The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
Paper ID #41758

Climate Change and Kinetics in an Undergraduate Laboratory: Injection and Tracking of CO_2 in a 7 Gallon Terrarium

Dr. Clint Guymon, Brigham Young University

Clint Guymon is a new Associate Teaching Professor in the Chemical Engineering Department at Brigham Young University. There he has developed multiple educational modules for undergraduate chemical engineering students. He previously worked for 15 years as an engineering consultant in the defense industry.

Joseph R Tuft

Climate Change and Kinetics in an Undergraduate Laboratory: Injection and Tracking of CO2 in a 7 Gallon Terrarium

Clint Guymon, PhD PE
Joseph Tuft
Chemical Engineering Department
Brigham Young University
Provo, UT 84602

Abstract

The concentration of CO2 in our Earth's atmosphere is increasing in part due to the large-scale use of fossil fuels as an energy source. This study reports on an undergraduate laboratory in Chemical Engineering where students are tasked with similarly dosing a sealable 7-gallon terrarium with CO2 and measuring the resultant increase in the CO2 ppm levels. An ESP32 microcontroller and a Sensirion SCD30 are used to track the CO2 concentration over time for varying light levels (low, medium, and high). An Android or Apple app can read, collect, export, and plot the history of the CO2 via Bluetooth where the students subsequently analyze the transient CO2 response to determine the rate of CO2 uptake by the terrarium plants given the rate of CO2 production by the soil bacteria and the diffusion rate of CO2 from the terrarium. As part of the assignment, the students are also asked to reflect on the similarities between the terrarium and the earth's atmosphere. This multifaceted project not only emphasizes fundamental chemical engineering principles but also explores the broader context of environmental sustainability and climate change. This activity is part of a recent curriculum change in the chemical engineering department with a greater emphasis on a larger quantity of focused laboratory activities in place of fewer and longer unit operation experiments. Preliminary results from that curriculum change and its effectiveness will also be summarized relative to the terrarium laboratory activity.

1. Introduction

The concentration of carbon dioxide in the Earth's atmosphere has been increasing [1] in part due to large-scale combustion of fossil fuels for energy. That CO2 consequential increase is correlated to multiple environmental outcomes [2,3]. It is generally accepted and very likely that many large-scale environmental consequences are not just correlated with but caused by an increase in atmospheric CO2 levels [4,5]. As such, students were asked to explore the relationship between CO2 and a simplified environment in an undergraduate chemical engineering laboratory class focused on chemical reactions. One of the statements proposed to the students was: "Increasing concentrations of CO2 in the atmosphere are negatively impacting the environment" where 36% strongly agreed, 53% were neutral, and 11% strongly disagreed. 61 students responded and although this is a minority of the enrolled students in chemical engineering at Brigham Young University, it does indicate that the relationship between energy, the atmosphere, and Earth's environment, could be better understood as there is strong evidence that anthropogenic sources of CO2 is negatively impacting the environment [6]. In hopes of helping students better understand those relationships, a laboratory activity was introduced to the curriculum treating the interplay between living plants, organisms in the soil, and carbon dioxide in a 7-gallon terrarium. The laboratory activity is described here as well as associated student outcomes. A small terrarium doesn't represent the many complexities of the global environment, yet there are valuable chemical and environmental learning opportunities such as interacting with a dynamic, living system, the rate of uptake of carbon dioxide through photosynthesis, the effects of light intensity on that rate, adsorption of CO_2 in water, production of carbon dioxide by the microbes in the soil, diffusion from an open port, and the effect of introducing carbon dioxide from an exterior source.

A terrarium is typically a glass enclosure with a layer of water and larger rocks beneath a layer of charcoal as an absorbent, with another layer of soil on top. The fraction of each may vary but will typically fill nearly half of the terrarium's volume altogether [7]. Appropriate plants such as ferns or broad-leaf types are added. It can be sealed or unsealed. The microbes in the soil can produce a significant amount of carbon dioxide (from breaking down the carbonaceous material) and if not controlled can lead to toxic levels of CO_2 above about 7000 ppm [8]. The microbes must be introduced, but are already present in most soils. In the terrariums highlighted herein, additional microbes were not added to those found in readily sourced potting soils.

This quantitative terrarium lab activity is the newest part of one of the four half-credit laboratory classes that are designed to give more hands-on experiences to reinforce fundamental principles of the chemical engineering curriculum classes: process principles and fluids, chemical reaction engineering and material science, thermodynamics and heat and mass transfer, and separations and process control. The credit hour requirements for the major were not increased with this introduction as a second semester of unit operations (2 credit hours) was exchanged for the 4 fundamental lab classes. Each of the 0.5 credit lab classes have between 8 and 13 weekly laboratory activities. The terrarium lab is one of the activities in the chemical reaction engineering lab (Ch En 345) and is designed to last one class period. Quantitative terrarium laboratory activities in the literature are scant but qualitative activities with terrariums have been used for a freshman climate control activity for wireless sensing [9], monitoring humidity and temperature of enclosed seeds [10], and teaching environmental awareness [11].

2. Terrarium Laboratory Description and Experimental Methods

The terrarium laboratory activity includes brief background information on the atmospheric composition of the earth, radiation energy from the sun, and the CO_2 and O_2 cycles. It also includes details of the first attempt at making a terrarium where after planting the plants the terrarium was sealed with the CO_2 measurement system in place. The concentration of CO_2 inside the terrarium quickly rose to over 40,000 ppm (the detection limit of the Sensirion SCD30 NDIR sensor) and the plants died within a month. The replanted terrarium together with plots of the changing CO_2 concentration are given to students with different levels of light for an unsealed terrarium (shown in Figure 1 and 2).

The terrarium was made for less than $200 with the largest expense from the Sensirion SCD30 NDIR CO_2, humidity, and temperature sensor. Instead of using activated charcoal, natural hardwood lump charcoal from the hardware store was crushed and used. Common potting soil together with washed rock and perlite was also used inside the approximately 7 gallon glass carboy. A fern (green spleenwort) and a small arrowhead plant were forced through the small opening of the carboy and planted. The SCD30 sensor was wired to an ESP32 microcontroller where code from Sensirion was uploaded to work with the Sensirion phone application "MyAmbience" through Bluetooth. The hardware used to dose the terrarium with CO2 is shown in Figure 1 and includes several valves and a calibrated 2.5 milliliter tube volume. The syringe with 5mL of air is used as a chaser to clear all of the CO2 into the terrarium during the dosage activity.

Students are given an assignment of two parts: (1) injecting the sealed terrarium with a known amount of CO2 to determine the internal gas volume and (2) estimating the reaction rate constant for the uptake of CO2 by the plants in the terrarium. The first activity is a good review using material balance principles and the second treats kinetics.

Figure 1: Image of the terrarium showing the rocks with water at the bottom, soil with charcoal, and plants (left). Also shown is a second image with the SCD30 NDIR device and the valved 2.5 cm^3 tube where CO2 can be filled then released with help of the syringe into the terrarium (right). Although pictured here as a sealed terrarium for dosing the CO2, the terrarium is usually left open.

2.1 Determining the Internal Gas Volume

The internal gas volume of the terrarium is unknown; students are asked to first review detailed video instructions and afterwards fill a small chamber (valved tube pictured in Figure 1) with 99% CO2 at 10 psig from a pressurized CO2 cylinder. In order to be dosed with CO2 the terrarium is sealed with a stopper that is run through by a down tube and the sensor cable as shown in Figure 1. Then the small 2.5 cm^3 pressurized tube is connected and the valves are opened, chasing the residual CO2 into the terrarium volume with 5 cm^3 of air. The resultant concentration increase of CO2 is documented over the next minute or two. The students can then find the total gas volume inside the terrarium using the consequent change in CO2 concentration.

Throughout the semester-long (14-week) laboratory activities, all groups were able to quickly obtain the MyAmbience app and readily link over Bluetooth with the sensor's data. The app provides an instantaneous reading of the temperature, CO2 concentration in ppm, and the relative humidity. It also yields a data plot versus time for those three variables. That history of data can be downloaded over the same Bluetooth connection to the phone's memory and then exported. Although the history of the CO2 concentration isn't required to be recorded and downloaded by the students, it easily could be. Instead, a previously recorded concentration profile with various lighting or illuminance conditions is given for analysis as outlined in the next section. The profile can then be fit to a model to estimate the CO2 uptake rate.

2.2 Determining the Reaction Rate Constant for CO2 Uptake

The uptake of CO2 by plants is dependent on multiple factors including plant species, plant size, plant health, number of plants, CO2 concentration, and light intensity among other things. Students are introduced to these variables as they are asked to estimate the uptake rate when given a profile of the CO2 concentration with respect to time at varying light exposures. Data is given to them as a csv file that can be downloaded from a GitHub repository [12]; a plot of that data is shown in Figure 2.

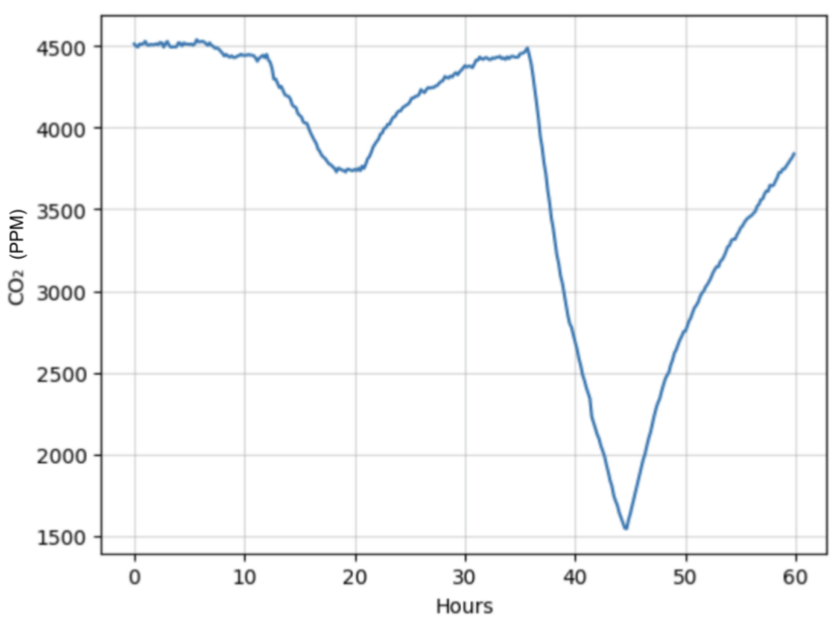

Figure 2: Plot of the CO2 concentration in ppm as a function of time with two significant areas of decrease in CO2 concentration: during the daylight hours with an illuminance of around 220 lux and with a lamp shining into the enclosure at a lux value of approximately 900 lux. In the other areas, the lux value is low at approximately 30 lux.

Students are given the different light levels at each distinct area and the specific rate of diffusion from the top of the open terrarium. The first area of decrease is during the daylight hours with an illuminance of around 220 lux. The second region of decrease is with a lamp shining into the enclosure with approximately 900 lux. In the other areas, the lux value is low at approximately 30 lux. During the entire duration of the experiment, the terrarium was open to the atmosphere allowing CO2 to escape. There is loss of CO2 due to diffusion with an estimated rate of:

$$\frac{dC_{CO2,ppm}}{dt} = -k_d \cdot (C_{CO2,ppm} - 400) \qquad \text{Eq. 1}$$

where k_d is the diffusion coefficient from the top of the terrarium and 400 is the concentration of CO2 in the surrounding atmosphere, $C_{CO2,ppm}$ is the concentration of CO2 inside the terrarium and t is time. k_d is approximately 7.41E-02 per hour. Students are given this relationship as well as the approximate rate of production of CO2 from the microbes in the soil. With no plants in the terrarium the rate of release of CO2 from the soil was measured over multiple days to be 340 ppm per hour.

Students are then asked to write out a transient mole balance of the CO2 inside the terrarium from the uptake by the plants, generation by the microbes, and diffusion out through the top of the terrarium. Absorption by the water in the bottom of the terrarium is assumed to be minimal. A hint is given that the rate of uptake by the plants (r_{up}) is assumed to be first order in the light intensity and the CO2 concentration according to:

$$r_{up} = -k_{CO2} \cdot C_{CO2,ppm} \cdot L \qquad \text{Eq. 2}$$

where k_{CO2} is the uptake parameter, and L is the light intensity in lux.

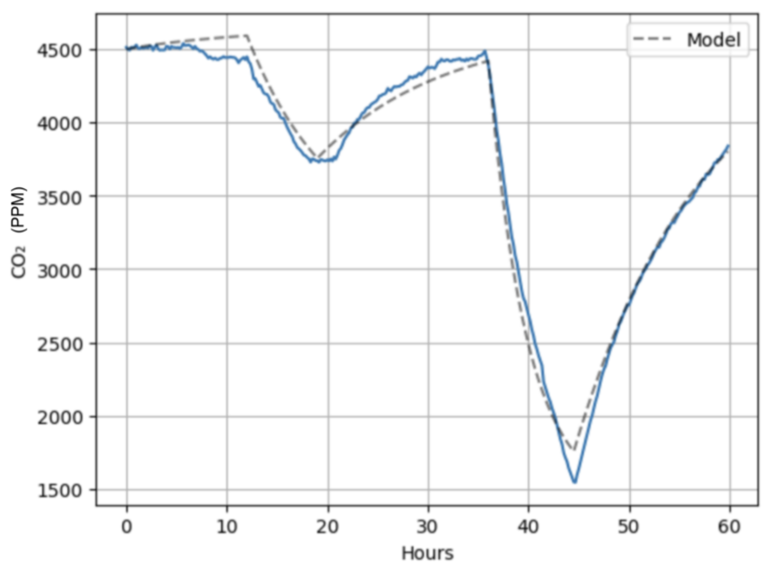

Figure 3: Plot of the model fit of the data shown in Figure 2.

From the above equations and estimating the slopes at the different light conditions, students can then solve for the plant uptake coefficient (k_{CO2}) or use a fitting method with an ordinary differential equation solver to determine k_{CO2}.

$$\frac{dC_{CO2,ppm}}{dt} = G - k_d \cdot (C_{CO2,ppm} - 400) - k_{CO2} \cdot C_{CO2,ppm} \cdot L \qquad \text{Eq. 3}$$

where G is the generation of CO2 by the microbes at 340 ppm per hour and k_d is the above given diffusion factor. Minimizing the sum of squared errors by varying k_{CO2} with the differential equation in Eq. 3 yields good agreement with the data as shown in Figure 3. The determined value of k_{CO2} from that fit is 2.1E-4/(lux hr). At a CO2 concentration value of 400 ppm and an illuminance of 1000 lux, the uptake by the plants in the terrarium is approximately 3.75E-5 moles per hour of carbon dioxide (13 L volume, 25 C and 85 kPa pressure). If the plant surface area is roughly estimated at 0.1 square meters, the uptake is approximately 0.1 micromoles per second per square meter which is close to but significantly smaller than that measured in Reference [13] for forage cactus Mexican Elephant Ear cultivated outside.

3. Alternate Terrarium Laboratory Activity

Although not completed by a class of students yet, an alternate setup of a terrarium could include controlling the concentration of carbon dioxide by varying the light illuminance. This would integrate principles of process control into a lab that would highlight topics like the relationship between CO2 producers and consumers with opportunities to highlight the difficulty of controlling the level of CO2 in our Earth's atmosphere as well as familiarize the students with the dynamics of controlling the reaction environment.

As previously described, the setup for this activity amounted to less than $200, though designed slightly differently. It incorporated a 1 gallon glass jar with a wooden lid, a 5V LED ring, double sided mounting adhesive, and a breadboard. In this terrarium a tropical plant (croton mammy) was planted. All other materials used were the same as those highlighted in the first terrarium activity. The wire for both the LED and the Sensirion sensor were fed through a small hole drilled in the wooden lid. The LED ring was connected to the lid using the mounting adhesive. The circuit below shows the method in which the LED was run through the ESP32 microcontroller to alter the light depending on the CO2 reading.

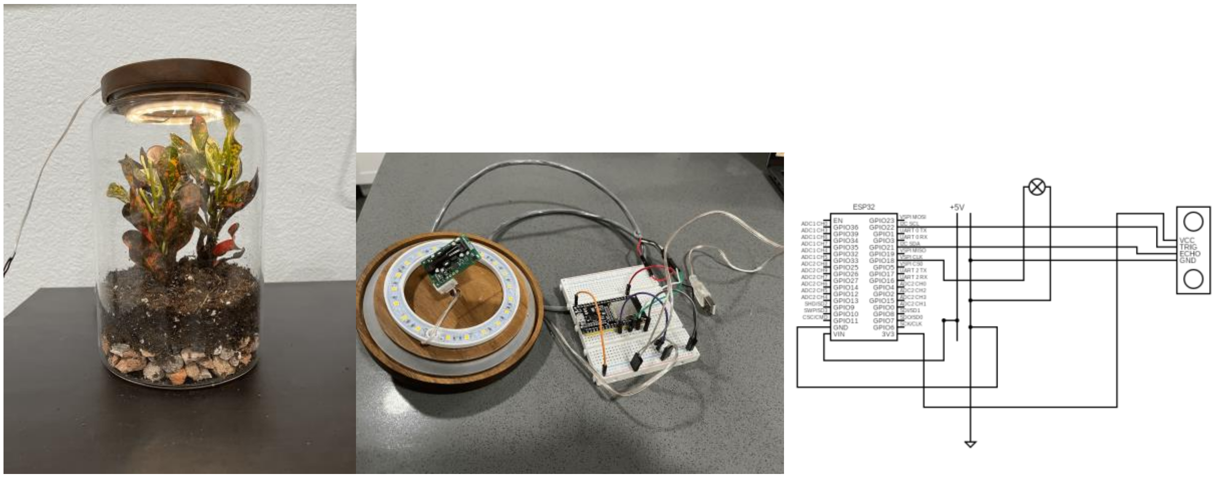

Figure 4: Picture of a smaller terrarium (left), SCD30 with ESP32 microcontroller and light in the terrarium lid (center), and an example wiring diagram (right).

An example of the code used to run the CO_2 sensitive light model is shown below.

```
float lightfraction =0;
int scaled255LF=0;
// the number of the LED pin
const int ledPin = 18;  // 18 corresponds to GPIO18
// setting PWM properties
const int freq = 5000;
const int ledChannel = 0;
const int resolution = 8;
void setup() {
   // configure LED PWM functionalities
 ledcSetup(ledChannel, freq, resolution);
  // attach the channel to the GPIO to be controlled
 ledcAttachPin(ledPin, ledChannel);
}
void loop() {
 float result[3] = {0};
 if (esp_timer_get_time() - lastMmntTime >= startCheckingAfterUs) {
   if (scd30.isAvailable()) {
     scd30.getCarbonDioxideConcentration(result);
     lightfraction = result[0]/4000; //fraction of CO2 measurement range
     scaled255LF = 255 - int(lightfraction*255);
     ledcWrite(ledChannel, scaled255LF);
   }
 }
 gadgetBle.handleEvents();
 delay(3);
}
```

The code starts by obtaining a value from the CO_2 sensor. It then divides this value by 4000, which is twice the desired CO_2 parts per million (ppm) value. This resulting percentage of 4000 is then multiplied by 255. The output is a value between 1 and 255. This value is inversely related to the desired brightness, with 255 corresponding to completely dim and 0 to maximum brightness. By subtracting this result from 255, we get a value that represents brightness inversely. If the CO_2 ppm reading is less than 2000, the LED input will be greater than 255/2, resulting in dimmer light. If the CO_2 ppm reading is greater than 2000, the LED input will be less than 255/2, resulting in brighter light.

4. Student Outcomes and Results

The terrarium lab activity was introduced in the Fall semester of 2023 at Brigham Young University for one of the exercises in the half credit hour class focused on chemical reactions engineering and material science. Students in groups of three were given one laboratory period (50 min) and then a week outside of class to complete the assignment. Twenty-five groups completed the activity. Student groups reported on average a 330-ppm change in the CO_2 concentration upon injection of CO_2 into the sealed terrarium. Based on the ppm change, they reported the gas volume of the terrarium to be 13 liters on average. Some students struggled to determine the gas volume and thus did not complete the second part of the activity (CO_2 uptake estimate) in the time constraint. Of those that did, 28% arrived at an answer that was within 20% of the correct value given the model and data. Some students were challenged with the mass balance between the initial pressurized and final atmospheric conditions in determining the gas volume. Most were challenged with the transient mass balance with reaction and diffusion.

In the same lab assignment, students were asked to reflect with the following prompt questions: "How does this relate to our atmosphere? Or, how has this made you think about our atmosphere?" Table 1 summarizes a categorization of the students' responses. In addition, following the activity at the end of the semester, individual students were asked to give their rankings of the following statements:

- The terrarium activity increased my awareness of the complexities of the earth's atmosphere. 33 strongly agreed, 23 were neutral, 5 strongly disagreed.
- The terrarium activity increased my awareness of some of the sources of carbon dioxide in the earth's atmosphere. 31 strongly agreed, 26 were neutral, 4 strongly disagreed.
- The terrarium activity increased my awareness of plant life and photosynthesis processes that affect the earth's atmosphere. 40 strongly agreed, 17 were neutral, 4 strongly disagreed.

Table 1: Topics and number of comments following student reflection on the terrarium activity

Comment Topic	Number of Comments
Relating the lab/terrarium to the atmosphere and carbon cycle	15
Impact of light/sun on CO_2 levels and plant growth	5
Importance of plants/vegetation for CO_2 absorption	4
Being conscious of CO_2 emissions and environmental impact	4
Showing new understanding about fluctuations in atmospheric CO_2	3
Self-regulating nature of the carbon cycle	2
Other	2

Some of the positive comments received regarding the terrarium activity included:

> "I enjoyed this lab; I thought it was a cool look into the earth's atmosphere and how plants control CO_2 concentrations."

> "It was interesting to see a small-scale example of how the earth and atmosphere work on a larger scale."

> "The terrarium activity helped us consider the different sources of CO_2 and how it is generated and consumed within the environment."

> "This lab relates to our atmosphere because it modeled the interaction between plants, bacteria, and CO_2 production/consumption. This lab changed our thinking about the atmosphere because we thought of it as a big ball of gas rather than a transient mole balance with lots of reactions going on."

5. Discussion and Conclusion

The student laboratory activity using the terrarium was successful in helping students practice applying chemical reaction principles involving carbon dioxide within a living environment. It also facilitated reflection on dynamic CO_2 interactions and effects within that smaller environment and in our own atmosphere. Utilizing a terrarium in an undergraduate chemical engineering laboratory can provide valuable experiences in quantifying reaction or diffusion rates and can also be used in a control scenario. The terrarium together with the CO_2 dosing and concentration, temperature, and humidity measurement system can easily be assembled with low cost materials. Quantitative measurements can be coupled with laboratory activities with the terrarium to help students better understand the dynamics of reactors, chemical diffusion, and process control within a complex living environment. The activity can also be helpful in fostering discussion and reflection on the environmental effects with CO_2 in our larger environment.

Acknowledgment

The authors acknowledge the Brigham Young University Chemical Engineering Department and its significant investment in making the fundamental laboratory activities available to students.

We also acknowledge helpful discussions with Matt Arrington of the Plant and Wildlife Sciences Department at BYU.

References

[1] P. Pearson and M. Palmer, "Atmospheric carbon dioxide concentrations over the past 60 million years," Nature, vol. 406, 2000, pp. 695–699. https://doi.org/10.1038/35021000G.

[2] P.C. Taylor, W. Maslowski, J. Perlwitz, and D.J. Wuebbles, 2017: Arctic changes and their effects on Alaska and the rest of the United States. In: Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, pp. 303-332, doi: 10.7930/J00863GK.

[3] C. Keeling, W. Mook, and P. Tans, "Recent trends in the 13C/12C ratio of atmospheric carbon dioxide." Nature, vol. 277, 1979, pp. 121–123. https://doi.org/10.1038/277121a0.

[4] P. M. Haugan and H. Drange, "Effects of CO2 on the ocean environment," Energy Conversion and Management, vol. 37, pp. 1019-1022. https://doi.org/10.1016/0196-8904(95)00292-8

[5] A. Cherchi, A. Alessandri, S. Masina, et al. "Effects of increased CO2 levels on monsoons." Clim Dyn 37, 83–101 (2011). https://doi.org/10.1007/s00382-010-0801-7

[6] B. Mai, Y. Diao, H. Yang, T. Deng, Y. Zou, Y. Wang, W. Lan, X. Liu, X. Deng, "Assessing atmospheric CO2 concentrations and contributions from biogenic and anthropogenic sources in the Pearl River Delta region," Urban Climate, vol. 54, 2024, 101864, ISSN 2212-0955, https://doi.org/10.1016/j.uclim.2024.101864

[7] D.R. Hershey, "Doctor Ward's Accidental Terrarium," The American Biology Teacher, *58*(5), 1996, 276–281. https://doi.org/10.2307/4450151

[8] M. Poudel and B. Dunn, Greenhouse carbon dioxide supplementation. Oklahoma Cooperative Extension Service, 2017.

[9] T. Keller, & J. Frolik (2005, June), "Wireless Sensor Networks: An Interdisciplinary Topic For Freshman Design," Paper presented at 2005 Annual Conference, Portland, Oregon. https://doi.org/10.18260/1-2--15128

[10] T. Balachandran, S. Sbenaty, and J. Walck, "Remote humidity and temperature real-time monitoring system for the study of the after-ripening process in seeds," Proceedings of 120th ASEE Annual Conference and Exposition, Atlanta, GA. June 2013.

[11] K.M. Doutt, D.L. Airhart, "Teaching Environmental Awareness Using a Terrarium," Teaching Exceptional Children, v23, n4, 38-41, 1991.

[12] Guymon, C. (2024). demos (Version 1.0.0) [Computer software]. https://doi.org/10.5281/zenodo.10625707

[13] J.T.A. Souza, J.S. Araújo, E. dos S. Félix, R. de C. Alves, T.J. de Oliveira Filho, and E.C. de Lira, "CO2 capture and water use efficiency in Opuntia stricta (Haw.) at different seasons and evaluation times". Revista Colombiana de Ciencias Hortícolas, 16(2), e13525, 2022. https://doi.org/10.17584/rcch.2022v16i2.13525.

# # #