

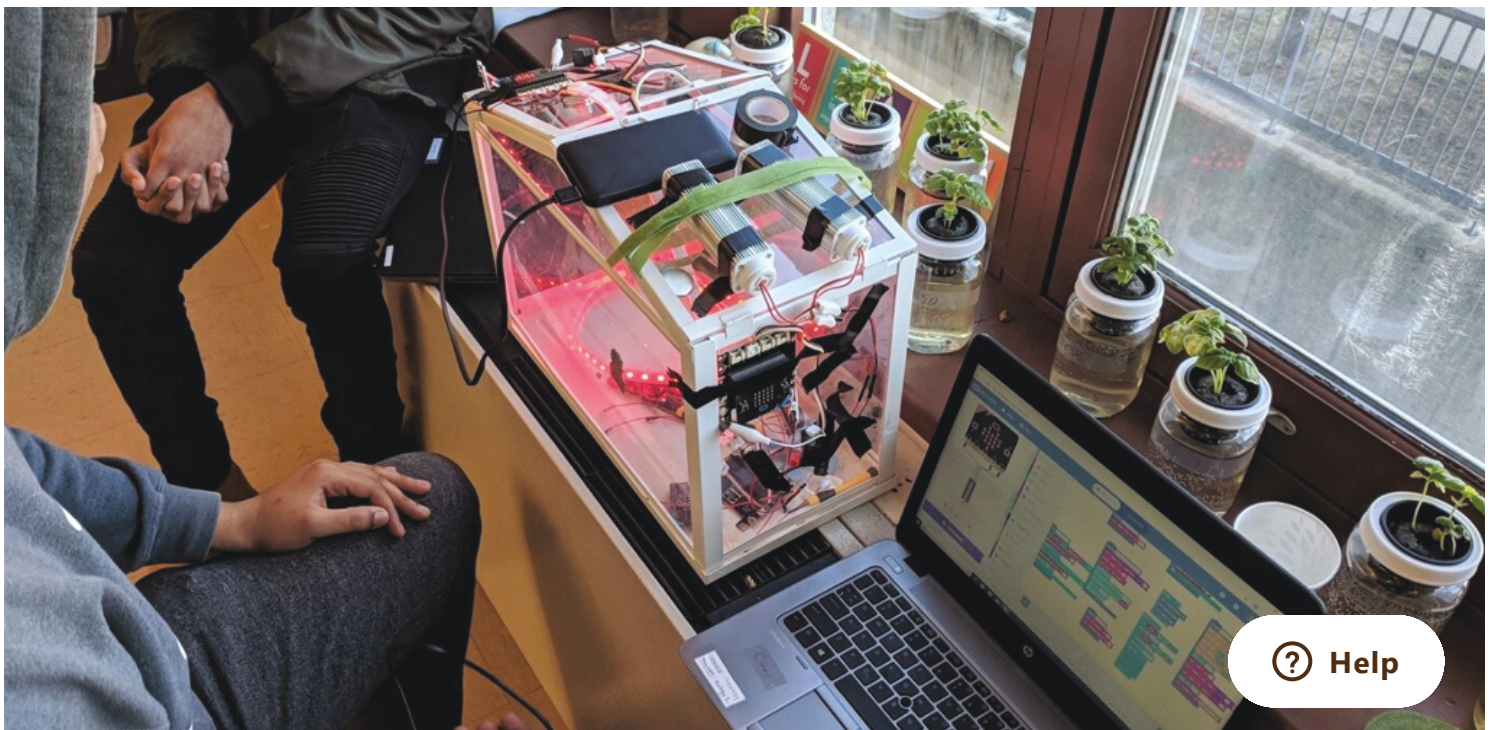
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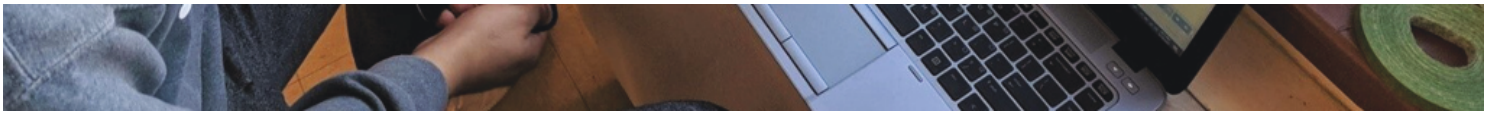
An Integrated STEM and Computing Curriculum for the Human-Technology Frontier

The Case of a Smart Greenhouse

Connected Science Learning March–April 2021 [Volume 3, Issue 2]

By Christian Konadu Asante, Amy Semerjian, Paul Xu, David Jackson, Yihong Cheng, Ariel Chasen, Ahmad Shah, Jessica Brett, and Meghan Broadstone





“Maybe we can find a way to use coding in subjects we haven't learned before.” —Gabriella [pseudonym], post-interview

Historically, K–12 science education and curriculum development has been organized and enacted in silos by subject areas (biology, chemistry, physics, Earth and space science) with very little focus on the connectivity and relationships between them. In recent decades, however, major educational stakeholders such as the National Science Teaching Association (NSTA) have called for an integrated and interdisciplinary K–12 science education (NSTA 2020). In addition, the *Next Generation Science Standards* (NGSS; NGSS Lead States 2013) include crosscutting concepts that link subjects, ideas, and practices. These calls for an interdisciplinary science, technology, engineering, and mathematics (STEM) education include broadening the canvas and focus to encompass computing and the computational sciences. Computing and computational thinking have received considerable attention because they are instrumental in solving the problems of the 21st century (Wing 2006), both known and unknown. Computing-based algorithms will be the drivers of healthcare, national security, and financial markets (Luckin 2018). As the student Gabriella noted in the opening quote, coding (and computational thinking) has potential uses in subjects not yet imagined—subjects both in the traditional school sense of the word, as well as personal and civic uses.

In support of these uses, the National Science Foundation (NSF) has committed resources to fund projects that integrate computing into formal and informal STEM education. In addition, non-governmental organizations such as NSTA have implemented programs to support the teaching, learning, and integration of computing into STEM. Despite the efforts of both government and non-governmental stakeholders, there are still significant challenges to the design and instruction of a curriculum that integrates computing into STEM. Some of these challenges include a lack of teacher computing expertise, inadequate computing and technological resources, curriculum-coverage pressures teachers face due to high-stakes testing, and a lack of curricula that guide and demonstrate how computing can be integrated into traditional STEM education (Blikstein 2018; Rodriguez and Lehman 2017).

In partnership with a wide range of stakeholders—students, families, science directors, school principals, K–12 science teachers, university researchers, graduate students, external evaluators, and K–12 informal learning instructors—we responded to those challenges by designing and implementing the Smart Greenhouse curriculum, an integrative greenhouse science unit that incorporates computing into the STEM subjects of biology, physics, and engineering.

In this article, we provide a comprehensive overview of the Smart Greenhouse curriculum and its enactment in both in-school and out-of-school environments. In addition, we outline

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The Smart Greenhouse Curriculum

We developed a Smart Greenhouse curriculum that combines the biology of the growth of specific plants like lettuce; the physics of light and temperature required to grow; and the electricity and electrical wiring used to automate physical processes, such as light and temperature. Engineering design considerations were introduced into the curriculum through constraints like the limited number of ports on a motherboard as well as the computational thinking required for systematically addressing recurring problems. Computer science was also a key feature through coding design and debugging. We incentivized students to make greenhouses by discussing access to fresh, nutritious food, which should be available to everyone. We then tasked students with creating a greenhouse environment that provides optimum conditions for plant growth, which they could take home after the unit was completed.

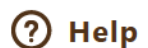
The core of this curriculum includes short computational thinking and computer programming mini-lessons followed by lengthier problem solving, coding, and construction sessions. Students learn how to control temperature, humidity, and light using sensors as inputs to trigger actions when conditions are not suitable for the specific plants that they are learning about (lettuce, basil, cilantro, or others). Please see [Table 1](#) for a comprehensive view of the format, structure, and learning objectives of the Smart Greenhouse curriculum.

TABLE 1. STRUCTURE OF THE CURRICULUM (XU 2020)	

Day	Topic	Goals	Learning Activities	CS/Tech	Reading Materials
1	Course Overview	- Learn the science of smart, automated greenhouses. - Understand microcontrollers, Python, and import statements.	- Introduce students to real-world greenhouses. - Conduct interactive coding in Python	Use Python to perform basic arithmetic operations on the microcontroller.	How do greenhouses work?
2	Light and Plant Growth	- Understand how colors of light affects plant growth. - Program the LED strip to mimic professional grow lights.	- Watch a video on photosynthesis. - Understand the light spectrum. - Program the LED strip.	- Create instances of objects. - Use functions (methods) to modify states of objects and passing function arguments (Parameterization) - Use lists (data structures) to control colors of light.	Can plants "see" light?
3	Light and Plant Growth	- Understand how intensity of light affects plant growth and the relationship between light intensity and distance to light source/color. - Program the digital light sensor to measure light intensity in lux.	- Use the light sensor to measure light intensity from the LED strip. - Hypothesize the nature of the relationship between distance to the light source and light intensity. - Graph the light sensor readings at different distances to test the hypothesis and understand the relationship.	- Continue using functions (methods) with return values to read light intensity values in lux. - Use loops to measure data at specific intervals.	Light intensity and duration impact on plant growth
4	Temperature/ Humidity and Plant Growth	- Understand how change of temperature affects (relative) humidity (think as a system). - Program temperature and humidity sensors to measure these two values.	- Watch a video on how temperature/humidity affect the photosynthesis/respiration. - Learn to collect data and automatically transmit data to other devices.	Understand how data is communicated between networked devices.	Temperature/ humidity and plant growth
5	Treasure Hunt With Live Data Visualizations	Make scientific hypotheses and use scientific reasoning with empirical data.	Game: Treasure hunt. Select groups of students to hide temperature/humidity sensors somewhere in the classroom for others to locate using live data visualizations.	Read real-time data visualization and make scientific arguments.	N/A
6	Manipulation of Temperature/ Humidity in Greenhouses	- Design an experiment to test hypotheses. - Use actuators (servos, relays, and fans) and "if" statements to achieve automation.	Come up with a scientific hypothesis on how variables (temperature, humidity, light intensity, etc.) affect plant growth. Design a smart greenhouse that can manipulate these variables and collect data that helps support the hypothesis.	Use if conditionals to achieve automation using sensor data and actuators.	N/A
7	Design and Build the Greenhouse	Students continue to design and build a smart greenhouse that could help them support their hypotheses or answer research questions that they came up with in Lesson 6.			

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Research has shown that problem-based curriculums that provide direct hands-on and applicable lesson plans, such as the Smart Greenhouse, help increase underrepresented students' (African American, Hispanic, and Native American) self-efficacy and subsequently their participation (Bicer and Perihan 2020) in natural sciences. Unfortunately, both girls and minoritized (African American, Hispanic, and Native American) students in general are also underrepresented in voluntary science projects.



and Native American) students in general are also underrepresented in volunteer access points to computer science education, such as afterschool programs. To counteract this, the in-school implementation of the Smart Greenhouse occurred as part of the regular science classes that required attendance by all students. In the schools we worked with, Latinx students were statistically significantly less likely to have had experience in computer science or computational thinking than were non-Latinx students [65% vs. 85%, $F(1, 118) = 1.412$, $p = .027$] (Semerjian and Roberto 2019). As such, pro-

viding this curriculum as part of a required course helped Latinx students to have similar coding, computer science, and computational thinking experiences as other students.

Smart Greenhouse Alignment with NGSS Performance Expectations

Our collaborative research group works with students in grades 6–12 at public schools in urban and urban ring cities in eastern, central, and western Massachusetts. The Smart Greenhouse curriculum was aligned with the *NGSS* (NGSS Lead States 2013) for four disciplines (biology, physics, engineering, computer science) in both middle school and high school grade bands. [Table 2](#) (see Supplemental Resources) details this *NGSS* alignment and shows that several of the science-based standards have connections with engineering.

Aligning K–12 Computer Science Core Concepts With the NGSS

To aid in schools' rationales for implementation of our curriculum, we aligned it to the *NGSS* standards. Our *NGSS* alignment delved deeply into *NGSS* Science and Engineering Practice #5: "Using Mathematics and Computational Thinking." Our curriculum aligned most heavily with grades 6–8, though there was some alignment with grades 9–12 and slight alignment with grades 3–5. A summary of the professional development, which included an alignment to the K–12 Computer Science Framework and the *NGSS*, is presented in [Table 3](#) (see Supplemental Resources).

Professional Development Scheduling and Implementation

To implement the curriculum in school, our university team conferred with headmasters, science directors, and teachers to identify schools in central and eastern Massachusetts interested in participating in the program. University professors and graduate students then scheduled and conducted a paid summer teacher professional development. Teacher professional development for the Smart Greenhouse curriculum was done with two main objectives in mind:

1. to allow teachers to become familiar with the curriculum and
2. to seek teachers' views on how to improve the curriculum.

This professional development allowed teachers to gain an informed understanding of the program's content and design, which provided a basis for informed opinions on alterations to the curriculum. The teacher professional development combined blended teacher choice (teachers suggested areas of interest and emphasis) with a more traditional approach to professional development (directed coaching from university researchers).

The curriculum development and teacher professional development evolved over the years 2017–2019, beginning with training two eighth-grade science teachers from the same school in the pilot year of 2017–2018 (specifically, in spring 2018 for five hours, over five one-hour meetings during teachers' prep periods or after school). Teachers were forthcoming with their challenges—mostly in the areas of coding and electronics. We provided technical support for problems with troubleshooting and addressed other teacher concerns throughout the professional development as well as during the program implementation. Teachers provided significant feedback on how to improve the curriculum and to make it age-appropriate and culturally relevant while keeping the computer science fundamentals.

In May 2018 the two eighth-grade teachers implemented the pilot curriculum with ongoing professional development, including 15-minute daily check-ins to further develop the curriculum that would follow the next day in a manner specific to their settings.

In August 2018 one more teacher from the same district joined the original pair for curriculum-designing professional development lasting three days (4 hours, 7 hours, and 4 hours). This August professional development was intended for implementation in the 2018–2019 academic year. During the August professional development, teachers once again provided valuable feedback and designed extension activities, vocabulary guides, and single-page cards that explained aspects of the unit that could be isolated, like actuators and sensors.

In 2018–2019 three more teachers joined the project—two from the same eastern Massachusetts city where all eighth-grade students in science had participating teachers, and one from central Massachusetts—totaling six teachers. Before implementation, professional development in spring 2019 concentrated on teaching the new teachers via seven in-person, one-hour sessions in their schools during their prep periods or after school. In 2019–2020, accompanying a planned expansion to three other Massachusetts cities, we similarly offered in spring seven one-hour sessions of professional development, but these were delivered via video conferencing due to COVID-19. The continuation of the pandemic upended implementation planning, leaving 2018–2019 as the main data collection year (with two teachers in one school opting in to data collection, for a total of 199 students).

Curriculum Implementation

The curriculum was implemented in two main environments: in-school and out-of-school implementations were of two main types:



1. The unit was taught to middle school students as an end-of-year capstone experience in two schools, by five teachers in five classrooms (in one eastern Massachusetts city, split between two schools of two and three teachers).
2. The unit was taught to high school students daily as a yearlong course in a central Massachusetts high school by one science teacher.

Dr. Mike Barnett, the university professor who was the principal investigator for this grant-funded work, taught in an out-of-school environment during a weeklong February vacation camp.

In-School Implementation: Eastern Massachusetts

In May 2019 teachers in the eastern Massachusetts city implemented the curriculum for 14 days of 56-minute class periods, for a total of 13 hours 4 minutes. With the goals of developing students’ computing skills and self-efficacy as well as teachers’ pedagogical knowledge, the curriculum was originally planned for 10 class periods, but teachers decided as a team to extend their meetings to 14 class periods to differentiate their instruction so that they could offer remediation as well as additional challenge, depending on students’ needs. As a side note, other future eastern Massachusetts in-school implementations were planned for a similar duration (10 to 14 days of roughly one hour per day) and were also to be scheduled late in the school year, after the conclusion of high-stakes testing.

One of the five teachers who implemented the curriculum in middle school was Mr. Wilson, who taught eighth grade in an eastern Massachusetts urban-ring public school. (All student and teacher names are pseudonyms.) Mr. Wilson customized his implementation of the Smart Greenhouse curriculum to feature engineering, bringing him outside his usual comfort zone as a specialist in teaching life sciences and allowing his student teams to implement their own design considerations. To accomplish this, each student group paired with another group to change exactly one design consideration between the two groups. For example, one group could turn on fans using computer codes when the internal temperature reached 75°F (~24°C) while its paired group turned on fans at 80°F (~27°C). Through this design, Mr. Wilson encouraged students to explore the ways that the Smart Greenhouse worked as a system, as temperature changes affected not only plant growth but also humidity and soil moisture. [Table 4](#) provides a step-by-step description of how Mr. Wilson implemented the curriculum in his classroom over a two-week period.

TABLE 4. IMPLEMENTATION IN AN IN-SCHOOL SETTING (XU 2020)			
Time	Activity	Detailed Activity	Researcher Template
1 Hour/Block/Day	Instruction Phase	On each instructional day, the teachers taught one lesson of the curriculum. (Please see Table 1 for detailed lesson plans.) Teachers also used non-instruction days to catch up or review content learned in previous instruction days.	• Teacher interviews (after Day 1) • Instruction videos • Observation notes
1 Hour/Block/Day	Design Phase	The students designed, built, and coded their smart greenhouse. The teachers set expectations and rubrics for greenhouses.	• Student observation videos • Observation notes



1 Day	Gallery Walk	The students showcased their greenhouses and presented their finished work to adults and peers, explaining how they worked and describing their experience with the project.	• Field notes
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[Click here to enlarge](#)



A fully functional version-1 greenhouse built by students

In-school Implementation: Central Massachusetts

The central Massachusetts in-school implementation took place in a public high school that serves majority immigrant students from Africa. The high school science teacher taught this unit for 45 minutes a day for two full semesters, totaling roughly 120 hours. Efficiency with coding among the students before the class was nonexistent. Students' prior computer skills did not extend beyond typing and Googling. The general class demographic included students not tracked for STEM careers by the school and students who had traditionally not done well with rote learning, with the two sets overlapping considerably.

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Out-of-School Implementation

We implemented the Smart Greenhouse with one experienced informal-science-teaching professor in an out-of-school setting during February vacation. We recruited high school youth ($n = 6$) from public schools in eastern Massachusetts, but also added some middle school students ($n = 8$) due to a scheduling issue with a different middle school vacation camp running concurrently. Through five daily sessions from 9 a.m. to 3 p.m. (for a total of 25 hours of program time) each youth set up their own mini greenhouse (which they could keep), learned basic concepts of coding, and applied the coding to physical parameters such as temperature and light, as outlined in Table 1.

Evaluation of the Smart Greenhouse Curriculum, Implementation, and Professional Development

Overall, teachers found that they had to learn a lot to teach this curriculum but the results were worth the effort because of the rich learning experiences it provided for both students and teachers. This section contains evaluative results concentrating on student engagement, student self-efficacy, teacher feedback, and recommendations for implementation based on lessons learned. Our data sources were varied:

- some qualitative (teacher journals, teacher and student interviews from two middle schools),
- some quantitative (student pre-post assessments and surveys taken by a subset of students ($N = 120$) from one eastern Massachusetts middle school), and
- some using mixed methods (classroom observations from that same middle school).

Student Engagement

Students' engagement is important both because it is a predictor of academic achievement (Fredricks et al. 2004) and because it is needed for students' interest to grow (Renninger and Hidi 2016), in combination with opportunities to engage (Semerjian and Roberto 2019; Jackson et al. 2019). We found evidence of positive student engagement in three of our data sources:

1. teacher observations recorded in journals and shared in interviews,
2. classroom observation notes from video and real-time observations conducted by graduate students, and
3. a quantitative survey given to students.

First, all five teachers in the eastern Massachusetts urban-ring city found their students were behaviorally engaged, to a greater degree than was typical. More importantly, teachers remarked that students who had previously been disengaged in class really excelled with the Smart Greenhouse. For example, one teacher shared that for a few students, "This project will ignite something in them

that has been non-existent for the entire year... all of a sudden it's like a different human being...they became leaders, they were directing things."

Second, based on observations from multiple classrooms, our research team of three professors and seven graduate students observed all students being behaviorally engaged. Specifically, all students did the project and exhibited positive attitudes, asking questions as needed. This finding was statistically significant at the $p = .001$ level using a binomial test on binary student-level data (0 = not engaged, 1 = engaged), comparing our results with a typical classroom for which we considered the proportion of students behaviorally engaged to be 90%. The Cohen's effect size ($d = 3.33$) was well beyond the "large" standard of 0.80 (Cohen 1988). Interpreting these results with the knowledge that behavioral engagement is a positive predictor of academic achievement, our students appear well-poised for future academic achievement.

The third type of evidence of student engagement comes from the amount of time that most students were willing to spend on difficult questions related to the curriculum. To study this, we designed a computer-delivered pre-post student assessment including four difficult cognitive items. However, the curriculum that we initially planned on delivering—the curriculum that resulted from the professional development—was not identical to what was delivered: Teachers further adapted the directions they wanted to take the curriculum, which resulted in a less-than-ideal relationship between the academic content of the assessment relative to what was actually taught. The content that was taught was certainly related to what was tested, but transference between learning goals that appear related can be difficult to obtain. Thus, we found that unfortunately, but sensibly, student learning gains in the assessed areas were not observed.

However, we hypothesized that behavioral engagement may have transferred. Students who had been behaviorally engaged in the curriculum might, by extension, show increased behavioral engagement in assessment items related to the curriculum. If so, students would spend longer trying to tease out cognitive items on posttests than they did on pretests. Before testing this hypothesis, we had to account for realities that could have altered the duration of students' answers. For example, students may have left their computers on one screen for hours, causing an inaccurate record of how much time was actually spent answering questions, or they may have clicked on an answer option in such a short amount of time that it was unlikely that they had read the question. To prevent any such data from obscuring analysis of data from students who interacted with the assessment in earnest—who read the questions, thought about them, answered them, and submitted their answers by clicking the "next" button without taking a break—the data set was trimmed for outliers. As a result, roughly 80% of student responses ($n = 89$) in the middle of the distribution were selected for analysis. We found that students in this sample spent an average of 12.6 seconds longer on a total of four cognitive items when completing the posttest compared to the pretest, which was statistically significant [$t(88) = 3.48, p < .001$] and practically significant between a small and medium effect size with a Cohen's $d = 0.36$.

Self-Efficacy Increased for Some Students

Our evaluation indicates that students who participated learned coding, but we also know that the project was difficult. Sometimes, inexperienced individuals overestimate their self-efficacy (defined as a person's beliefs in their own skills) compared with individuals of the same skill level but more experience, so students might gain skill as their self-efficacy drops. For many students the Smart Greenhouse project was their most significant coding and computer science opportunity. Fortunately, more students believed that they were better at coding after engaging in the Smart Greenhouse unit than had possibly been disheartened by the difficult work (13 believed they were worse, 64 believed they were the same, and 43 believed they had improved). On a five-point Likert-type scale where "1" represented the lowest self-assessment of skill at coding, "3" average, and "5" the highest self-assessment, the pretest means of 1.99 increased to 2.26 after the Smart Greenhouse unit. The Related-Samples Wilcoxon Signed Rank test showed that this increase was statistically significant (standardized $W = 4.06$, $p < .001$) and Cohen's d showed a practical significance of $d = 1.04$, which is greater than the "large" Cohen's d value of 0.8 (Cohen 1988).

Teachers' Evaluations of the Curriculum and Professional Development

Teachers were overwhelmingly positive in their interview evaluations of the curriculum and mixed in their interview evaluations of the professional development. Teachers also provided suggestions for improvement of the professional development, detailed in the next section.

Relating to the curriculum, teachers believed that the Smart Greenhouse motivated students with its specific, real-world challenge, stating:

"This format of, 'I've gotta grow some plants and figure out how to make this greenhouse thing work,' just was fun and interesting for [students]. So the student buy-in was one of the best things about the whole process."

"It's a unique real-world situation for them to be working with ... kids always want to know what are we going to use this for? They could probably see right off the bat a lot of positive uses for this, which I think is great for kids."

Teachers believed that the curriculum was impactful because it helped students get over fears of technology, to the point that this curriculum unit could influence students' futures, with one stating:

"Kids who usually were afraid of technology or hadn't used it a lot were now all of a sudden it's not so scary and it opened their minds to other things they could do. They feel more like they could go

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into tech as a career.”

Additionally, teachers believed that the curriculum provided students with fun and unique skill-development opportunities, building their greenhouses and working with plants to complete a big project and solve a real-world problem. One teacher commented:

“It gives students an opportunity to be really hands on, do a big project, and ultimately make something that’s pretty cool. Also develop skill sets—whether that’s wiring, whether that’s cultivating plants for the first time, or coding, doing all those things—those are all things that kids don’t typically get.”

Recommendations for Implementation

1. *Professional Development:* Before implementing the unit, teachers will likely need seven to ten hours of professional development (with a stipend) to learn its contents. During the unit, teachers will benefit from the support of colleagues who are also implementing the unit or have in the past. During the school year teachers preferred to schedule at least some of the professional development for times other than after school (summer, student vacation days, during school hours).
2. *Materials:* Teachers wanted to preorder all materials so that they could be received before their first possible use. Supply teachers in advance of the professional development with enough materials to construct at least one greenhouse with parts to spare to allow them to compare different configurations side by side. Order students’ materials so that they all arrive before the unit starts, so teachers can inventory them and check them for quality. Anticipate additional needs for materials.
3. *Timing:* If the unit is to be taught in-school and limited in duration (not yearlong), implement the unit after high-stakes accountability testing.
4. *Program Content Additions:* Introduce more complex topics, such as climate change, into the curriculum.
5. *Accessibility:* Translate curriculum into languages such as Spanish and Creole to expand access to ESL learners from different backgrounds.

Cost of Implementation

We tried to keep the cost of the system as low as possible, approximately \$290 per classroom. Most of the materials can be used multiple times, perhaps requiring occasional minor repairs. BBC Micro:bit devices (detailed in supplementary materials) and the associated sensors are physically robust, rarely requiring replacement. Most recurring costs will be for fresh seeds (they can get stale over time), seed-starting pellets, and nutrient solution.

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Safety Concerns

Safety Concerns

The Smart Greenhouse System can be safely operated, as it does not use any potentially hazardous chemicals or dangerous instruments. All the electronic equipment used in the system requires a very low amount of power. Compared to fluorescent or incandescent lights, LED lights are much colder and possess no threat of heat-related injury if touched accidentally. Additionally, don't plug any fast-charging power adapter (with voltage much higher than 3.3 V) into the Micro:bit device or connect alligator clips in a way that may short-circuit. The exhaust and propeller fans should be placed to avoid possible finger injury. Wires around the system should be organized properly to avoid any electricity-related accidents (arcs and sparks). The nutrient solution formulation for the system does not carry any toxic chemical ingredients, but drinking the solution can be harmful, so it should be kept away from young children.

Implementing the Curriculum

If you implement the curriculum, please reach out to the authors to share your experiences, so we can account for additional implementation variations and other considerations in the Smart Greenhouse resource materials. Linked supplementary materials are included in this article, but as the Smart Greenhouse curriculum is an evolving curriculum, we advise teachers and educational stakeholders interested in implementing the curriculum to contact us with questions, suggestions, and comments.

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On the Web

- <https://docs.google.com/spreadsheets/d/1uw60kfb70jFg1ZQ0bYDNpC6jJTqm8tc4xpny7IKLRM/edit?usp=sharing>. This document contains a price list of items needed to assemble the greenhouse.
- <http://growthings.netlify.com/unit1/lesson1/>. This curriculum website contains the curriculum, lesson plans and content. This should be used in conjunction with Tables 1, 2, and 3.

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