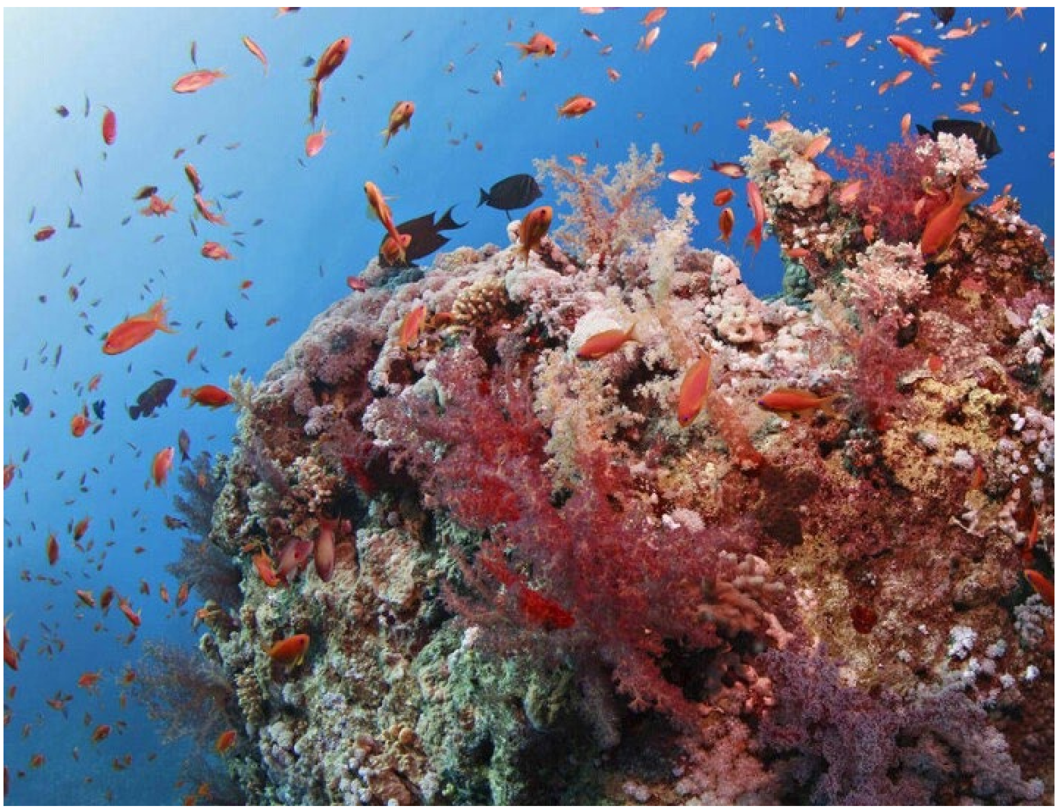
Ocean Acidification:
Why Buffering Matters



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This lesson plan was produced by the CO_2 Learning Center, a project of the CO_2 Coalition

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A note about our lesson plans:

Our CO_2 Learning Center lesson plans all have the same format, which includes student learning objectives, background information on the science concepts covered in the book or video, suggested activities including labs to enrich the lesson and reinforce use of the scientific method, and formative and summative questions.

This lesson plan is based on a report published by the CO_2 Coalition and written by Marty Cornell, which can be found here: https://co2coalition.org/wp-content/uploads/2024/03/Teaching-Ocean-Acidification.pdf

A follow-along video for this lab is also available: https://co2coalition.org/publications/an-experiment-in-ocean-acidification-why-buffering-matters/

Lesson Plan: Ocean Acidification: Why Buffering Matters

Grades 8-12

Student Learning Goals

After researching the issue of ocean acidification, students will be able to do the following:

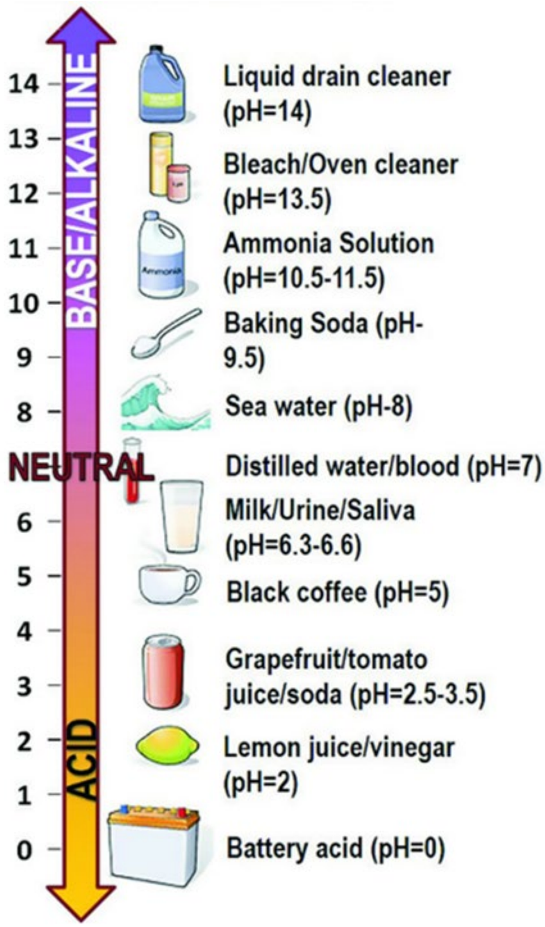
- Use the scientific method to determine if ocean acidification is a problem.
- Find existing research that addresses the issue of ocean acidification.
- Develop a testable hypothesis.
- Design an experiment to test the hypothesis.
- Collect data from the experiment.
- Draw conclusions from their data.
- Write a report or give a presentation on the results of the experiment, including suggestions for further study and an error analysis of their experimental methods.

Background Information

Alarm over ocean "acidification" is based on the hypothesis that elevated atmospheric CO_2 causes more CO_2 to be dissolved into the ocean, increasing the concentration of carbonic acid, particularly near the surface, and making it impossible for shelled invertebrates (such as crabs or corals) to create the calcium carbonate that makes up their shells and exoskeletons. A further lowering of pH, so the extremists say, would lead to "ocean acidification" and begin dissolving the shells of existing creatures, resulting in an oceanic apocalypse.[1]

But are the oceans acidifying? How is this being determined? What is the pH of "average" ocean water, and does this change from place to place? Will a shift in pH affect organisms' ability to construct their shells or reefs? Can the pH of ocean water be changed by the increase of CO_2 in the atmosphere? How much CO_2 from the atmosphere is absorbed by the oceans? All of these are important questions and are considered in the process of critical thinking: When presented with information, how reliable is it? How credible are the studies? Can the results be reproduced by experimentation?

What is ocean "acidification?" Here is a quick refresher on acidity, alkalinity and pH. The measurement of acidity or alkalinity, known as pH (that is, the proportion of hydrogen ions compared with distilled water), ranges from very acidic (pH 0), such as battery acid, to very alkaline (pH 14), such as lye or drain cleaner (see figure below). Neutral is pH 7.0. Rainwater is quite acidic, at pH 5.4, while seawater is pronouncedly alkaline, at pH 7.8 to 8.1.



The "calcifying organisms"—creatures that make their shells or exoskeletons out of calcium carbonate, already are used to very large swings in pH on the continental shelves near the mouths of rivers, particularly during floods. The rivers that flow into the bays and estuaries are often significantly acidified, yet oyster communities thrive in those areas. In fact, the federal government acknowledges this with a lower allowable limit of 6.5 (that's acid) for the Clean Water Act. For example, the wonderfully delicious oysters from the Chesapeake Bay of the eastern U.S. do quite nicely in a bay that commonly approaches 7.0 due to river influx, far lower than the most radical predictions of those raising alarms about ocean pH.

The pH of the ocean varies slightly, depending on season, water depth and latitude. The pH level trends slightly less alkaline in the tropics, during the winter, and at depth. According to many estimates, the oceans' pH has declined slightly (~0.1 pH) since the beginning of the Industrial Revolution.

Models from the Intergovernmental Panel on Climate Change (IPCC) predict that ocean alkalinity may decline another 0.3 pH by the year 2100. Although this level is unlikely to be reached, even if it were true, the ocean would remain firmly alkaline. In fact, since the current range of estimates of ocean alkalinity is pH 7.8 – 8.1, the small change predicted by the alarmists is barely beyond the estimates of alkalinity today. They dare not predict large changes; instead, they pretend that the small changes they predict will have large effects.

The prediction of increasing acidity and the doom of the sea is based almost entirely on models that use the following reasoning:

More CO_2 ⇒ more carbonic acid ⇒ more acidic oceans ⇒ seashells dissolve

Modeling studies show that the pH of the oceans would need to drop by two full units, or to a pH of 6.0, for carbonate to dissolve at current temperatures.[2] Even the most extreme projections of decreasing alkalinity do not forecast that the oceans will approach neutral, let alone become truly acidic.

These models can predict pH in the controlled settings of a university laboratory, but not so much in the real world. The models do not account for various processes that act to modify or "buffer" any increase in carbonic acid. The primary buffering agents are the chemical reactions of limestones and other minerals in ocean water. Limestones ($CaCO_3$) are among the primary rocks exposed on the surface of the Earth and beneath its oceans. Their presence guarantees that the oceans cannot become acidic under modern conditions —and certainly nowhere near as acidic as the rainwater that falls on them daily.

Carbonic acid reacts with limestones on land and at sea to increase the alkalinity and add calcium to streams and oceans. Other minerals also add significant buffering as a backstop to the limestone reactions.

Several other important factors act to buffer changes in ocean pH but are not included in the models. For instance, warmer water and increasing CO_2 are expected to increase algal photosynthesis, which has been shown to increase the alkalinity of the ocean significantly. Some climate modelers are all too anxious to include variables that fit their preconceived notions, calling them "multiplier effects," but conveniently avoid them when they might disprove their theories. Note that, even with the most radical modeling of lower pH, the oceans remain significantly alkaline and cannot even approach neutrality at pH 7.0.

There are many studies that claim to prove that elevated levels of CO_2 cause the ocean to become less alkaline, but they have experimental errors, such as making conditions in the experiment unrealistic and not representative of nature or designing the experiment to get a desired outcome instead of an honest one. Frequently, the authors use models of questionable accuracy instead of basing their experiment on empirical data.

Some "Ocean Acidification" labs for students use improper lab materials to achieve a preordained result of acidic water. One popular lab "experiment" is found in the Houghton Mifflin Harcourt's "Into Science Student Activity Guide" for grades 6-8 on Climate Change, which we will examine here.[3] This lab directs students to take antacid tablets, dissolve them in tap water, put them in a closed box so that the air in the box becomes high in CO_2 concentration, then measure the pH of a separate container of tap water that has been enclosed in the box and compare it to the pH of tap water that remained outside the box. The pH of the water in the box should drop dramatically over several hours.

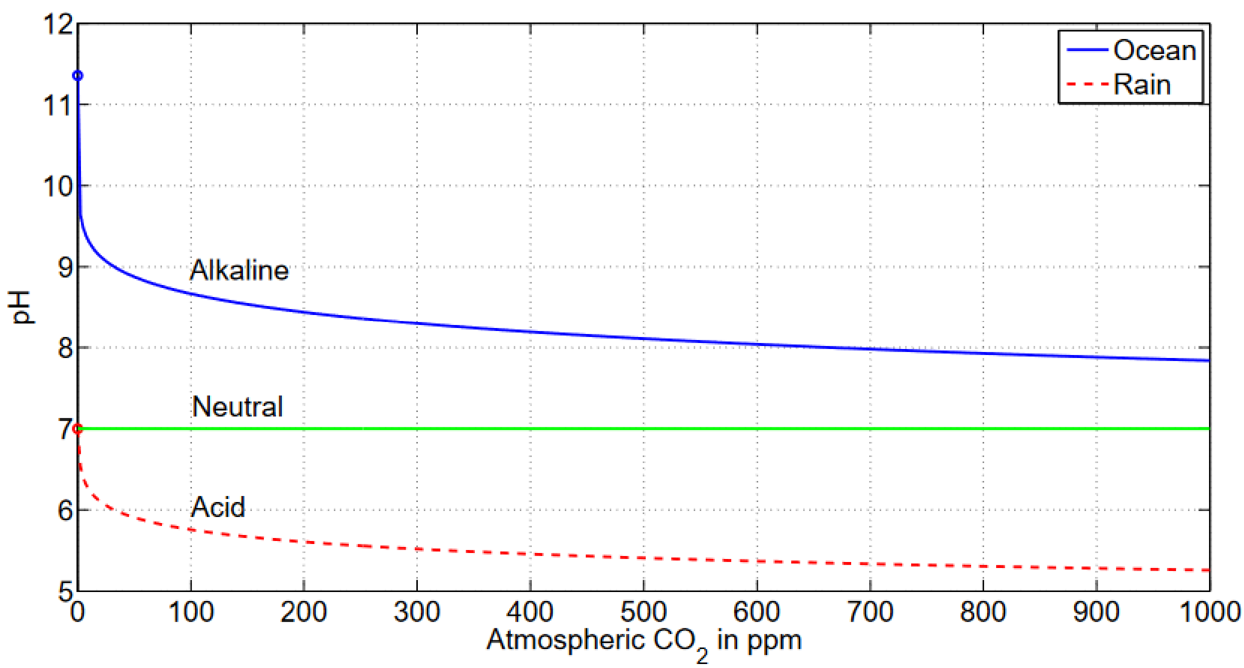
Critical to understanding why the experiment is poorly designed is an understanding of what a buffered solution is. This concept should be taught to the students before they design their experiment.

A buffered solution is simply one that resists changes in pH when an acidic or basic substance is added. Buffered solutions are used in many medicines or products. A great example is eye products, specifically eye drops and contact solutions. It is important that the pH of the solution stays the same as the pH of tears, so the solutions are buffered.

It is easy to make a buffered solution. Without discussing complicated chemistry, it is simply a mixture of weak acids or bases and mineral salts dissolved in water or another solvent. These salts will neutralize acidic or basic substances that are added to the solution. Chemistry students may already be familiar with the concept of buffering and the chemistry involved.

Ocean water is a mixture of weak acids and bases along with dissolved mineral salts and is therefore a well-buffered solution, as has been discussed previously.[4]

The problem with the common lab is that it is not a realistic lab. When pure water is exposed to extremely high levels of CO_2, its pH will drop immediately and dramatically because it is not buffered. One lab online recognizes this fact and cautions teachers to use an aquarium salt that "does not contain calcium or calcium carbonate, as they act as buffers to prevent pH change. Some seawater-salt mixes have enhanced levels of calcium to promote coral reef health."[5] This is particularly problematic because carbonate and bicarbonate are the most common buffers in the ocean.[6] Ocean water contains calcium ions, bicarbonate ions, and carbonate ions along with many others. In fact, ocean water has a high concentration of buffering molecules and will therefore show very little change in pH.[7]



pH of ocean water and rainwater versus concentration of CO_2 in the atmosphere[6]

The other problem with the lab is the use of antacid to generate high levels of CO_2, which are so high as to be completely unrealistic in the environment. Over 5,000 ppm (parts per million) CO_2 will concentrate in the closed container,[8] whereas ambient air contains only about 420 ppm CO_2 (or 0.042%). The disparity between these two values makes this lab unrealistic because the concentration of CO_2 in Earth's atmosphere has not been as high as 5,000 ppm in over 350 million years.[9] It does, however, provide more evidence that even a large rise in CO_2 in the atmosphere will not significantly affect the pH of the ocean. The other lab cited[5] also uses CO_2 levels that do not exist in the ambient atmosphere and is therefore unrealistic. Students are instructed to blow through a straw into 100 mL of a buffered solution and watch the solution turn acidic. The important detail that is left out is that humans exhale approximately 40,000 ppm of CO_2 with every breath, which is 100 times more than that present in the atmosphere.[10]

How much CO_2 is absorbed by the oceans annually? This is an interesting question, because oceans both absorb and emit carbon dioxide. Ocean water will absorb more gases, including oxygen, as it cools because the solubility of these two gases increases as the water temperature decreases. Conversely, oceans will emit carbon dioxide and oxygen as the water warms.

According to the IPCC Climate Change document *The Physical Science Basis (2013),* oceans emit an average of 291.1 gigatons/year and absorb an average of 293.3 gigatons/year, leaving a net change of 2.2 gigatons or 1.1% of total CO_2 in the atmosphere absorbed. But oceans aren't the only things on Earth that emit carbon dioxide.

In addition to ocean outgassing, the release of carbon dioxide as a byproduct of cellular respiration, emissions from vulcanism, and weathering of rocks containing carbon (such as limestone) account for 95.7% of total CO_2 emissions. Therefore, only 4.3% of all emissions come from anthropogenic (manmade) sources.

Since CO_2 molecules act the same regardless of their source, we can assume that the 1.1% absorbed comes from a combination of all sources and not just those that are anthropogenic. The point here is, if humans worldwide were to reduce 100% of their emissions (ignoring that which they exhale), it would reduce the amount of CO_2 absorbed by the oceans by 4.3% of 1.1%, or a negligible amount (about 0.047%).

How Added Fossil Fuels Affect the Carbon Cycle

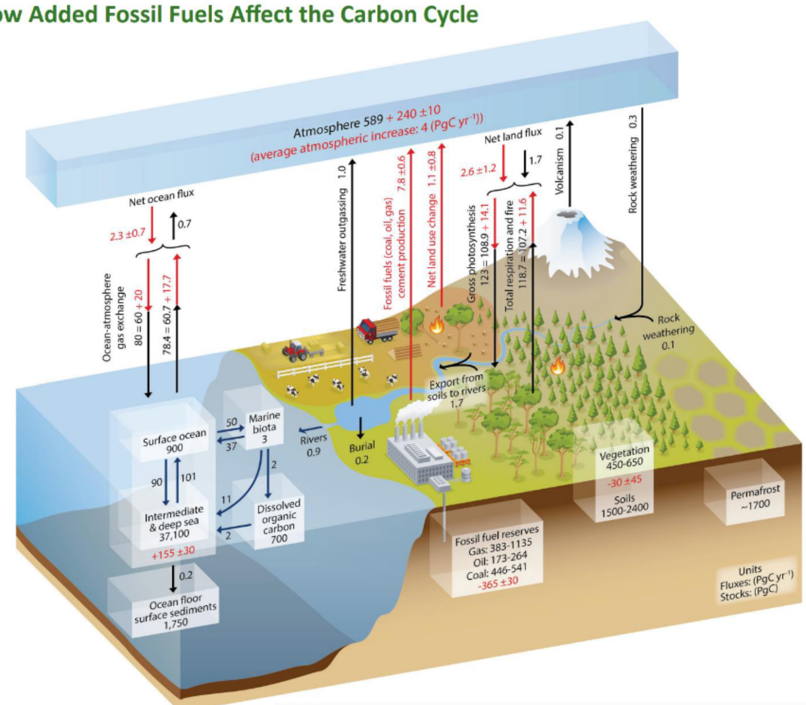


Figure 1 The Global Carbon Cycle from IPCC *CLIMATE CHANGE 2013: The Physical Science Basis - figure 6.1, p. 471*

CO2 Emissions, GT/Year

Oceans	291.1	38.3%
Respiration/Decay	435.2	57.2%
Volcanos/Rock Weathering	1.5	0.2%
Total Natural	**727.8**	**95.7%**
Fossil Fuels & Cement	28.6	3.8%
Land Use Change	4	0.5%
Total Anthropogenic	**32.6**	**4.3%**
Total CO2 Emissions	760.4	100.0%

CO2 Sinks, GT/Year

Oceans	293.3	39.4%
Photosynthesis	451.0	60.6%
Total	**744.3**	**100.0%**

References

1) Wrightstone, G. (2017). *Inconvenient Facts*. Large portions of this lesson plan were taken verbatim from this book with the author's permission.
2) Segelaastad T (2008) Carbon Isotope Mass Modelling of Atmospheric vs. Oceanic CO_2. 33rd International Geological Congress (Session TC), Oslo, Norway 6-14 August 2008.
3) Houghton Mifflin Harcourt Into Science Texas 6-8, Texas Student Activity Guide, Global Climate (TEKS 8.11), pages 273-274. Please note that this lab is used by HMH for other states as well.
4) Middleburg, Jack J., Soetaert, Karline, Hagens, Mathilde (2020). Ocean Alkalinity, Buffering and Biogeochemical Processes. Review of Geophysics **58**(3). https://doi.org/10.1029/2019RG000681
5) hhmi Biointeractive, Ocean Acidification Lab, https://www.biointeractive.org/sites/default/files/media/file/2023-11/OceanAcidification-EdMat-act_0.pdf
6) Ocean Health – Is there an "Acidification" problem? https://co2coalition.org/wp-content/uploads/2021/08/Ocean-Health-White-Paper-REV-061120.pdf
7) Fundamentals of Ocean pH. R. Cohen and W. Happer, September 18, 2015. https://co2coalition.org/wp-content/uploads/2021/11/2015-Cohen-Happer-Fundamentals-of-Ocean-pH.pdf
8) The maximum reading on the CO_2 meter used in the experiment is 5000 ppm, so the actual amount of CO_2 in the closed container was much higher.
9) Mark Pagani et al., "Marked Decline in Atmospheric Carbon Dioxide Concentrations during the Paleocene." Science 309, no. 5734 (2005): 600-603
10) The Chemical Composition of Air Exhaled from Human Lungs. Johnson, D (2018) Sciencing.com https://sciencing.com/chemical-composition-exhaled-air-human-lungs-11795.html

Ocean Acidification Lab

The best way to approach this lab is to NOT show the PowerPoint to the students before they design and perform their experiments. The PowerPoint is best used by the educator to see how the experiment should be set up and performed.

The educator should guide the students through the experimentation process. First, have the students research the topic. Note that almost all sources online will promote the argument that increased CO_2 will cause ocean water to become acidic. Reference #4 above is a good resource that argues the opposite, which is that increased levels of CO_2 do not make ocean water more acidic. After the students have done their research (and perhaps submitted a short list of their sources and a summary of their contents), the teacher should explain how to design an experiment to test a hypothesis.

First, explain that a testable hypothesis is one that can be easily determined to be false based on empirical data. In this case, there are three possible hypotheses: increased CO_2 levels in the air will decrease the pH of ocean water; increased CO_2 levels will increase the pH of ocean water; and there will be no change in the pH of ocean water when exposed to high levels of CO_2 in the air. Have the students divide themselves into groups of two or four (depending on the class size), and have each group write their preferred hypothesis on a sheet of paper. Have a short discussion with the class concerning their choices of hypotheses, then have each group write the reason why they chose the hypothesis they did. Please note that while the procedure will be the same for all groups, allow each one to choose their own hypothesis.

Next, have the students discuss what kind of results they would expect if their hypothesis was supported. Finally, ask the students what kind of data they would need to collect to determine if their hypothesis was supported or not supported. (Please avoid using the word "proved," as no hypotheses, scientific theories, or scientific laws are ever proved; they can only be supported. They can be disproved, however.)

Make sure the students have a good understanding of what pH is and how to measure it. You may also want to introduce the concept of an indicator solution. Younger students probably have experience with litmus paper, which is coated with an indicator. Unfortunately, litmus paper will not provide precise results. For that, you will need to use an indicator solution, which changes color in the presence of acids and bases. You may or may not want to introduce the concept of a buffer solution just yet depending on the age of the student. A good time to introduce the concept would be after the students have gotten their results.

You may want to give the students a chance to brainstorm ideas on experimental design before you introduce the steps for the experiment. The students will probably be able to come up with the main components, such as the need for sea water, a freshwater control, some container to prevent the carbon dioxide from escaping, a carbon dioxide source, some way to measure the concentration of carbon dioxide given off by the source, and some way to measure the pH. At this point, you will be allowing them to design their experiment in part before performing it. They should also identify the control, the experimental group, the constants, the independent variable (the amount of time the solutions were exposed to high CO_2 levels), and the dependent variable (change in pH). Each solution represents a separate experiment.

Once all the concepts have been covered and the hypotheses have been determined, it is time to introduce the experimental procedure using the PowerPoint. Be careful not to reveal the expected results in advance. The purpose of the experiment is for them to discover new information, as opposed to verifying the results of someone else's experiment.

After getting all the materials, give them the lab instructions (attached to the end of this lesson plan), and go over it with them carefully. They should have a lab notebook or other way of recording their procedure and their results. The lab notebook should be written in ink so that students cannot change any entry. Also make sure they know that they should use a single line to cross out mistakes and to never use anything to cover their mistakes, such as white-out. If you want, you may allow them to use the instruction sheet you give them instead of copying it into their notebook.

You may decide to use either tap water or bottled water. Be sure to drive off all dissolved gases by boiling then cooling the water first. You may also decide to use ocean water if it is easily obtained. Otherwise, use a kit designed to mimic ocean salinity for use in saltwater aquariums. One such kit is Instant Ocean Sea Salt. Bromothymol blue is a chemical that changes color with different pHs. This solution will stain clothing and skin and clearly should not be ingested. If possible, put the solution in dropper bottles to make it safer for the students to use.

Once the students have set up and run their experiments, it is important that they write a report that outlines their results and their conclusions. Remember, the conclusion must address the hypothesis (was it supported or not), and what this means about the threat of a slightly lower pH to ocean species. It is up to you to decide whether you want the report written or orally presented. The report, regardless of how it is presented, should include the following sections: introduction, summary of procedures, results, discussion and conclusion. The report should also include a section for further study and an examination of the experimental procedure to identify possible problems with it. Suggestions for correcting identified errors should also be included. Since much of the data will be qualitative, the results are best presented in pictures as is done in the PowerPoint summary. The quantitative data (pH values) should be presented in a graph. The independent variable should be plotted on the x-axis and the dependent variable should be plotted on the y-axis. Since there are several different solutions that were tested, the pH changes of each one can be plotted on the same graph using a different colored line. The student should include a key that labels each line.

An Experiment in Ocean Acidification: Why Buffering Matters Lab Instructions

Based on a lab of the same name by Marty Cornell (https://co2coalition.org/wp-content/uploads/2024/03/Teaching-Ocean-Acidification.pdf)

A follow-along video for this lab is also available: https://co2coalition.org/publications/an-experiment-in-ocean-acidification-why-buffering-matters/

The purpose of this experiment is to determine how high levels of atmospheric CO_2 will affect a sample of ocean water.

Materials: Instant Ocean Sea Salts or ocean water, dechlorinated tap or purified water, hydrometer, tap water, six 8-ounce clear cups, measuring cup, antacid tablets, bromothymol blue indicator, CO_2 meter, labels, gallon jug, translucent plastic storage container with lid, aluminum foil.

Experimental Procedure:

1. Prepare a solution of sea water by adding about ½ cup of aquarium sea salts to a gallon jug, then fill the jug with bottled water. Using a hydrometer, adjust the sale content to 35 ppt salinity. Or, if available, obtain about a gallon of sea water.

2. Label each cup with the following: (1) Tap Water Control, (2) Tap Water High CO_2, (3) Boiled Bottled Water Control, (4) Boiled Bottled Water High CO_2, (5) Tap Water + Sea Salts (35 ppt Salinity Control), (6) Tap Water + Sea Salts (35 ppt Salinity High CO_2)
3. Boil and cool the bottled water to remove any residual carbonation. Bottled spring water is likely to have some degree of natural carbonation and must be stabilized by degassing for 24 hours under open air or by boiling and then cooling.
4. Add 200 mL (or 3/4 cup) of the appropriate water to each cup
5. Add 30 drops of bromothymol blue to each cup and stir to mix.
6. Record the color of all solutions at the start of the experiment using the bromothymol blue color chart as a guide.
7. Record the ambient air CO_2 content in the room. Because human breath will increase the CO_2 reading, this is best done before the room is filled with students. Be sure to calibrate the CO_2 meter according to manufacturer's instructions before using.
8. Position the sensor of the CO_2 meter on an inside wall of the container, making sure it remains attached to the meter.
9. Place the three cups labeled "High CO_2" along with the measuring cup filled with about 200 mL of tap water inside the container. Add two antacid tablets to the water-filled measuring cup.
10. Place a sheet of aluminum foil over the container, then cover with the lid and lock it
11. in place. The aluminum foil will provide a tighter seal and preserve elevated CO_2 at about 5,000 ppm for at least ten hours.
12. Note the change of color of the specimens exposed to high CO_2 levels at 4 hours and 24 hours without removing the cups from the container. Record the pH of each solution, both experimental and control, using the bromothymol blue color indicator chart.
13. Remove the test cups from the container after 48 hours and record their pHs. Record the pHs of the control cups.

Results:

The results should be recorded in the lab notebook and also included in the report. It would be best if both pictures (qualitative data) and measured pH (quantitative data) were recorded. Be sure to include pictures of the lab set up, the color changes of the cups while in the container, and the final color changes at the end of two days.

Discussion and Conclusion:

The conclusion can be composed of only one line, which states whether the hypothesis was supported. The discussion should explain what the results mean and defend the conclusion. Questions that should be answered are whether or not the high levels of CO_2 in the container were a realistic representation of the amount of CO_2 in the Earth's atmosphere with increased CO_2 emissions, whether or not there was a change in the color and therefore the pH in the solutions, how the pH change of unbuffered water compared to the pH change of the buffered water, how the pH change of the control solutions compared to the pH change of the test solutions, and whether or not significant acidification of the ocean solution occurred.

Error Analysis and Suggestions for Further Research

This section can be optional, if desired. Mistakes always occur when setting up an experiment. List the mistakes and explain what possible impact these mistakes may have had on the results of the experiment. Also, suggest one or two ideas for further research and explain each.

Formative and Summative Assessment

1. What is a testable hypothesis? Give an example from this lab.
2. What are the necessary components of a lab experiment?
3. What are some examples of how empirical data can be presented in a report?
4. Why is it important to address the hypothesis when writing a conclusion?
5. What are some suggestions for further study or experimentation to determine the effects of atmospheric CO_2 levels on ocean water?
6. What are some procedures that could be improved in your experiment?
7. Is it likely that increased amounts of CO_2 in the atmosphere will significantly change the pH of ocean water?

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What is the CO_2 Coalition?

The CO_2 Coalition was established in 2015 as a 501(c)(3) for the purpose of educating thought leaders, policymakers, and the public about the important contribution made by carbon dioxide to our lives and the economy.

The CO_2 Coalition is a group of the top scientists, engineers and energy experts who study and report on the important contribution made by carbon dioxide to our lives and the economy.

Learn more at CO2Coalition.org and CO2LearningCenter.com.