JOURNAL OF CHEMICAL EDUCATION

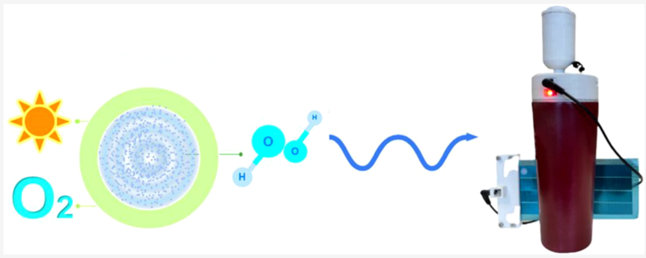
pubs.acs.org/jchemeduc Article

Invention as a Complement to High School Chemistry

Elliott Ewell, Hailey Haglid, Emily Truszkowski, Clare Walicki, Patrick De Meulder, Matthew De Meulder, Theodore Stephens, Xun Zhang, Carina Trama, Ashli Hamilton, David Mo, John Wohner, Ryan Furrey, Michael Labowsky, Anthony Perry, Shu Hu,* and Hsuan Lillian Labowsky*

Cite This: https://doi.org/10.1021/acs.jchemed.2c00135 Read Online

ACCESS | Metrics & More | Article Recommendations



ABSTRACT: Does invention belong in the chemistry classroom? This article attempts to answer this question by describing how invention education first took root in a chemistry class at Ridgewood High School in Ridgewood, NJ, and then expanded to other students with diverse interests to find a solution to two worldwide problems: satisfying the need for safe drinking water and reducing plastic waste. Specifically, it describes the students' journey step-by-step during the COVID-19 pandemic to invent a self-sanitizing and sustainable Solar Aqua Tech water bottle. The concept underlying this invention was to quickly produce hydrogen peroxide (H_2O_2), a well-known sanitizing agent, on-demand within the confines of a bottle using only water, dissolved oxygen (O_2), and solar power to eliminate pathogens in untreated water. Students had to convert this chemistry classroom concept into reality without a prescription and without knowing if their goal was even attainable. Since the journey did not take a linear path but veered in different directions as unexpected problems arose, the students sought guidance from academics, mentors, and local experts. Along the way, they acquired new knowledge with deepened understanding and overarching perspectives. Success was achieved only after many setbacks. In the end, the sense of accomplishment for finding a solution to two global problems instilled confidence in the students that, with empathy, perseverance, and resilience, they are equipped with essential skills to tackle 21st-century challenges. Invention, therefore, can be a valuable complement to the standard chemistry curriculum and is unparalleled in sparking a lifelong passion for learning.

KEYWORDS: *High School/Introductory Chemistry, Interdisciplinary/Multidisciplinary, Hands-On Learning/Manipulatives, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Problem Solving/Decision Making, Communication/Writing, Electrochemistry, Green Chemistry, Water/Water Chemistry*

■ INTRODUCTION

Does invention belong in the chemistry classroom?

Typical high school chemistry projects are developed by teachers with targeted pedagogies, well-established procedures, and quickly attainable goals. They are usually fun experiences for students to confirm various concepts. Unfortunately, without engagement in the development process, the students' interests and memories often fade shortly after the project ends.

Invention projects are different as the chemistry teacher (H.L.L.) learned at a Lemelson-MIT (LMIT) Professional Development Summer Workshop in 2019. They are student-driven with no prescribed procedures or even guarantees of success. The students have to identify a problem, develop a concept, and then work to reduce the concept to practice. Knowing their invention is for the common good is an essential motivating factor, especially when facing setbacks. Empathy unlocks critical thinking, creativity, and resilience,[1] qualities needed to accomplish the task. Although invention journeys change paths as unexpected problems arise, there are clear benefits from the students' perspective. They acquire new knowledge and skills and learn the value of collaboration and teamwork.

From the perspective of educators, with the inclusion of engineering practices in the Next Generation Science Standards,[2] invention is an engaging and inclusive approach to engineering design that encourages boundary transgression and transdisciplinary learning.[3] It integrates core pedagogies with a high order of mental activity that the inventor usually accesses even if the invention is not a commercial success.[4] An

Received: February 17, 2022
Revised: April 2, 2022

invention project, after all, connects the classroom to real-world problem solving that makes learning relevant.

In order to inspire her students to take the invention path, H.L.L. decorated her classroom with NJ State Inventor Thomas Edison's quotes, a copy of his light bulb patent, and photos of his electric car. She issued a *call for inventors* schoolwide with flyers encouraging students to join the newly formed engineering club where she was the advisor. To initiate the club, she asked members to form teams and talk with friends, police officers, and firefighters in an attempt to identify a school or community problem in need of an innovative solution. Knowing that invention for the common good is an essential motivating factor, H.L.L. introduced students to the UN Sustainable Development Goals (UNSDGs).[5] The UNSDGs outline 17 ambitious goals that would benefit the world. They provide an entry for students to explore the science of issues like clean water or pollution and align local issues with these problems of global significance. This scaffolding provided the students a starting point to leverage their chemistry knowledge in the context of invention.

This article focuses on the particular student-led invention journey at Ridgewood High School (RHS), Ridgewood, NJ. The RHS students took advantage of the LMIT grant and the professional guidance of online webinars/training courses set up by the LMIT Program. By the end of this journey, the students invented a self-sanitizing, sustainable, point-of-use (POU) Solar Aqua Tech (SAT) bottle that quickly produces hydrogen peroxide (H_2O_2), a well-known sanitizing agent, on-demand using only water, dissolved oxygen, and solar power to purify drinking water. The effectiveness of SAT in eliminating water-borne pathogens in raw water was certified by a New Jersey Department of Environmental Protection (NJDEP) accredited laboratory. The certification validated that the novel SAT technology could produce immediate health benefits by purifying drinking water and reducing plastic waste in the environment. Further, the thrill of competitions and presentations with stakeholders and experts sustained the student's sense of accomplishment when their goals were reached. It was an educational experience they will long remember. For high school chemistry teachers seeking to develop students' enduring understandings with overarching ideas, invention could be a complementary enrichment component concurrent with the regular chemistry curriculum.

As shown in the timeline (Figure 1), the journey spanned two school years with six stages chronologically: conceptualization, team building, design and testing, certification, prototyping, and completion. Each stage provided significant educational benefits, as reflected in the italicized comments of the RHS student participants.

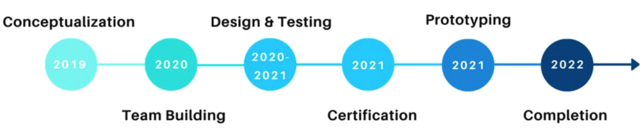


Figure 1. Timeline of the invention cycle of the RHS Solar Aqua Tech water bottle.

■ CONCEPTUALIZATION

Going through inventing our Solar Aqua-Tech bottle opened my eyes to the real invention process with collaboration and cooperation as key components. —RHS Student

The RHS invention journey started with four chemistry students, sitting at the same table as a cohort, responding to their teacher's call to solve problems in their school and community that aligned with the UNSDGs. They were shaken to read a WHO-UNICEF report that stated that one in three people worldwide does not have access to safe drinking water.[6] The demand for clean water is so universal that an estimated one million plastic bottles are purchased worldwide *every minute*. With a 450 year lifecycle, single-use bottles are an ecological nightmare.[7] Some students who belonged to the school's hiking club immediately identified the need for safe drinking water without disposing of plastic bottles. The four students committed to finding an innovative solution to tackle both the safe drinking water[8] and plastic waste problems.[9]

Students were familiar with hydrogen peroxide (H_2O_2), a powerful sanitizing agent that could be made from water and dissolved oxygen. They sought advice from Professor Shu Hu of Yale University, a long-time mentor to the chemistry honors class through an NSF high school outreach program. The inquiry led students to read Hu's paper titled "Membrane-Less Photoelectrochemical Devices for H_2O_2 Production".[10] They learned an electrochemical cell with an uncoated titanium cathode and a titanium anode coated with Hu's manganese-alloyed titanium oxide (Ti,Mn)Ox catalyst[11,12] could quickly produce H_2O_2 at a *low* voltage on *both* the anode and cathode according to the following reactions:

$$O_2 + 2H_2O \rightarrow 2H_2O_2 \quad E\text{cell} = -1.083\ \text{V}$$

$$\text{cathode: } O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \quad +0.68\ \text{V}$$

$$\text{anode: } 2H_2O \rightarrow H_2O_2 + 2H^+ + 2e^- \quad -1.763\ \text{V}$$

Reading Hu's paper empowered them to envision a POU water bottle using a version of Hu's electrochemical cell with a small portable solar panel to provide the required power. A POU approach is "the most promising intervention strategy for producing immediate health benefits in the most vulnerable rural populations".[13] The concept of a self-sanitizing Solar Aqua Tech (SAT) water bottle was thus born.

Community Engagement

Just days before the COVID-19 pandemic closed RHS, the SAT team visited Ridgewood Water (RW), the local water department.[14] RW is a New Jersey Department of Environmental Protection (NJDEP) accredited facility that meets the protocols set by the US EPA and the NSF. At the meeting, the team learned about the operation and problems in water treatment. They also learned that the RW lab routinely performs certified bacteria tests to ensure the quality of the town's drinking water. RW offered to perform certified bacteria tests at no cost, an offer that proved essential for the project.

RW revealed that an advanced oxidation process (AOP)[15,16] was piloted in a nearby water treatment facility. In the AOP, highly concentrated H_2O_2 is delivered to the facility and carefully metered into the raw water to achieve the proper concentration, between 1 and 15 ppm, which is needed for killing pathogens. This information set the goal for H_2O_2 concentration in the SAT bottle and showed the value of establishing relationships with local experts.

STEM Competitions

The four-student team had to further develop the SAT concept from home in light of the pandemic. They began to build a conceptual model for presentation at STEM competitions

https://doi.org/10.1021/acs.jchemed.2c00135
J. Chem. Educ. XXXX, XXX, XXX−XXX

Table 1. Comparison of Solar Aqua Tech to Existing Water Sanitizing Technologies

	Technology				
	Microfiltration	Ion Exchange	UVC LED	NaDDC Tablet	Solar Aqua Tech
Sanitizing power	Bacteria removed but not killed	Bacteria removed but not killed	Bactria killed but not in cloudy water	Bacteria killed with NaDDC residue	Bactria killed throughout with no residue

which kept them engaged in the invention process. As a study shows, students who participate in STEM-related competitions are more likely to express continued interest in STEM disciplines.[17] Participation in STEM competitions with deadlines and rubrics builds team spirit, hones communication skills, and boosts resumes on college applications.

The first competition was the NJSTEAM Tank Challenge. The team applied their chemistry, media, and artistic talents for the first round to create a 2 min video that pitched the SAT concept. The team earned a place in the final round that, unfortunately, was canceled due to the pandemic.

The team then participated in the 2020 Thomas Edison Pitch Contest. On the basis of a video submission, the team was selected as one of the three national finalists in the high school category. The final competition was held via a video conference. After an oral presentation, the team faced questions from a panel of judges. This experience allowed the students to demonstrate their communication skills and the chemistry that formed the basis of the SAT bottle. As a result, they were awarded a 3D printer for finishing first in the competition. With the COVID-19 closure of RHS, the printer was set up in a student's home and would prove to be indispensable later in the project.

■ TEAM BUILDING

What I have learned over this year is how a successful project manager needs to know everything about all aspects of their team. —RHS Student

The results of these competitions inspired the team to continue the project and apply for a competitive grant from the LMIT Program. With this grant, the team formally became the LMIT InvenTeam, one of only 13 in the country. Accepting the LMIT grant came with expectations to properly account for the grant, participate in technical reviews, and produce a working prototype for display and celebration at the LMIT EurekaFest at the end of the grant cycle.[18]

LMIT guidelines provided the team with the needed structure and discipline. Seven new members were added to the initial four, including an engineering design teacher and chemical engineer mentor. The makeup of the new team reflected the gender and racial diversity of RHS. A Google Classroom and shared Drive were created to organize and communicate among three subgroups: chemistry, engineering, and business. The chemistry group's primary task was to develop the SAT electrodes. The engineering group was primarily tasked with building, designing, handling 3D printing components, and integrating electronics. The business group created a budget, tracked expenses, performed market searches, and oversaw videos, presentations, newsletters, and social media. A project manager was selected to hold weekly virtual meetings and coordinate the activities of each group. Thus, the InvenTeam set to work throughout the summer and the following school year as an extracurricular activity.

Remote Inventing

Fabrication Day was an incredible boost to the team's morale. —RHS Student

Like other obstacles in life, the pandemic posed a tremendous challenge for teachers and students. RHS transitioned to a virtual/hybrid mode. The students worked from home, communicating via email, phone, text, or weekly videoconference with teachers and mentors. Contactless delivery was the norm. Teachers had to make tough choices to modify and perform tasks that needed supervision. During a lull in the pandemic, teachers set up a safe *fabrication day* under a tent outside the RHS building. With the appropriate PPE and social distancing, the team was able to gather after eight months of virtual meetings. They titrated H_2O_2 samples, machined parts, spray painted, and tested solar panels. It was such a fun, productive, and memorable day of the invention journey and a testament to what creative thinking could accomplish.

Market Research

An invention has to be unique and useful. To eliminate devoting resources to an invention that has already been patented or commercialized without a patent, the team conducted thorough patent and market searches. These searches indicated no patents or products that use the SAT technology.

The next step was to evaluate if there would be a market for an SAT bottle. The business group performed market research and produced a comprehensive report on the $31 billion water treatment industry. Knowing specifically what consumers want is essential. Students passed the Human Subject Research course and developed an Institutional Review Boards (IRB)[19] approved survey for one class of beneficiaries, avid hikers. The survey showed that 80% of hikers were not satisfied with the current sanitizing methods and preferred an innovative way to purify water.

The market searches also established that there were basically three types of POU water sanitation methods: filtration (such as activated carbon, ion-exchange cartridges, and microfiltration straws);[20] UVC sanitation;[21] and chemical tablets. Each of these methods, however, suffers from limitations. For example, accumulated bacteria on filter cartridges could be ingested upon reuse, defeating the purpose of this disinfection method. UVC sanitation is recommended only for clear water. Consumers are specifically instructed not to use the bottle with murky water due to the attenuation of the UVC light.[22,23] Finally, consumers were concerned about ingesting chemicals and complained about the limited shelf life and aftertaste of the sodium dichloroisocyanurate (NaDDC) tablets.

As shown in Table 1, the SAT concept of producing sanitizing agents on-demand is unique in the water purification market. It kills, rather than just removing bacteria throughout the water, clear or cloudy. As opposed to NaDDC, H_2O_2 occurs naturally in the lungs, gut, and thyroid gland to marshal white cells to defend against infections.[24,25] SAT is chemical

https://doi.org/10.1021/acs.jchemed.2c00135
J. Chem. Educ. XXXX, XXX, XXX−XXX

technology that mimics how the body produces/regulates H_2O_2.[26,27]

Design Specification

This project has provided me with many opportunities in different fields like sustainability, chemistry, engineering, and human resources, helping me find my passion. —RHS Student

After verifying that SAT was unique and useful, the team established design specifications. This step was essential as a standard for measuring progress. The team set a goal of producing H_2O_2 in sanitizing concentrations between 1 and 15 ppm in 700 mL (24 oz.) of water within 30 min using only a solar panel and/or a solar-rechargeable 9 V battery. They reasoned that consumers would become impatient waiting any longer than 30 min.

The team next began to consider what materials should be used. In this regard, the students took a professional-level course and were certified in sustainable design. Guided by what they learned, they chose only biodegradable and recyclable materials so that the bottle would reduce plastic waste. A commercially available stainless-steel bottle with a large mouth and tapered bottom to fit a coffee holder was chosen due to corrosion resistance and durability. Indeed, every component was carefully assessed. Learning about sustainable design was as enlightening as it was educational.

■ DESIGN AND TESTING

My involvement allowed me to understand how influential a simple shift in perspective can be and the slight difference ideas could make on projects. —RHS Student

By attempting to develop a new technology, the team was entering uncharted territory. Students engaged in hands-on learning coupled with critical thinking and creativity. They were exposed to advanced concepts and methods not taught in the class and acquired/honed skills such as CAD drawing, 3D modeling, and 3D printing to aid this task.

Atomic Layer Deposition

Hu used the atomic layer deposition (ALD) method to catalyst-coat all of the anodes. Although they could not participate in the coatings, the students studied this cutting-edge technology. They learned that ALD applies such a strongly bonded atomic layer of catalyst on the titanium substrate that leaching is minimal and, consistent with sustainable design, requires a minimal amount of catalyst.

Electrode Development

Developing a suitable set of electrodes for an electrochemical cell that met the design specifications required testing several configurations in over 100 experiments. Titanium (Ti) was used for all of the anodes and cathodes. Experiments were conducted in 700 mL (or equivalent) of distilled water for consistency during the development phase. An industry-standard HACH Hydrogen Peroxide Test Kit based on drop count titration was used to measure H_2O_2 in two ranges: 0−4 ppm and 0−10 ppm.[28] In addition, Indigo strips in the range 1−100 ppm provided quick checks.

The first set of experiments was performed with cylindrical electrodes consisting of a coated anode rod inside a cathode cylinder with drilled holes so water/oxygen could diffuse into the anode and H_2O_2 could diffuse out. Unfortunately, this simple design proved ineffective due to insufficient catalyst surface area. The best result produced only 0.01 ppm of H_2O_2 in 2 h (Table 2), far outside the design specifications.

Table 2. Best Results Summary in 700 mL (or Equivalent) of Distilled Water

Electrode Design	Run time(mins)	H_2O_2(ppm)
Cylindrical	120	0.01
Planar Sandwich (no stir)	120	0.1
Planar Sandwich (stir)	120	2
Mesh Sandwich (stir)	15−60	3−6

The subsequent experiments were conducted using a *planar sandwich* design where a double-coated anode plate was sandwiched between two Ti cathode plates. As before, holes were drilled in the cathodes for diffusive mass transfer. A thin Teflon spacer, typically used to bake cookies, with open areas, provided insulation. This design provided roughly four times the catalyst surface area of the cylindrical design; however, the 0.1 ppm produced was below sanitizing levels (Table 2).

Mass Transfer

Chemistry students often wonder why reactions do not occur as fast in practice as they should based on theoretical kinetics.[29] In principle, the electrodes should have quickly produced an abundance of H_2O_2. In practice, they did not because the actual production rate also depends on how quickly reactants reach and products escape from the reaction site; in other words, it depends on mass transfer. In the cylindrical and initial planar designs, mass transfer was limited by the relatively slow process of diffusion. Upon placement of a 3D-printed stirrer powered by a small DC motor in proximity with the planar sandwich, mass transfer was enhanced by convection. Stirring also had the side benefit of oxygenating the water. With the convective effect of stirring the H_2O_2, the yield improved dramatically to a sanitizing level of 2 ppm (Table 2). However, the 2 h run time required to reach this concentration was too long. Further refinements were needed.

The final design consisted of Ti meshes instead of Ti plates. The open structure of the mesh would enhance mass transfer while avoiding manually drilling holes. Similar to the planar design, the *mesh sandwich* design had a double-coated Ti mesh anode sandwiched between two uncoated mesh cathodes, electrically insulated with a Teflon spacer as before. The entire assembly was held together by a 3D-printed holder (Figure 2). When coupled with the DC-powered stirrer, the mesh design would have the additional advantage of convective transfer both along and through the electrodes.

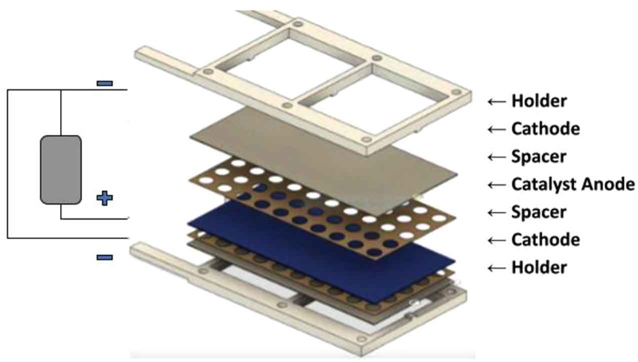
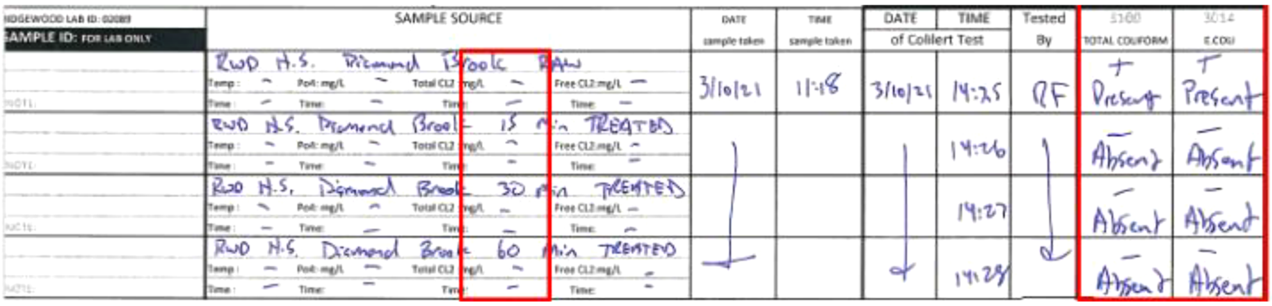


Figure 2. Mesh sandwich electrode schematic.



AMPLE ID: FOR LAB ONLY	SAMPLE SOURCE	DATE sample taken	TIME sample taken	DATE of Colilert Test	TIME of Colilert Test	Tested By	TOTAL COLIFORM	E.COLI
	RWD H.S. Diamond Brook RAW	3/10/21	11:18	3/10/21	14:25	QF	+ Present	+ Present
	RWD H.S. Diamond Brook 15 min TREATED				14:26		− Absent	− Absent
	RWD H.S. Diamond Brook 30 min TREATED				14:27		− Absent	− Absent
	RWD H.S. Diamond Brook 60 min TREATED				14:28		− Absent	− Absent

Figure 3. Diamond Brook water bacteria certificate: certified Total Coliform-free and *E. coli*-free.

The mesh sandwich was thoroughly tested by varying the electrode voltage, mesh combinations, stirring speed, and the % open area of the Teflon spacers. The sanitizing level was finally achieved within 30 min (see Table 2) with 2 in. × 4 in. mesh electrodes and a stirrer motor powered with 9 V DC, the maximum voltage of a small solar panel. In the end, the mesh sandwich results represented a 300−600-fold improvement compared with the initial cylindrical design.

The importance of the surface area and convective mass transfer on reaction rates, concepts typically taught in college-level chemical engineering courses, was a significant learning experience for high school chemistry students.

CERTIFICATION

Up to this point, the team showed they could produce sanitizing H_2O_2 in distilled water. However, the true test was to eliminate waterborne pathogens in raw water. In this regard, aquarium water is notoriously filled with bacteria, so it was a good choice for testing SAT's sanitizing power. Four samples were sent to RW for testing: raw aquarium water and aquarium water that was SAT treated for 15, 30, and 60 min. RW performed a US EPA-approved Colilert test covering WHO's designated indicators of hazardous water-borne pathogens,[30] such as Total Coliform bacteria, *E. coli*, Legionella, Cryptosporidium, and Giardia. The test results showed that the raw aquarium sample had Total Coliform bacteria, while all three SAT treated samples were certified to be Total Coliform-free.

This was great news but did not go far enough because the aquarium water did not have *E. coli*. Another test had to be performed with water from a natural source: Diamond Brook, which runs next to the RHS football field. The above procedure was repeated by submitting the raw Diamond Brook water and raw water that was SAT treated for 15, 30, and 60 min. As shown in the certificate (Figure 3), the raw Diamond Brook water was found to have both Total Coliform and *E. coli*, while all SAT treated samples were certified to be Coliform-free and *E. coli*-free. This meant the SAT effectively eliminated these pathogens in as little as 15 min, the "Eureka!" moment for the team.

PROTOTYPING

> *This experience helped me understand everything that goes into creating a project, the research, the implementation, and the constant changing of needs and ideas. —RHS Student*

While the ability to kill pathogens was the *heart* of the SAT bottle, the *brain* was the electronic circuit that controls the sanitation cycle. The chemistry group communicated the power requirements to the engineering group, who then faced the challenge of making an efficient *brain* small enough to fit into a suitably designed 3D-printed cap for the stainless steel body. This step required close coordination between electronics and 3D printing. The cap went through several iterations until it finally accommodated not only the electronics but also the stirrer, battery, motor, and electrodes.

The bottle was powered either directly with a solar panel or by a 9 V DC solar-rechargeable battery when there was insufficient light. The circuit was based on an ATtiny45 programmable microprocessor.[31] The control sequence worked as follows: The DC stirrer motor and electrodes were energized with the push of the start button. A red LED on the cap turned on, indicating that the cycle started. After 30 min, the microprocessor turned off the red light, motor, and electrodes and turned on a green light indicating the water was safe to drink.

At this point, the InvenTeam thought the project was complete, but their dedication was to be tested one more time.

Refinement

LMIT required a Mid-Grant Technical Review (MGTR). Outside experts' review of a project is another critical step in the invention process. Inventors are often so focused on their work that they overlook factors obvious to objective observers and stakeholders. The MGTR served to alleviate possible tunnel vision as well as to cement the student's identity as inventors, thus motivating them to continue developing/improving their inventions.[32]

The MGTR raised questions about the safety of drinking water with H_2O_2 residue. While ppm-level H_2O_2 is safe to drink, to ease users' concern, provision was made in the electronics for a 255 nm UVC LED to convert H_2O_2 residue back to water and O_2 and serve as an auxiliary sanitation method.[33] A UVC LED was purchased as an accessory but not installed due to safety concerns.

Another MGTR suggestion was to evaluate more water sources. This suggestion led to discovering that one commercial spring water source caused immediate catalyst deactivation. An internet inquiry revealed the problematic water source had a high arsenic content. This was another college-level lesson for students: Arsenic could poison the catalyst, rendering SAT ineffective.

This was a serious problem. The team originally thought a simple coffee filter to remove large particles that could plug electrodes was all that was needed. In light of the arsenic problem, the filter had to be more robust. The team designed and 3D-printed a prefilter accessory containing activated carbon/ion-exchange resin, similar to those commercially available, that could eliminate arsenic and other hazardous chemicals/heavy metals.

https://doi.org/10.1021/acs.jchemed.2c00135
J. Chem. Educ. XXXX, XXX, XXX−XXX

The team next had to tackle the problem of the deactivated catalyst. They discovered full catalytic activity was restored after dipping the electrodes in vinegar for a few minutes. The ability to restore instead of disposing of spent electrodes became another sustainability feature of SAT. As this example demonstrates, problems encountered during an invention journey are often unexpected educational opportunities. In this case, the students coupled what they learned in chemistry class with critical thinking and new insights into solving a potentially fatal flaw in their invention.

3-in-1 Solar Aqua Tech Water Bottle

My experience has taught me what it means to apply engineering to the real world and how much of a difference we, as young students, can make if we work together to invent. —RHS Student

The team collectively used their artistic talents to make the SAT water bottle functional and attractive. The stainless-steel bottle with the 3D-printed cap was painted with RHS's color, maroon. A laser engraver was used to etch a custom logo. Figure 4 shows the "3-in-1" SAT prototype water bottle in operation powered by a solar panel with the prefilter accessory on top. This was called "3-in-1" because it has two other sanitizing technologies (UVC, prefilter) in addition to SAT. As such, it would be the only POU water bottle on the market that eliminates not only pathogens but also harmful chemicals, minerals, and heavy metals.

Figure 4. 3-in-1 Solar Aqua Tech water bottle in operation with prefilter powered by a solar panel.

■ CONCLUSION

Before this experience, I would never have considered myself an inventor. However, this experience has opened my eyes to other career and life paths that I would not have expected. —RHS Student

The RHS invention journey began with a "look for a problem" assignment that inspired empathetic students to seek solutions for the global problems of the scarcity of clean drinking water and the abundance of plastic waste. Their concept of in situ production of sanitizing H_2O_2 was successfully reduced to practice by expanding the team with diverse interests and by seeking guidance from teachers and mentors. Despite COVID-19 constraints, the many trials and failures, their hard work, dedication, creativity, resilience, and success in STEM competitions resulted in a workable *Solar Aqua Tech (SAT)* POU water bottle prototype that was certified to eliminate water-borne pathogens using only water, dissolved oxygen, and the power of the sun.

Along the journey, the students applied what they learned in chemistry class with a newly acquired insight into college-level subjects: sustainable design, ALD, electrocatalytic reactions, and convective mass transfer. They also had to develop/hone skills in CAD design, 3D printing, electronics, management, art, communications, and media to reach their goal.

The enthusiastic audience responses to the presentations of this two year project at the local science fair, EurekaFest, town council, and Board of Education meetings were gratifying. The final presentation at Ridgewood's George Washington Middle School, where they introduced over 200 enthusiastic eighth graders to the invention culture, was perhaps the most gratifying. The message that a Solar Aqua Tech water bottle can provide safe drinking water that prevents illnesses, thereby saving lives while reducing plastic waste, was a message that resonated with all audiences.

From the perspective of university research, educators recognize that invention integrates basic research materials with K−12 chemical education. Invention education, especially when coupled with programs like the NSF high school mentorship, creates a new pathway that connects basic university research to practices, thus contributing to the US's competitiveness and success in fundamental research as called for in the 2018 Federal STEM Strategic Plan Committee on STEM Education.[34]

In conclusion, invention could be introduced either in class or as a club activity by simply encouraging students to apply the classroom knowledge to a societal problem. That problem could be on a grand scale or something that helps a friend or a neighbor but always should align with UNSDGs. Once students select a topic, teachers play a vital role in guiding and empowering the students by connecting them with subject matter experts from the community and academia. A connection to academia is particularly important since it gives the students a glance at cutting-edge technologies and better prepares them for college.

Invention projects tend to be long-term. Keeping the students engaged over the long haul is essential. Choosing a project that appeals to the student's natural empathy is important. Entering STEM competitions also motivates students and prepares them to meet deadlines. These competitions often provide materials such as maker kits and monetary prizes that, as with the LMIT grant, can be used to turn concepts into realities along with provisions for teacher stipends. Participating in competitions has the further benefit of enhancing college applications, so students, not teachers, propel the project forward. Finally, students always take special pride in their accomplishments, knowing the work is the result of their own initiative.

On the basis of the RHS experience, the answer to the question "Does invention belong to the chemistry classroom?" is yes! Invention is a vehicle to 21st-century skills and new knowledge. That invention makes classroom lessons relevant with enduring understandings and overarching ideas suggests

https://doi.org/10.1021/acs.jchemed.2c00135
J. Chem. Educ. XXXX, XXX, XXX−XXX

that it should be a complement to the regular chemistry curriculum to endow students with lifelong passions for learning.

■ AUTHOR INFORMATION

Corresponding Authors

Shu Hu − *Chemical & Environmental Engineering Department, Yale University, New Haven, Connecticut 06520, United States;* orcid.org/0000-0002-5041-0169; Email: shu.hu@yale.edu

Hsuan Lillian Labowsky − *Science Department, Ridgewood High School, Ridgewood, New Jersey 07451, United States;* orcid.org/0000-0002-1661-3798; Email: hlabowsky@ridgewood.k12.nj.us

Authors

Elliott Ewell − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

Hailey Haglid − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

Emily Truszkowski − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

Clare Walicki − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

Patrick De Meulder − *Ridgewood High School, Ridgewood, New Jersey 07450, United States;* Present Address: Georgetown University, 3700 O St NW, Washington, DC 20057

Matthew De Meulder − *Ridgewood High School, Ridgewood, New Jersey 07450, United States;* Present Address: Georgetown University, 3700 O St NW, Washington, DC 20057

Theodore Stephens − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

Xun Zhang − *Ridgewood High School, Ridgewood, New Jersey 07450, United States;* Present Address: Purdue University, 610 Purdue Mall, West Lafayette, IN 47907

Carina Trama − *Ridgewood High School, Ridgewood, New Jersey 07450, United States;* Present Address: University of Michigan, 500 S State Street, Ann Arbor, MI 48109

Ashli Hamilton − *Ridgewood High School, Ridgewood, New Jersey 07450, United States;* Present Address: John Jay College of Criminal Justice, 524 W 59th Street, New York, NY 10019

David Mo − *Ridgewood High School, Ridgewood, New Jersey 07450, United States*

John Wohner − *Visual & Fine Arts Department, Ridgewood High School, Ridgewood, New Jersey 07451, United States*

Ryan Furrey − *Chemistry Laboratory, Ridgewood Water, Ridgewood, New Jersey 07450, United States;* Present Address: Water and Sewer Utility at Rockaway Township, Rockaway, NJ 07866

Michael Labowsky − *Ansama Research, LLC, Wayne, New Jersey 07470, United States*

Anthony Perry − *Institute for Data, Systems, and Society, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, United States;* orcid.org/0000-0002-6497-8345

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.2c00135

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The RHS InvenTeam is indebted to the Lemelson-MIT Program for the generous grant and the support to young inventors' development. H.L.L. is especially grateful to the Invention Educator Officer, Dr. Leigh Estabrooks, for offering her an Excite Award to attend the LMIT Summer Professional Development Session that started it all. The InvenTeam is also grateful to Ridgewood Water for making the "Eureka!" moment possible: the certified bacteria tests that validated the SAT technology. The RW Director of Operations, Mr. Rich Calbi, arranged the team's visit to RW that opened the community engagement collaboration channel. The team was honored to have the advice from Professor Jae-Hong Kim, the chair of Chemical and Environmental Engineering of Yale University, a leader in the National Alliance for Water Innovation, whose insight impacted the final product. The invitation to visit Yale Engineering was a special honor. The culture and environment at RHS provided InvenTeam with the opportunity and drive to succeed. In the unprecedented year of pandemic challenges, the InvenTeam is grateful for the unwavering support of the student's parents, the RHS faculty, and institutional leaders. Prof. Shu Hu gratefully acknowledges the financial support of the National Science Foundation Award No. CBET-2055416.

■ REFERENCES

(1) Perry, A.; Estabrooks, L. Let's Invent! *Science Teacher* **2019**, *86* (6), 37−43.

(2) The National Academies of Sciences Engineering Medicine. *Next Generation Science Standards: For States, by States*; The National Academies Press: Washington, DC, 2013. https://www.nap.edu/catalog/18290/next-generation-science-standards-for-states-by-states (accessed 2021-11-05).

(3) The Lemelson-MIT, Committee for Study of Invention. *Invention: Enhancing Inventiveness for Quality of Life, Competitiveness, and Sustainability*; National Science Foundation and the Lemelson-MIT Program, 2004. https://lemelson.mit.edu/node/2522 (accessed 2021-11-05).

(4) inventED. *Researching Invention Education: A White Paper*; The Lemelson Foundation, 2019. https://inventioneducation.org/researching-invention-education/ (accessed 2021-11-05).

(5) United Nation, Department of Economic and Social Affairs Sustainable Developments. *The 17 Goals*; United Nation 2015. https://sdgs.un.org/goals (accessed 2021-11-05).

(6) World Health Organization. *1 in 3 People Globally Do Not Have Access to Safe Drinking Water*; UNICEF, WHO. 2019. https://www.who.int/news/item/18-06-2019-1-in-3-people-globally-do-not-have-access-to-safe-drinking-water-unicef-who (accessed Oct 2021).

(7) Parker, L. How the Plastic Bottle Went from Miracle Container to Hated Garbage. *National Geographic*, August 2019. https://www.nationalgeographic.com/environment/2019/08/plastic-bottles/ (accessed 2021-11-05).

(8) United Nation, Department of Economic and Social Affairs Sustainable Developments. *Ensure Availability and Sustainable Management of Water and Sanitation for All*; United Nations, 2015. https://sdgs.un.org/goals/goal6 (accessed 2021-11-05).

(9) United Nations. Department of Economic and Social Affairs Sustainable Developments. *Ensure Sustainable Consumption and Production Patterns*; United Nations, 2015.

(10) Hu, S. Membrane-Less Photoelectrochemical Devices for H2 O2 Production: Efficiency Limit and Operational Constraint. *Sustainable Energy Fuels* **2019**, *3* (1), 101−114.

(11) Li, J.; Solanki, D.; Zhu, Q.; Shen, X.; Callander, G.; Kim, J.; Li, Y.; Wang, H.; Hu, S. Microstructural Origin of Selective Water Oxidation to Hydrogen Peroxide at Low Overpotentials: A Study on Mn-Alloyed TiO2. *J. Mater. Chem. A* **2021**, *9* (34), 18498−18505.
(12) Tang, J.; Zhao, T.; Solanki, D.; Miao, X.; Zhou, W.; Hu, S. Selective Hydrogen Peroxide Conversion Tailored by Surface, Interface, and Device Engineering. *Joule* **2021**, *5* (6), 1432−1461.
(13) Chu, C.; Ryberg, E. C.; Loeb, S. K.; Suh, M. J.; Kim, J. H. Water Disinfection in Rural Areas Demands Unconventional Solar Technologies. *Acc. Chem. Res.* **2019**, *52* (5), 1187−1195.
(14) Ridgewood Water. *2020 Annual Drinking Water Quality Report*; Ridgewood Water, 2020. http://mods.ridgewoodnj.net/pd5/water/WQR/2020WQR.pdf (accessed 2021-11-05).
(15) Barazesh, J. M.; Hennebel, T.; Jasper, J. T.; Sedlak, D. L. Modular Advanced Oxidation Process Enabled by Cathodic Hydrogen Peroxide Production. *Environ. Sci. Technol.* **2015**, *49* (12), 7391−7399.
(16) Hodges, B. C.; Cates, E. L.; Kim, J. H. Challenges and Prospects of Advanced Oxidation Water Treatment Processes using Catalytic Nanomaterials. *Nat. Nanotechnol.* **2018**, *13* (8), 642−650.
(17) Miller, K.; Sonnert, G.; Sadler, P. The Influence of Students' Participation in STEM Competitions on their Interest in STEM Careers. *International Journal of Science Education Part B* **2018**, *8* (2), 95−114.
(18) Estabrooks, L.; Couch, S. Failure as an Active Agent in the Development of Creative and Inventive Mindsets. *Thinking Skills and Creativity* **2018**, *30*, 103−115.
(19) Under FDA regulations, an Institutional Review Board has been formally designated to review and monitor biomedical research involving human subjects.
(20) Frauchiger, D.; Bottema, R.; Frandsen, V. Drinking Straw with Hollow Fibre Liquid Filter. United States Patent US8852439b2, 2014.
(21) Liao, Y.; Walker, R. C.; Collins, D. UV-LED Liquid Monitoring and Treatment. United States Patent US10570028b2, 2020.
(22) Shin, J.-Y.; Kim, S.-J.; Kim, D.-K.; Kang, D.-H. Fundamental characteristics of deep-UV light-Emitting diodes and their application to control foodborne pathogens. *Appl. Environ. Microbiol.* **2016**, *82*, 2−10.
(23) cfpub.epa.gov: Final Report. 2001−2005. Effectiveness of UV Irradiation for Pathogen Inactivation in Surface Waters. Available from https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.highlight/abstract/1128/report/.
(24) Niethammer, P.; Grabher, C.; Look, A.; et al. A tissue-scale gradient of hydrogen peroxide mediates rapid wound detection in zebrafish. *Nature* **2009**, *459*, 996−999.
(25) Jelcic, M.; Enyedi, B.; Xavier, J. B.; Niethammer, P. Image-Based Measurement of H2O2 Reaction-Diffusion in Wounded Zebrafish Larvae. *Biophys. J.* **2017**, *112* (9), 2011−2018.
(26) Schwarcz, J. *Hydrogen Peroxide: The Body's Best Defense System*; McGill, January 18, 2017. https://www.mcgill.ca/oss/article/general-science-you-asked/hydrogen-peroxide-bodys-best-defence-system (accessed 2021-11-05).
(27) Chelikani, P.; Fita, I.; Loewen, P. C. Diversity of structures and properties among catalases. *Cell. Mol. Life Sci.* **2004**, *61* (2), 192−208.
(28) HACH Hydrogen Peroxide Test Kit, Model Hyp-1. https://www.hach.com/hydrogen-peroxide-test-kit-model-hyp-1/product?id=7640218476 (accessed 2021-11-05).
(29) Yan, Y. K.; Subramaniam, R. Using a Multi-Tier Diagnostic Test to Explore the Nature of Students' Alternative Conceptions on Reaction Kinetics. *Chem. Educ. Res. Pract.* **2018**, *19* (1), 213−226.
(30) Peletz, R.; Mahin, T.; Elliott, M.; Montgomery, M.; Clasen, T. Preventing Cryptosporidiosis: The Need for Safe Drinking Water. *Bull. W. H. O.* **2013**, *91* (4), 238−8A.
(31) Microchip. Attiny45. https://www.microchip.com/en-us/product/ATtiny45 (accessed 2021-11-05).
(32) Couch, S.; Skukauskaite, A.; Estabrooks, L. B. Invention Education and the Developing Nature of High School Students' Construction of an "Inventor" Identity. *Technology & Innovation* **2019**, *20* (3), 285−302.
(33) Chen, J.; Loeb, S.; Kim, J. H. Led Revolution: Fundamentals and Prospects for UV Disinfection Applications. *Environ. Sci. Water Res. Technol.* **2017**, *3* (2), 188−202.
(34) National Science and Technology Council, Committee on STEM Education of the National Science & Technology Council. *Charting a Course for Success: America's Strategy for STEM Education*; Executive Office of the President of the United States, December 2018. https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf (accessed 2021-11-05).

https://doi.org/10.1021/acs.jchemed.2c00135
J. Chem. Educ. XXXX, XXX, XXX−XXX