uptake over highly porous N-doped activated carbon monoliths prepared by physical activation. *Chemical Communications*, 48(83), 10283-10285.
7. Hajra, S., & Biswas, A. (2020). Efficient chemical fixation and defixation cycle of carbon dioxide under ambient conditions. *Scientific reports*, 10(1), 15825.
8. Hiraide, S., Sakanaka, Y., Kajiro, H., Kawaguchi, S., Miyahara, M. T., & Tanaka, H. (2020). High-throughput gas separation by flexible metal-organic frameworks with fast gating and thermal management capabilities. *Nature communications*, 11(1), 3867.
9. Modak, A., Nandi, M., Mondal, J., & Bhaumik, A. (2012). Porphyrin based porous organic polymers: novel synthetic strategy and exceptionally high CO<sub>2</sub> adsorption capacity. *Chemical Communications*, 48(2), 248-250.
10. Qiao, Z., Zhao, S., Wang, J., Wang, S., Wang, Z., & Guiver, M. D. (2016). A highly permeable aligned montmorillonite mixed-matrix membrane for CO<sub>2</sub> separation. *Angewandte Chemie*, 128(32), 9467-9471.
11. Yang, Y., Guo, Y., O'Brien, A. M., Lins, T. F., Rochman, C. M., & Sinton, D. (2020). Biological responses to climate change and nanoplastics are altered in concert: full-factor screening reveals effects of multiple stressors on primary producers. *Environmental Science & Technology*, 54(4), 2401-2410.
12. Lee, J. J., Yoo, C. J., Chen, C. H., Hayes, S. E., Sievers, C., & Jones, C. W. (2018). Silica-supported sterically hindered amines for CO<sub>2</sub> capture. *Langmuir*, 34(41), 12279-12292.
13. Creamer, A. E., & Gao, B. (2016). Carbon-based adsorbents for postcombustion CO<sub>2</sub> capture: a critical review. *Environmental science & technology*, 50(14), 7276-7289.
14. Ko, Y. G., Lee, H. J., Oh, H. C., & Choi, U. S. (2013). Amines immobilized double-walled silica nanotubes for CO<sub>2</sub> capture. *Journal of Hazardous Materials*, 250, 53-60.
15. Gentry, P. R., House-Knight, T., Harris, A., Greene, T., & Campleman, S. (2014). Potential occupational risk of amines in carbon capture for power generation. *International archives of occupational and environmental health*, 87, 591-606.
16. Sorimachi, K. (2022). Innovative method for CO<sub>2</sub> fixation and storage. *Scientific Reports*, 12(1), 1694.
17. Sorimachi, K. (2021). Epoch-Making Discovery for CO<sub>2</sub> Characteristics: "Pseudo Osmosis" in the Gas Phase.
18. Sorimachi, K. (2022). Novel Method for CO<sub>2</sub> Fixation and Storage Preventing Climate Crisis: an "Artificial Forest" Model. *Petro Chem Indus Intern*, 5 (1), 01, 4, 1-4.
19. Sorimachi, K. (2022). Novel Method for CO<sub>2</sub> Fixation and Storage Preventing Climate Crisis: an "Artificial Forest" Model. *Petro Chem Indus Intern*, 5 (1), 01, 4, 1-4.
20. Eccles, J., Pratson, L. F., & Chandel, M. K. (2012). Effects of well spacing on geological storage site distribution costs and surface footprint. *Environmental science & technology*, 46(8), 4649-4656.
21. Carroll, S. A., Iyer, J., & Walsh, S. D. (2017). Influence of chemical, mechanical, and transport processes on wellbore leakage from geologic CO<sub>2</sub> storage reservoirs. *Accounts of Chemical Research*, 50(8), 1829-1837.
22. Xie, H., Liu, T., Hou, Z., Wang, Y., Wang, J., Tang, L., ... & He, Y. (2015). Using electrochemical process to mineralize CO<sub>2</sub> and separate Ca<sup>2+</sup>/Mg<sup>2+</sup> ions from hard water to produce high value-added carbonates. *Environmental Earth*

- 
- Sciences, 73, 6881-6890.
23. Sorimachi, K. (2021). Study on ultimate human evolution: Cooperation of cerebral and five-fingernail development. *New Visions in Biological Science Vol. 3*, 50-64.
24. Araújo, T., Bernardo, G., & Mendes, A. (2020). Cellulose-based carbon molecular sieve membranes for gas separation: a review. *Molecules*, 25(15), 3532.
25. Hsu, S. F., Rommel, S., Eversfield, P., Muller, K., Klemm, E., Thiel, W. R., & Plietker, B. (2014). A rechargeable hydrogen battery based on Ru catalysis. *Angewandte Chemie International Edition*, 53(27), 7074-7078.
26. Wei, D., Sang, R., Moazezbarabadi, A., Junge, H., & Beller, M. (2022). Homogeneous carbon capture and catalytic hydrogenation: toward a chemical hydrogen battery system. *JACS Au*, 2(5), 1020-1031.
27. Hunt, A. J., Sin, E. H., Marriott, R., & Clark, J. H. (2010). Generation, capture, and utilization of industrial carbon dioxide. *ChemSusChem: Chemistry & Sustainability Energy & Materials*, 3(3), 306-322.
28. Guil-López, R., Mota, N., Llorente, J., Millán, E., Pawelec, B., Fierro, J. L. G., & Navarro, R. M. (2019). Methanol synthesis from CO<sub>2</sub>: a review of the latest developments in heterogeneous catalysis. *Materials*, 12(23), 3902.
29. Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. *Iscience*, 103990.

**Copyright:** ©2023 Kenji Sorimachi, et al . This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.