Teaching Acid-Base Fundamentals and Introducing pH using Butterfly Pea Flower Tea

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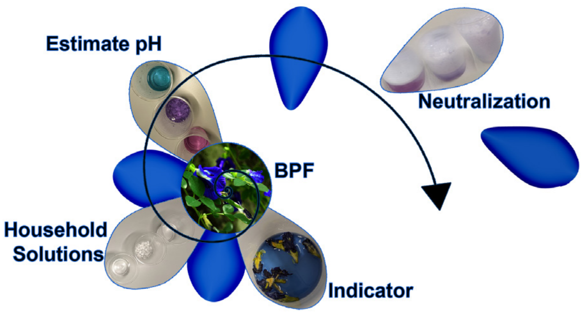
ABSTRACT

Stimulating interest in science at an early age is important for STEM education. This work details an educational activity utilizing the anthocyanins found in the butterfly pea flower (*Clitoria ternatea*). This activity was developed for use in official classroom settings, online, and/or at-home with parental or educator guidance. Primary and high school students aged 7 to 14 performed a straightforward extraction of anthocyanin pH indicators from *Clitoria ternatea* with hot water. Students were able to use this indicator and its vast range of colors to compare the acidity and basicity of different household solutions. Most responses recorded show that students used reasoning from the indicator and a subsequent chemical reaction to correctly differentiate acids from bases and compare their strengths. Overall, this activity's application of non-toxic and easily accessible indicators from the butterfly pea flower assisted in introducing young students to various concepts in acid-base chemistry, including acid/base strength and pH, solute dissolution, neutralization reactions, and qualitative analysis.

KEYWORDS

Informal Learning, Elementary / Middle School Science, High School / Introductory Chemistry, Public Understanding / Outreach, Hands-On Learning / Manipulatives, Acids / Bases, pH.

GRAPHICAL ABSTRACT



INTRODUCTION

Informal education programs in science, technology, engineering, and mathematics (STEM) tailored for early-age education curricula expose students to scientific phenomena through engagement, demonstrating the relevance of science in daily life. Participating in these programs at young ages cultivates students' interest in STEM, which is pivotal for influencing their future choice of STEM career.[1] Young students are often more attentive to visually stimulating reactions in chemistry,[2,3] and the opportunity to mix chemicals with their own hands contributes to future chemistry identity on career intention.[4] Acid-base chemistry is a natural phenomenon present in everyday life that is also important in research settings, such as wastewater treatment,[5,6] fertilizers,[7–10] catalysis,[11–15] drug development and delivery.[16–18] Additionally, pH indicators provide a direct visual portrayal of the concepts behind acids and bases. Thus, there is a unique opportunity in presenting acid-base chemistry in an exciting manner to help foster curiosity and drive young students to explore fundamental chemistry. Recently, there have been plenty of remote and at-home learning activities developed and implemented for accessible education during the COVID-19 quarantine. These activities cover topics such as titrations, equilibria, buffers, and redox chemistry.[19–21] However, these experiments often target undergraduate or high school levels, which is why we developed a hands-on activity involving pH indicators suitable for a younger demographic. This type of experiential learning activity enhances the students' overall learning.[22] Additionally, hands-on experiments stimulate primary and secondary school students' interest in STEM is essential for fostering a diverse and inclusive community in these fields of study.[23]

pH indicators come in numerous chemical forms, which result in differences in sensitivity, toxicity, cost, and accessibility. [24] Specifically, anthocyanins (common flavonoid compounds) produced by flowers, are a natural pH indicator.[25] Anthocyanins are usually made up of anthocyanidin, giving it its color, and a sugar molecule, contributing to its water-solubility. Anthocyanins are widely used as pH indicators due to their water-solubility and ability to cover a large range of pH values (pink color at pH 1-2, purple at 3, blue at 4-6, cyan at 7, dark green from 8 to 13, and yellow at 14).[25] For instance, non-toxic and naturally available red cabbage anthocyanins have been popularly used to teach students basic laboratory practices and acid-base chemistry.[26]

Despite the utility of red cabbage anthocyanins as vibrant pH indicators and their extraction requires lengthy processing, which prevents the use of red cabbage anthocyanins in brief learning activities and outreach events, especially considering that shorter engagement times are more suitable for children.[27,28] Furthermore, there is a risk of exposure of natural pathogenic bacteria from red cabbage to students which requires extra time for sterilizing containers and supplies.[29] Therefore, there is an interest in developing simple acid/base chemistry experiments for young students that involve safe, assessable, and affordable materials. These experiments would enable them to evaluate different acidic and basic household solutions.

Clitoria ternatea, also known as the butterfly pea flower (BPF), offers an opportunity to address this need, since it contains ternatins (a type of anthocyanin). These ternatins exhibit clearly distinguishable color changes at a broad range of pH compared to phenolphthalein, bromophenol blue and natural pigments like turmeric, *Hibiscus rosa-sinensis*, and Morning Glory.[29–34] Typically, anthocyanidins resemble the flavylium cation, which is an aromatic structure made up of three rings containing an oxonium ion. However, this polyphenolic structure is susceptible to oxidation, which can cause colors to fade. The ternatins found in BPF are more stable, so fading becomes less of an issue.[35] Additionally, BPF is safer than other common educational synthetic indicators, such as phenolphthalein, which is a GHS-classified health hazard. For example, the food-safe and indicator properties of BPF have facilitated its use as a freshness monitor of seafood.[36,37] Furthermore, obtaining the anthocyanin from the BPF can easily be done *via* extraction in warm water similar to a regular tea brewing process, offering rapid and environmentally-friendly preparation.[29,38] Overall, the BPF offers a promising route for developing a short acid-base chemistry outreach activity.

The Activity

The goals for the activity are to stimulate primary and secondary school students' interest in chemistry and teach them basic acid-base chemistry and the use of a pH indicator. In the first portion of the activity, the participants (age 7-18) compare the pH values of household solutions using the BPF indicator. In the second portion, students perform a neutralization reaction between baking soda (weak base) and two acids with different strengths. Additionally, the students will handle wet chemicals themselves, providing them with practical skills to prepare them for future courses, and lay the foundation for developing basic laboratory techniques.

Moreover, every material used in this activity is of commercial food-grade (safe for human consumption). This safety assurance makes the activity possible to perform at home, and the waste can be discarded into regular city sewers. We purposely implement this feature to address the recent needs in online and hybrid education. Finally, this activity is designed to be visual, and to have a large tolerance for human error. Even though we implemented the activity in a hybrid remote/in-person outreach event, the same procedures could be easily applied in a formal classroom setting.

Materials

All materials can be obtained from common grocery stores and E-commerce platforms and used as-is. The solutions to be tested by the participants were prepared with sodium bicarbonate (baking soda, Arm & Hammer™) and water, citric acid (7-UP™ and ReaLemon™ 100% Lemon Juice packets), and acetic acid (White Distilled Vinegar, Heinz). The indicator solution was made with BPF petals in tea bags (Hida Beauty Brand). The supplies the students used consisted of two 3 mL plastic pipettes and half-teaspoon plastic measuring cups. Clear plastic cups were used to contain each solution. Water (filtered by a drinking fountain) was heated using an electric tea kettle or microwave oven (see **Supporting Information**).

Hazards

The major potential hazard of this experiment is handling boiling or hot water from the tea kettle or microwave oven. The burn risk to students must be addressed by the instructor or supervising adults of the experiment: For primary school students, the adults should handle the hot water for the students and express care to avoid spills. For secondary school students, the students can handle the hot water if heat-resistant gloves are provided.

RESULTS

This activity was split into two parts; in the first, students compare strengths of household acids and bases using the BPF tea indicator. Second, students track pH changes by performing a neutralization reaction (**Figure 1**).

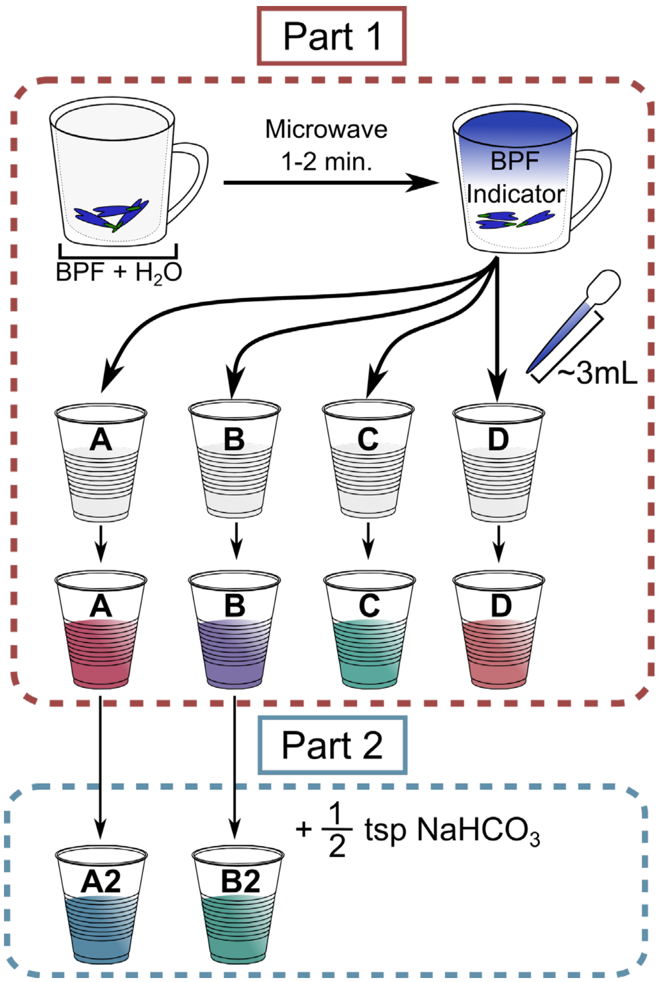


Figure 1. Schematic of the activity procedure. Students will first prepare the butterfly pea flower (BPF) indicator, then household acid-base solutions. Then, they will use the indicator to estimate the pH values of these solutions, and compare them (**A-D** are vinegar, lemon-lime soda, baking soda, and lemon juice, respectively). Finally, they will perform a neutralization reaction with baking soda, and make inferences based on the chemical reaction.

Part 1: Estimating pH of Household Acids and Bases.

The primary goal for this part is to teach the participants how to qualitatively analyze a variety of household solutions using the BPF indicator and a provided pH scale (see **Supporting Information**). The secondary goals are to introduce them to simple extraction, dissolving of solutes, usage of simple pipettes, and the general motor skills needed for handling of wet chemicals. Thus, the following procedures were given to the participants.

Like regular tea brewing, the BPF anthocyanins can be extracted from the dry petals (either loose-leaf or in tea bags) by hot water infusion (**Figure 2(I)**). Heating the dry flowers and water together in a household microwave oven for 1-2 minutes is a more efficient way to achieve the desired concentration. The final blue color should be no lighter than the one shown in **Figure 2(II)**. This intensity is sufficient for students to be able to make reasonable comparisons between the indicator color and the pH scale. The color of the indicator tea shows a pH of about 5-6 due to formation of carbonic acid from ambient CO_2.[39] Approximately 3 mL of BPF indicator was added to freshly prepared vinegar, lemon-lime soda, baking soda, and citric acid solutions (see **Supporting Information**). The indicator was added to each solution to make it clear that the solutions' environment was the cause of color change in the indicator. The expected color changes are shown in **Figure 2(III)**; where upon addition of the indicator, vinegar, lemon-lime soda, baking soda, and citric acid exhibit color changes to pink, purple, green, and pink, respectively. Matching the observed colors to the pH scale reference shown in **Figure 2(IV)**, the students rank the solutions from most acidic to most basic as follows: citric acid, vinegar, lemon-lime soda, and baking soda solution, and estimate pH values as follows: vinegar – pH = 1 or 2, lemon-lime soda – pH = 3, baking soda solution – pH = 8 or 9, and lemon juice – pH = 1 or 2. The exact pH values as measured with a pH meter were comparable to the estimated values from the BPF indicator. These values were 2.27 for vinegar, 3.00 for lemon-lime soda, 8.05 for baking soda, and 2.32 for lemon juice.

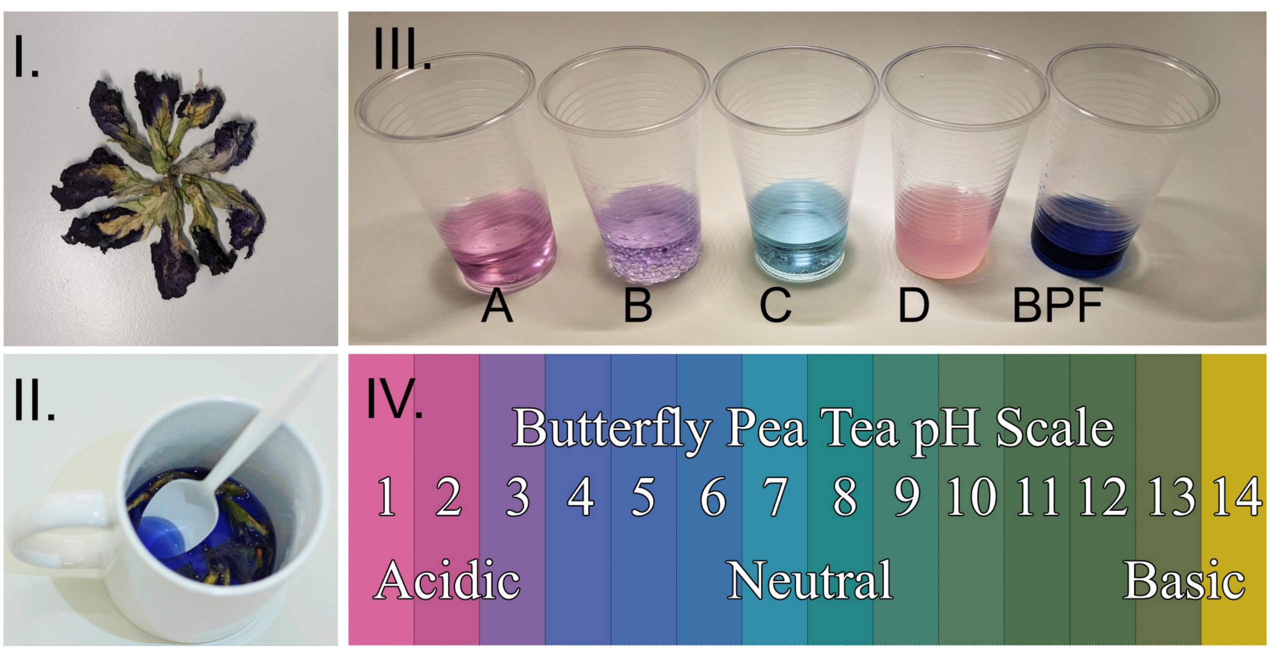


Figure 2: I) BPF petals are shown. **II)** BPF Tea (indicator). **III) A-D** are vinegar, lemon-lime soda, baking soda, and lemon juice, respectively, showing expected color after adding BPF indicator. BPF indicator is shown at the far-right. **IV)** pH scale reference provided to the students.

Part 2: Neutralization Reaction.

The primary goal of the second part of the activity is to show students additional experimental evidence suggesting that lemon-lime soda is a weaker acid than white vinegar. This was done by performing an acid-base neutralization reaction, so the students can observe the effects of the indicator. Baking soda was added to the vinegar (A) and lemon-lime soda (B) as shown in **Figure 3**. The students observed that the reaction between vinegar and baking soda produces significant bubbling, and that both reactions result in a color change. Sometimes the reaction would be rapid enough to cause overflow, which is a spectacle capable of evoking engagement and curiosity among the participants, especially the younger students.[1] This reaction confirms the students' initial interpretations of the pH values from Part 1 or gives them another opportunity to correctly identify that vinegar is a stronger acid than lemon-lime soda. Students are then asked to observe the color change following the neutralization reaction. They found that vinegar had changed color matching a pH range of about 5-6 and lemon-lime soda changed to about a pH of 7. Thus, the pH of the lemon-lime soda solution is still higher than that of the vinegar-based solution, which assists in providing qualitative reasoning emphasizing the different strengths of the two acids.

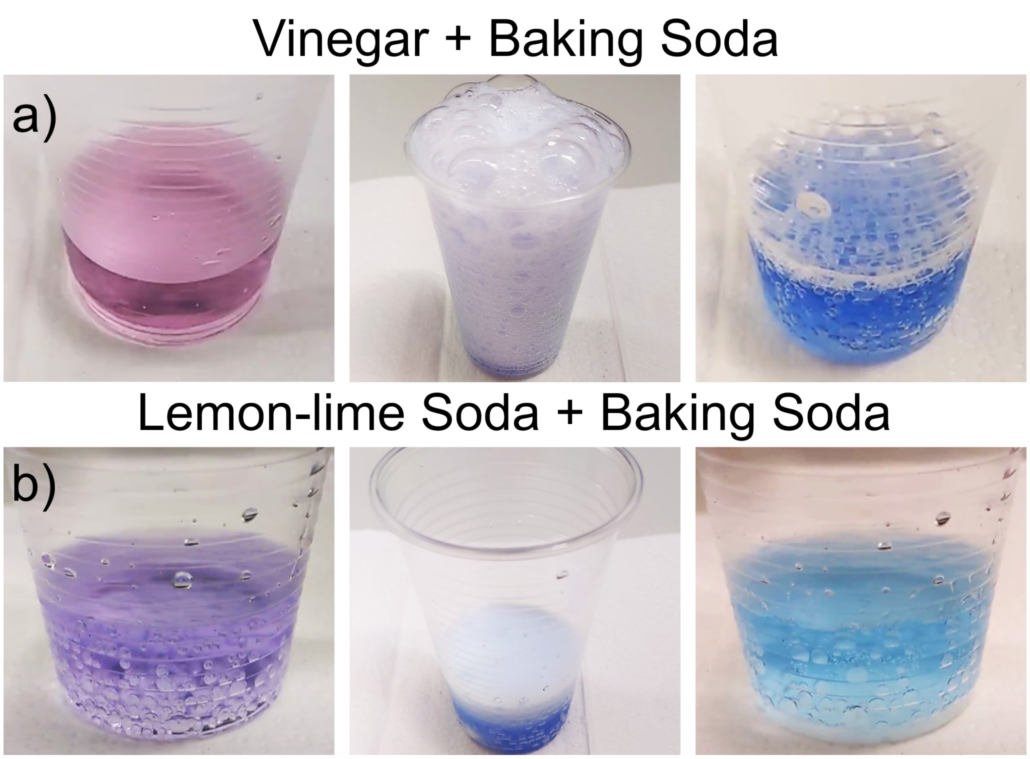


Figure 3: **a)** From left to right, vinegar solution with BPF indicator shows a light pink color (pH = 2), then shows major effervescence after baking soda is added. The final color is dark blue, indicating pH = 5-6. **b)** From left to right, lemon-lime soda solution with BPF indicator is purple (pH = 3). After baking soda, some bubbling occurs, then color stabilizes to cyan (pH = 7).

The observation of vivid color changes is the main strength of this activity because of how easily distinguishable different pH values become when using the BPF indicator. However, color recognition may pose a challenge to color-blind participants. We discuss additional options related to this in the following section.

Implementation

This activity was implemented at the University of Houston's STEM Zone outreach program with 101 students from public schools in the Houston Independent School District (HISD). The STEM Zone program invites students from the surrounding community who represent traditionally marginalized communities and underrepresented groups in the STEM field. This activity was performed simultaneously online and in-person, with 70 in-person elementary and junior high school participants (age 7-14). In person, elementary school students performed the activity in a separate classroom from junior high school students. About 30 students participated from home *via* a remote meeting platform. In both cases, UH undergraduates, graduate students, postdoctoral associates, and parents were available to assist in coordinating and guiding students throughout the activity. The parents' involvement was encouraged since it has a profound positive linkage to early interest in STEM.[40] Due to the affordability for each experimental kit ($1.50/kit), it was possible to provide each student with their own activity kit. However, if desired, this activity is also possible to perform in small groups.

In person, at the very start of the program, a microwave oven and an electric kettle were used to heat water to a temperature slightly below the boiling point. Online, students were also instructed to heat up their water if possible. Otherwise, they would prepare the tea the night before in room temperature conditions before achieving a usable indicator for the activity the next day. Additionally, presentation slides were shown for every section of the activity to all groups of students to manage the time within the hour allotted for the activity. Then, all sections were instructed to prepare the BPF indicator by incubating their tea bags in hot water. The students were then instructed to follow the experiment packet (**Supporting Information**). Guidance was provided by volunteers who rotated around the rooms, but elementary school students were also able to receive some additional guidance from their parents or guardians if needed. At the end of each part of the activity, students were prompted to record their observations and answer questions provided in their experiment packet (**Supporting Information**). A summary of the student responses to conceptual questions is provided in **Table 1**.

Table 1. Evaluation of Student Responses (age 7-14).

Evaluation Criteria (Questions)	*Percentage of correct responses*	*Total number of responses evaluated (n)*
PART 1:		
Is baking soda acidic, basic, or neutral?	78.9	19
Used the color of the solution as reasoning for their answer to the above question.	100	15
Is vinegar more acidic than lemon-lime soda?	62.5	16
Used the color of the solution as reasoning for their answer to the above question.	100	10
Correctly identified that vinegar and lemon-lime soda were both acids.	61.9	21
PART 2:		
How many students used the results of the neutralization reaction to answer: "Which solution had a greater change when you added the baking soda?"	87.5	8

The students generally showed a positive response to the activity. Younger students enjoyed the colorful changes of the solutions and in the neutralization reaction. All in-person participants were able to complete the activity within 45 minutes to 1 hour. However, although the online students were able to perform some parts of the activity, they were unable to fully complete each part within the given timeframe. Thus, it should be noted that online implementation requires more time, likely 1 h 15 min or 1 h 30 min in total. Additionally, care should be taken to avoid technical and organizational challenges in synchronizing the activity between all sections. For one, mobile or wearable microphones are better for effective hybrid implementation. Students worked individually, but some received guidance from helpers or their own parents. Responses were recorded if only given parental permission to do so. Out of the total number of responses evaluated for each criterion (as shown in Table 1), nearly 80% of students correctly identified that baking soda is basic. More than 50% of students correctly identified that vinegar was more acidic than lemon-lime soda. 62% correctly identified both lemon-lime soda and vinegar as acidic. All students with the correct answer for each question analyzed for part 1 used the color of the solutions in their reasoning. This suggests that the visual aid of the indicator color assisted in the student's understanding of the experiment and the utility of indicators. In the second part of the experiment, almost 90% of students who revisited the comparison between lemon-lime soda and vinegar were able to correctly note that vinegar had the stronger reaction with baking soda. The color change as shown in **Figure 3** allowed them to reassess their answers to part 1 and assisted them in identifying that white vinegar is indeed the stronger acid.

From the responses, we identified common misunderstandings by the students and various routes towards addressing them in future implementations of the activity. The suggested revised manual (**Supporting Information**) was cut down in text to prevent students from becoming lost in verbose questions, avoiding misunderstandings on the execution of the experiment. These types of questions were especially difficult for younger students and dampened the pace of the activity for them. Additionally, we observed students focusing too much on details such as obtaining exact measurements, which can set them behind, as well. As for conceptual misunderstandings, one common error included 12.5% students identifying white vinegar as less acidic than the lemon-lime soda because they compared the intensity of the color of the solutions rather than their shade. This was most likely due to students' tea solutions being more concentrated than others because of differences in extraction time. Additionally, the students could have had differences in the amount of indicator they dispensed into the household solutions. Therefore, it is important for instructors to emphasize to students to focus on the shade of the colors. In the revised manual (**Supporting Information**), online students without access to a microwave are now instructed to brew the tea at room temperature about 10-15 minutes before the program begins. This avoids discrepancies caused by BPF becoming darker when stored overnight. Another common misconception was that the indicator was responsible for changes in pH, rather than the solutions themselves. As such, it is important to clearly communicate the indicator's role for this activity. Moreover, the inclusion of lemon juice is redundant because the pH of lemon juice and vinegar are very close (vinegar at 2.27 and lemon juice's citric acid at 2.32). Therefore, future implementations can avoid the inclusion of lemon juice.

The worksheet problems included questions for students within a broad age range. Thus, to improve students' focus on questions relevant to their academic level, another improvement is to keep questions corresponding to different educational levels on separate worksheets. Therefore, in the revised copy of the student worksheet (**Supporting Information**), a dedicated challenge sheet is appended to the end of the worksheet for students who are ahead of the activity's pace. Additionally, UV-visible spectroscopy could be performed with a smartphone and Legos[41] to improve accessibility for vision-impaired or color-blind students, so that they may compare the colors of the solutions using spectra.[42] Finally, the use of a pH-meter could improve accessibility options and enable more quantitative comparisons. These modifications would also offer an opportunity to adjust this activity for implementation in undergraduate academics. Overall, the inclusion of these improvements is expected to enhance the efficacy of the experiment even further.

CONCLUSIONS

An introductory activity to acid-base chemistry, which was approachable for a wide range of students from different academic levels, was made from assessable and affordable over-the-counter materials. A chemical indicator from the butterfly pea flower was used to qualitatively estimate the pH of various household solutions. Due to the ease of access of the setup, the activity is versatile in that it can be performed in an official classroom setting as well as at-home with virtual guidance. In the activity, students compared pH levels of four different solutions utilizing a provided pH color scale. They also practiced dissolving solutes, simple handling of wet chemicals, and performing neutralization reactions. Students were then given assessment questions to gauge their understanding of acids and bases following the activity. Ultimately, most students (>50%) were able to correctly identify and compare the household acids and bases from most acidic to most basic, with many of the students using the color of the solutions to rationalize their ranking. Thus, this activity is a useful hands-on tool for teaching students about acid/base chemistry and is amenable to implementation at home or in grade school chemistry or science classes (US K-12).

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Learning objectives, Materials, and Hazards

Implemented student worksheet

Revised student worksheet

Teacher manual & Key

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NOTES

The authors declare no conflict of interest.

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