Epoch-Making Discovery for CO₂ Characteristics: “Pseudo Osmosis” in the Gas Phase

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Research Article

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Abstract

Recently, unprecedented torrential rains have deluged the globe, resulting in disastrous floods. These disasters were caused by climate changes because of an increase in carbon dioxide (CO₂) concentration in the atmosphere since the industrial revolution. Therefore, atmospheric accumulation of CO₂ should be reduced to avoid a future climate crisis. Many methods to fix CO₂ have been developed, but a practical method has not been established, except for the method using amines based on moderate plant constructions. However, the membrane method has not yet been established because of the conflicting relationship between penetrability and specificity, although membrane technology can be used for CO₂ separation. Epoch-making discoveries for CO₂ characteristics have been presented as follows: 1) the high penetrability of CO₂ in the gas phase caused “pursued osmosis” against polymer elasticity; 2) highly penetrable CO₂ passed through polymer membranes such as authentic polymers and natural cellulose, whereas neither O₂ nor N₂ penetrates these polymers examined; 3) CO₂ is absorbed by plastics; 4) H₂ and CH₄ gases penetrate through polymer membranes, but their penetration was completely blocked in the presence of water; and 5) using a polytunnel made of polymer sheets (an artificial forest or positive green house), which allows CO₂ penetration, instead of hard chamber, steel, or plastic could be cost effective. Therefore, polymer membranes could be practically and economically useful for CO₂ separation from the exhaust gas and atmosphere.

Background

According to recent news, we do not doubt that climate change has progressed throughout the globe. Torrential rains caused severe flooding in Europe. Recently, in Japan, the meteorological agency has issued several warnings about severe torrential rains that strike once every 50 or 100 years, whereas severe debris flows attacked mountain areas every year. Based on scientific evidence for the relationship between global temperature, atmospheric CO₂ increases and hydroclimate changes¹⁻³, the intergovernmental panel on climate change concluded on August 9th, 2021, that climate change has been caused by human activities that have produced carbon dioxide (CO₂) since the industrial revolution⁴.

None denying that atmospheric CO₂ concentrations on Earth have increased since the industrial revolution began ~200 years ago, with the invention of steam engines using fossil coal as fuel and internal combustion engines using oil and our present developed civilization has owed to these technical inventions. However, we have paid little attention to the effect of increased atmospheric CO₂ concentration for a long time, while the young generation represented by a Swedish high school student, Greta Thunberg, led to climate change activities “Friday for Future” events as global movements. Unfortunately, this movement would not reach all people on the planet. One of the reasons is our high tolerance of CO₂ concentration in our daily lives. The atmospheric CO₂ concentration in a house room is ~400 ppm, but it easily doubles in the presence of several persons in the same room without ventilation.

Even under high CO₂ concentrations of ~1,000 ppm for a certain time in a confined space, our lives do not show any abnormal symptoms. Eventually, many people would be insensitive to a small increase in atmospheric CO₂ concentration, although this small change can be induced climate change crises on Earth.

The greenhouse effect of methane is much significant than that of CO₂, and climate change has resulted in thawing permafrost followed by methane emission in Siberia⁵⁻⁷. In addition, as temperature rise activates microorganisms' activity, methane emission might be naturally accelerated without human activities⁸⁻¹⁰. Indeed, methane has been currently produced from biomass materials by microorganisms^{11,12}.

The 7th G summit was held in Cornwall, England, on June 12–13, 2021, with climate change being one of the main themes. Electric vehicles have been developed and used instead of ordinary automobiles using gasoline, to reduce atmospheric CO₂ concentrations. While electric vehicles do not exhaust CO₂ directly into the atmosphere, the current electricity generated by renewable energy is insufficient to power electric vehicles. However, hydrogen vehicles have been developed, although the cost is expensive. Indeed, hydrogen usage does not exhaust CO₂; however, its production process using brown coal and high-temperature water produces a significant amount of CO₂, except for the electrolysis of water.

CO₂ can be captured from the atmosphere or from flue gas via several techniques, including absorption¹³, adsorption¹⁴⁻²⁰, and membrane gas separation^{15,21}. Absorption with amines is currently the dominant technology, while membrane and adsorption processes are still in the developmental stages with the construction of primary pilot plants anticipated in the future. Synthetic membranes are useful for desalination, dialysis, sterile filtration, food processing, dehydration of air, and other industrial, medical, and environmental applications because of their energy requirements, compact design, and mechanical simplicity. In addition, biopolymer cellulose membrane can be used instead of synthetic membranes because they have similar characteristics²²⁻²⁴. Recently, we developed a novel method for CO₂ fixation and storage²⁵. This method is based on simple chemical reactions involving NaOH and CaCl₂. Using low concentrations of these chemicals prevented the formation of Ca (OH)₂ in the absence of CO₂, but resulted in CaCO₃ formation in the presence of CO₂ bubbling. Note that the products of our developed method are CaCO₃ and NaCl, which naturally exist as coral or limestone. Moreover, CO₂ fixation could be achieved without any external addition of chemicals using seawater instead of NaCl electrolysis and CaCl₂. We proposed a large chamber comprising spray nozzles to fix CO₂ efficiently by mists or droplets of the NaOH solution²⁵. Using a polytunnel made of polymer sheets (an artificial forest), which allows CO₂ penetration, instead of the chamber could be cost effective. CO₂ storage, geo-sequestration by injecting CO₂ into underground geological formations, such as oil fields, gas fields, and saline formations, has been suggested^{26,27}, although these systems are still projects for the future. However, the proposed method can achieve both CO₂ fixation and storage²⁵ simultaneously. This study contributes membrane technology to separate CO₂ from other gases such as O₂, N₂, H₂, and CH₄.

Materials And Methods

Chemicals. NaOH and CaCl₂ were purchased from Wako Jyunyaku Co., Ltd. (Tokyo, Japan). Seawater was obtained from. CH₄ gas was purchased from Asone (Tokyo, Japan). Plastic bottles, light density polyethylene (LDPE), high-density polyethylene (HDPE), Teflon, and polycarbonate, plastic sheets, such as polyethylene mesh, 92-#18, and nylon mesh, PA-2 (6 μm) were purchased from Asone (Tokyo, Japan). The rubber plates (KGR 1100 and KGR 3100) were products of Iteck, Co., Ltd. (Tokyo, Japan). Seamless cellulose dialysis membrane tube (Visking tube), type 24/32, and was purchased from Sanko Junyaku, Co., Ltd. (Tokyo, Japan). Party latex balloons (~12 in) were obtained from Daiso (Tokyo Japan). Polyurethane balloons (0.02 mm) were purchased from Sagami Gum Co., Ltd. (Sagamihara, Kanagawa, Japan).

Methods.

H₂ gas was prepared with electrolysis of seawater with an electric current converter, SKY Top power, Shinsen Tentakugen Dengen Co. Ltd., (Shinsen, China).

CO₂ concentration measurement.

To measure the CO₂ emitted by plastic bottles, sheets, and rods, they were placed in 450 ml glass bottles which were filled with cooling-carbonated beverages, CO₂ saturated water, or CO₂ gas, under various conditions. After washing, plastic materials and a bottle inside were left in the room or the temperature-controlled box. CO₂ analyzers, CX-6000 (for high concentration), Riken Keiki, Co., Ltd., (Tokyo, Japan), and XP-3140 (for low concentration), Cosmo, Co., Ltd., (Tokyo, Japan), were used to measure the concentration of CO₂ released from the plastic materials. In some experiments, CO₂ concentrations inside bags were directly analyzed.

Gas volume measurements.

Bags or swelled wraps were sunken into water containers and the volumes of overflowed water were measured to estimate their volume. In some experiments, CO₂ gas volume in the graduated cylinder was directly observed, and the CO₂ volume in the experiments using syringes was also directly observed.

CO₂ saturated water.

Water (1 L) was mixed with CO₂ gas (1 L) in a PET bottle (2 L) and shaken vigorously by hand for 30 s. The bottle was completely dented after the water and CO₂ were mixed. After opening the bottle, CO₂ was bubbled into the CO₂ saturated water.

Statistical analysis.

Statistic calculations via the t-test were performed using Windows 10. Values of $p < 0.05$ and $p < 0.01$ were considered significant and highly significant, respectively.

Results

CO₂ absorption in plastics.

Polyethylene terephthalate (PET) bottles are commonly used to store liquids, such as water, carbonated beverages, seasonings, and liqueurs, in daily life. In this study, we found that the empty PET bottle that was used for cooling-carbonated beverages, such as Coca-Cola, remained a moderate amount of CO₂ inside the bottle. CO₂ was removed from the bottle after washing the empty bottle three times with fresh water (Additional Data Figure 1a). However, after leaving the washed bottle in the room, CO₂ which was released from the plastic was significantly detected (Additional Data Figure 1b), and CO₂ release was much faster at 50°C than at 20°C.

CO₂ release from the plastic bottles made of high-density polyethylene (HDPE), low-density polyethylene (LDPE), polycarbonate, and polytetrafluoroethylene (Teflon), were examined. These plastic bottles absorbed CO₂ followed by CO₂ release, which was pretreated with a carbonated beverage or CO₂ gas, (Additional Data Figure 2a). Although carbonated beverages containing various chemical substances, except for CO₂ showed the same effect as CO₂ gas in the pretreatment. Only PC showed much higher CO₂ absorption with CO₂ gas than that with a carbonated beverage. Other plastic materials, such as polyethylene mesh, nylon mesh, acrylic rods, and natural gum plates, were examined. These materials also absorbed and emitted CO₂ (Additional Data Figure 2b). Furthermore, high CO₂ absorption and release were observed with a grooved natural gum plate, and very high CO₂ absorption was observed in it treated with CO₂ gas.

CO₂ release through the latex membrane.

The medical glove was filled and expanded with CO₂ gas and then left in the room. The volume of the expanded latex glove time-dependent decreased, reaching half of its initial volume after 2 h (Fig. 1a) and ~10% after 6 h. This demonstrates that CO₂ penetrates through the latex membrane. Using cellulose tube (Visking tube), CO₂ release through a cellulose membrane was considerably faster than that through a latex membrane (Fig. 1b). Furthermore, different thicknesses of polyethylene bags are used. CO₂ release was significantly faster through a thin polyethylene membrane bag than through a thick membrane (Fig. 1c).

Volume increase by CO₂ absorption.

Instead of plastic sheets, two types of bubble wraps were used: a single layer bubble wrap with bubbles attached to a single polyethylene film (bubble wrap I), and another with bubble was sandwiched between two polyethylene films (bubble wrap II). Before CO₂ treatment, the bubble wraps were easily inserted into

glass bottles, but the babble wraps treated with CO₂ resisted being removed from the glass bottle. This means that the volume of the babble wraps increased with CO₂ treatment. Indeed, the volume of the babble wraps increased significantly (Fig. 2, upper panel). However, when the swelled babble wraps were left in the room, the swollen condition returned to its original volume.

When a latex balloon inflated with air and sealed was left in a glass bottle filled with 80% CO₂ for 4 h, it swelled (Fig. 2, lower panel, a and b). However, the empty balloon without air did not swell even in the presence of high CO₂ concentrations. Using a latex glove, the consistent result was obtained (Fig. 2, lower panel, c and d).

CO₂ absorption at low concentrations.

To investigate whether CO₂ absorption occurs at low CO₂ concentrations, polyethylene bags prefilled with air without CO₂ were left in a room. Then, CO₂ concentration in the bags was measured at different time periods. CO₂ concentration equilibrium between the inside and outside bags was achieved after 6 h.

When different thicknesses of polyethylene bags were examined, CO₂ was absorbed time-dependently (Fig. 3), and CO₂ absorption depended on the thickness. The polyurethane balloon and cellulose tube produced consistent results (Visking tube).

CO₂ absorption and release.

When the knotted Visking tube with air inside was left in the glass bottle containing 100% CO₂, the tubing swelled and its volume increased to ~2.5 times. When the Visking tube was left in the room, the volume returned to its original volume. Following that, the original volume was maintained (Fig. 4a). The same phenomenon was observed with a latex balloon (Fig. 4b). These results show that CO₂ diffusion occurred in the presence of plastic elasticity because of a flow from high concentration to low concentration. However, the fact that the bag volume returned to the original volume and was maintained after that shows the simultaneously contained air did not diffuse outside the cellulose tube (Visking tube).

CO₂ penetration through a membrane in water.

Latex balloons were inflated with CO₂ gas and then immersed into water. CO₂ gas penetrated through a latex membrane and diffused into the water along with decreasing their volumes (Fig. 5a). After 4 h, the volume reduced to ~40% of the initial state.

Polyethylene bag containing CO₂ saturated water was inserted into a glass bottle of water and then left in a room. The same amount of CO₂ was identified in both phases of the membrane, inside and outside (Fig. 5b). Thus, CaCO₃ precipitation based on a chemical reaction revealed that CO₂ that was contained in the saturated water penetrated through a polyethylene membrane into the fresh water.

CO₂ absorption into water.

The graduated glass or plastic cylinder containing CO₂ gas was immersed in water stored in a water bath or refrigerator. Three types of water were prepared as follows. Milli-Q water (pure water), city water, and seawater. CO₂ gas volume was measured at several periods. Among the three water samples, CO₂ gas volume in the graduated cylinders decreased time-dependently (Figs. 6a and 6b). CO₂ gas absorption into the seawater was significantly slower than the other two types of water. This salt effect on CO₂ absorption into water depended on the temperature, and the absorption was significantly reduced at 55°C. This temperature effect on CO₂ absorption in water differs from the previously reported result²⁸. However, using a 12-ml plastic syringe instead of the cylinder, CO₂ gas absorption increased drastically at 4°C compared to 55°C (Fig. 6c). The latter result is consistent with the currently reported result²⁸.

H₂ and CH₄ penetration through a polymer membrane.

Polyethylene, polyurethane, and cellulose membrane bags were used. The polyurethane membrane passed H₂ gas more efficiently than the other membranes, but their membrane thicknesses differed (Additional Data Figure 3a). When CH₄ gas was used instead of H₂ gas, similar results as H₂ gas were observed, and CH₄ gas released from these three membrane bags was slower than that of H₂ gas. When these three types of polymer membrane bags containing H₂ or CH₄ gases were immersed in water, H₂ and CH₄ gases were unable to pass through the polymer membranes. However, latex balloons were expanded with CO₂ and then immersed in water. The balloon volume reduced time-dependently (Additional Data Figure 3a). This result shows that CO₂ can penetrate through the rubber membrane in the presence of clear water. Thus, the combination of polymer membranes and water can separate CO₂ from H₂ or CH₄. To my knowledge, there is no perfect system which can separate CO₂ from these gases, although some experiments have been performed^{29,30}.

CO₂ absorption and release by plants through PE bags.

A top part of Taiwan pineapple with moderate number of leaves has been immersed into city water contained in a glass bottle for almost half a year. During this period, the number of leaves increased along with root development (Additional Data 4a). To determine whether CO₂ metabolisms can be detected, the pineapple planter was inserted into a PE bag of 0.005-mm thickness for 4 h in the room (Additional Data Figure 4b). CO₂ concentration was reduced to 200 ppm from ~500 ppm. Conversely, its CO₂ concentration increased to almost 2,000 ppm for 4 h in a corrugated card-box.

Similarly, cyclamens planted on the soil were used instead of pineapple, because cyclamen planters are commercially available (Additional Figure 4c). When cyclamen planters were left in the corrugated card-box, CO₂ significantly increased in the PE bag after 1 h, reaching a plateau level of ~1800 ppm (Fig. 7a). Contrary, CO₂ concentration reduced by almost 200 ppm after 2 h in the presence of light.

Cut cycad leaves were used instead of a whole plant (Additional Data Figure 4d). The consistent CO₂ metabolisms were obtained as observed by cyclamens (Fig. 7b). Using cut small camellia branches and

“yatsude” plant leaves (Additional Data Figure 4d), similar CO₂ absorption and release were observed with and without light, respectively. However, the cut leafstalk of “yatsude” plant did not absorb CO₂ in the presence of light (data not shown).

In the system which uses PE bags of 0.005-mm thickness (25 × 34 cm), the plateau CO₂ concentrations in the presence of whole plants or leaves may converge at ~200 ppm and 2,000 ppm with and without light, respectively. These values are based on the balance between CO₂ metabolisms of plants and CO₂ penetrability through PE membranes.

Discussion

Generally, plants absorb CO₂ from the atmosphere and release O₂ during photosynthesis by chlorophyll using CO₂, H₂O, and light. However, all organisms release CO₂ to maintain their lives, which require energy daily, and this metabolism is independent of light. Therefore, when the CO₂ production exceeds CO₂ absorption in plants, the organisms are CO₂ producers. Although it is assumed that tropical forests, especially the Amazon, is the main CO₂ absorber on Earth, because of large forest fires and fire agriculture emitting large amounts of CO₂, it changed to a CO₂ producer in the total CO₂ balance^{31–33}. Note that it is easy to destruct forests but difficult to reconstruct the original forest, which takes a long time.

Leo Baekeland in 1907 invented Bakelite, the world’s first fully synthetic plastic. Presently, different types of plastics are produced, such as polyethylene, which is widely used in product packing and in making plastic bottles, sheets, and plates, polyvinyl chloride, which is used in construction and pipes because of its strength and durability. Because plastics are not damaged by ethylene oxide or γ-irradiation sterilization, they have been commonly used as medical products, such as gloves, clothes, goggles, and blood bags, although some plastics are heat unstable. These products are designed to protect the human body not only from bacteria but also from viruses, and they are beneficial to medical staff because of their lightweight. Furthermore, thin plastic bags are used to prevent food not only from bacterial contaminations but also from oxidation. Therefore, plastics research has focused on the penetration of molecules such as O₂, H₂O, and microorganisms³⁴.

Recently, plastic waste has been shown to be a significant environmental pollutant³⁵, and plastics have been found to effect marine organism^{36,37}. However, if a simple method of fixing CO₂ becomes available, this waste could be readily disposed of burning without any environmental concerns and with the potential to generate energy²⁵.

Membrane technology, like the other objects that use plastics, has been developed. Scientists classically found that small molecules penetrate thin plastic membrane sheets in liquid solutions, and dialysis membranes have been commonly used to remove small molecules such as salts from protein solutions. This technology has been used in nephrosis artificial dialysis. Recently, membrane technology has

advanced rapidly, along with the need for membrane filters that can separate CO₂ from their mixtures of O₂, N₂, and H₂^{38–42}. Based on these results, it was found that many gas molecules can penetrate very thin plastic films, whereas thick films, such as PET bottles, which are commonly used, can completely block the gas penetration. In these studies, CO₂ possesses the highest penetrability among various gases examined^{38–42}. This shows that the CO₂ penetration is independent of molecular size because CO₂ molecular weight is the largest among the gases examined. The separation of CO₂ from O₂, N₂, and H₂ are not due to the molecular sieve effect. This means that the highest CO₂ penetrability is one of the CO₂ characteristics, although this characteristic could not be evaluated in this study. However, this CO₂ penetrability can be used to separate CO₂ from the other gases using simple plastic membranes, which are inexpensive. This study shows that many plastic membranes, such as polyethylene, polyurethane, latex, natural gum, and cellulose membranes have high penetrability for CO₂. Furthermore, the plastic samples whose thickness was 0.005–0.02 mm completely blocked O₂ and N₂ penetration (Fig. 4), and the cooperation of plastic membranes with H₂O also completely blocked the H₂ and CH₄ penetration (Additional Data Fig. 4a). Based on the current results, it can be possible to separate CO₂ from other gases such as O₂, N₂, H₂, and CH₄, using plastic membranes and H₂O. However, many membrane scientists are suffering from the relationship between high penetrability and low specificity to select plastic membranes^{38–42}.

CO₂ dissolves into H₂O, and its solubility in H₂O is 0.145 g/dl at 100 hp, 25°C. When CO₂ gas was vigorously mixed with H₂O by hand for 30 s, the PET bottle was completely dented with small gas space. In addition, it was reported that CO₂ solubility in H₂O increased at low temperatures because CO₂ diffusion reduced at low temperatures²⁸. In this study, this theory was confirmed using a plastic syringe (Fig. 6c), whereas, in a different system using a graduated cylinder sunken upside down inside water, CO₂ solubility to H₂O decreased at 4°C compared with 55°C (Fig. 6c). This difference in CO₂ solubility in H₂O is based on differences in the area where CO₂ gas contacts H₂O. When the global phenomena obey the syringe model used in this study, CO₂ from the sea might increase along with the global temperature. This means that increasing global temperature may accelerate CO₂ accumulation in the atmosphere, even in the absence of human CO₂ production. Therefore, the release of CO₂ from the sea, which contains a large CO₂ reserve, may cause climate changes.

In this study, not only the membrane but also the other polymer membranes had extremely high CO₂ penetrability and the same results were reported by the other groups^{38–42}. Furthermore, the other gases H₂ and CH₄ can penetrate through polymer membranes. However, the cooperation of polymer membranes and H₂O completely blocked the penetration of H₂ and CH₄ (Additional Data Figure 3). These phenomena represent CO₂ absorption into plant cells because efficient CO₂ absorption from the extremely low CO₂ concentration in the atmosphere occurs with high CO₂ penetrability and blocking of O₂ and N₂. Furthermore, other gases such as H₂ and CH₄ molecules whose molecular masses are much less than that of CO₂ can penetrate polymer membranes including cellulose membranes based on membrane

characteristics. However, in the presence of H_2O , the penetration of H_2 and CH_4 was completely blocked. This shows that the plant cells, which contain H_2O , exclude all other gases except CO_2 . However, water plants, including seaweeds, conducted photosynthesis in the water, and CO_2 absorption and O_2 exclusion occur. We previously reported that the origin of life might start from the ocean⁴³. Organisms' evolution from microorganisms to human being absolutely adapted to high CO_2 penetrability. Plasma membranes and other organelle membranes, which are mainly made of polysaccharides, have similar characteristics against various gas molecules.

Except for mycoplasma, bacteria have a cell wall that is composed of polysaccharides or peptidoglycans to protect cells against environmental conditions such as osmotic pressure. Bacterial cell walls have special channels consisting of protein molecules called "porins," which allow the passive diffusion of low molecular weight hydrophilic compounds such as sugar, amino acids, and certain ions. However, bacterial cell walls do not have the same system for transporting gas molecules such as CO_2 produced because of the tricarboxylic acid cycle, which uses glucose as an energy source. Therefore, because of the high CO_2 penetrability through cell walls, bacterial CO_2 exclusion from cells was accomplished through passive diffusion. The *naisseriae*, *meningococci* and *gonococci*, prefers high CO_2 concentration (5%) in the growth, using a candle jar which provides CO_2 in the historical culture method. As these bacteria do not possess any preferential CO_2 uptake mechanism, external high CO_2 concentration induces passive transport of CO_2 thorough cell walls.

This study demonstrated that CO_2 concentration gradient acts as "pseudo osmotic pressure" not only through cellulose membrane but also authentic polymer membranes in the gas phase and that CO_2 metabolisms occur in the whole cells in all organisms. Therefore, CO_2 exclusion in our bodies is extremely rapid via blood circulation. Recently, we found that NaHCO_3 and Na_2CO_3 accelerate glucose consumption in cultured cells^{44,45}. However, CO_2 metabolism in plant mesophyll cells plays an important role⁴⁶. Because the O_2 penetration through polymer membranes is much slower than CO_2 penetration in this study and the other studies, this cell plays a critical role in O_2 exclusion rather than CO_2 absorption⁴⁷. In this system, O_2 penetration was not observed in polymer membranes, including cellulose membranes (Fig. 5). These results indicate that plant CO_2 absorption exceeded our expectations because of extremely high penetrability. Therefore, the forest should be preserved and protected not only from fires but also from commercial land development to maintain sustainable development goals in the future. The combination of large scale polytunnels that spontaneously absorb CO_2 from atmosphere could be imitated like an "artificial forest" using simple technology. The ultimate human evolution has been achieved based on the industrial revolution⁴⁸ which has resulted in climate change. Thus, as we are responsible for this crisis, we have amoral duty to address the situation through global cooperation.

Declarations

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AUTHOR CONTRIBUTIONS

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

COMPETING FINANCIAL INTERESTS

The author declares that the present data have been used to support applications to the Japan Patent Office (2021-090928 and 2021-126892).

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Figures

Figure 1.

Figure 1

CO₂ release from plastic bags. Polymer materials: (a) latex glove, (b) cellulose tube, and (c) polyethylene bags with 0.03-mm and 0.08-mm thicknesses. CO₂ was blown into polymer bags or gloves, and then they were sealed. These bags or gloves were placed inside glass bottles, and the amount of CO₂ released inside the bottle was measured using CO₂ analyzers. The vertical axis shows the ratio of the initial volume of CO₂ to the latter volume, and the values are the mean for four experiments.

Figure 2.

c

d

Figure 2

CO₂ absorption into plastic bags, and volume increase by CO₂ absorption. Upper panel: Bubble wrap II (10 × 60 cm) was inserted into a glass bottle and treated with CO₂ gas for 5 h, and its volume was estimated as described in the Method section before and after CO₂ treatment. The vertical axis shows the volume of the bubble wrap, and the values are the mean of eight experiments ± S.D. Lower panel: Pseudo osmosis in the gas phase. (a) the initial state of latex balloon, (b) the balloon treated with 80% CO₂ in 4 L

glass bottle for 4 h, (c) the initial state of a latex glove, and (d) the grove treated with 100% CO2 in 450 mL glass bottle for 4 h. *: $p < 0.05$.

Figure 3.

Figure 3

CO2 absorption into plastic bags. Two types of thicknesses were used: 0.005 and 0.02 mm. After polyethylene bags were filled with air without CO2 and then sealed, they were left in a room. The concentration of CO2 inside the bag was analyzed. The vertical axis shows the CO2 concentration (ppm), and the values are the mean of four experiments $\pm$ S.D.

Figure 4.

Figure 4

CO2 absorption and release. Knotted cellulose tube was filled partially with air (a), and left in a glass bottle that was filled with 100% CO2 gas. (a) After 1 h, the volume of the cellulose tube was estimated according to the method described in the method section. Then, the tube was left in the room for 1 h and the volume was estimated again. (b) Latex balloon was used instead of cellulose tube.

Figure 5

Figure 5

CO₂ is released into the water through the polymer membrane. (a) Latex balloons were blown with CO₂ gas and they were sealed. The sealed balloons were sunken into the water for stated periods, and then their volume was estimated by the previously described method of initial CO₂ volumes in the method section. The vertical unit is the ratio of the initial CO₂ volume to the latter volume. The values are the mean of four experiments ± S.D. (b) 150-ml CO₂ saturated water was flowed into the polyethylene bag

with 0.04 mm thickness, and the bag was inserted into the 450-ml glass bottle filled with fresh water. After 14 h, 1.8 ml of water was removed from the both sides, inside and outside bag, and CaCO_3 was precipitated by addition of the solution consisting of 0.2-ml 1 N NaOH and 2-ml 0.1 M CaCl_2 in a plastic tube. Precipitates were collected by centrifugation at 3,000 rpm for 10 min and then weighted. The vertical axis shows the weight (g/tube) and the values are the mean of five experiments $\pm$ S.D.

Figure 6.

Figure 6

CO₂ absorption into water. CO₂ gas (70 ml) was blown into a 100-ml cylinder that was sunken upside down into a container filled with 1 L water. The gas volume was observed directly. The left, middle, and right columns represent Milli-Q (pure water), city water, and seawater, respectively. (a) 4°C, (b) 55°C, and (c) syringe. In panel (c), the left and right columns represent 4°C and 55°C experiments, respectively. The vertical axis represents CO₂ volume (ml), and the values are the mean of five experiments $\pm$ S.D.

Figure 7

Figure 7

CO₂ absorption and release by plants via PE bags. CO₂ concentrations were measured in plastic bags. The vertical and horizontal axes represent CO₂ concentration (ppm) and time (h), respectively. (a) Cyclamen planters with ~40 cm leave assembly and ~15 cm high were used. (b) A cycad leaf was cut into four pieces. The value is the mean of three or four different experiments $\pm$ S.D.

Supplementary Files

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