# Disciplinary and Interdisciplinary Science Education Research

## 3D plants: The impact of integrating science, design, and technology on high school student learning and interests in STEAM subjects and career

--Manuscript Draft--

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| **Abstract:** | STEM education is often disconnected from innovation and design, where students self-identify as solely scientists, artists, or technophiles, but rarely see the connection between the disciplines. The inclusion of arts (A) in STEM education (STEAM) offers an educational approach where students see how subjects are integrated through learning experiences that apply to everyday, developing personal connections and becoming motivated learners who understand how skills from each subject are needed for future careers. This project addresses both the disconnect between science, design, and technology and how high school students can benefit from innovative learning experiences in plant science that integrate these disciplines while gaining invaluable skills for future STEM careers. We used the Science-Art-Design-Technology (SADT) pedagogical approach, characterized by its project-based learning that relies on student teamwork and facilitation by educators. This approach was applied through a STEAM educational 3D plant module where teams: 1) investigated plants under research at a plant science research center, 2) designed and created 3D models of those plants, 3) experienced the application of 3D modeling in augmented and virtual reality platforms, and 4) disseminated project results. We used a mixed-method approach using qualitative and quantitative research methods to assess the impact of the 3D modeling module on students' understanding of the intersection of art and design with science, learning and skills gains, and interests in STEAM subjects and careers. A total of 160 students from eight educational institutions (schools and informal programs) implemented the module. Student reflection questions revealed that students see art and design playing a role in science mainly by facilitating communication and further understanding and fostering new ideas. They also see science influencing art and design through the artistic creation process. The students acknowledged learning STEAM content and applications associated with plant science, 3D modeling, and augmented and virtual reality. They also acknowledged gaining research skills and soft skills such as collaboration and communication. Students also increased their interest in STEAM subjects and careers, particularly associated with plant science. The SADT approach, exemplified by the 3D plant module, effectively integrates science, art, design, and technology, enhancing student literacy in these fields, and providing students with essential 21st century competencies. The module's flexibility and experiential learning opportunities benefit students and educators, promoting interdisciplinary learning and interest in STEAM subjects and careers. This innovative approach is a valuable tool for educators, inspiring new ways of teaching and learning in STEAM education. |
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**Abstract**

STEM education is often disconnected from innovation and design, where students self-identify as solely scientists, artists, or technophiles, but rarely see the connection between the disciplines. The inclusion of arts (A) in STEM education (STEAM) offers an educational approach where students see how subjects are integrated through learning experiences that apply to everyday, developing personal connections and becoming motivated learners who understand how skills from each subject are needed for future careers. This project addresses both the disconnect between science, design, and technology and how high school students can benefit from innovative learning experiences in plant science that integrate these disciplines while gaining invaluable skills for future STEM careers. We used the Science-Art-Design-Technology (SADT) pedagogical approach, characterized by its project-based learning that relies on student teamwork and facilitation by educators. This approach was applied through a STEAM educational 3D plant module where teams: 1) investigated plants under research at a plant science research center, 2) designed and created 3D models of those plants, 3) experienced the application of 3D modeling in augmented and virtual reality platforms, and 4) disseminated project results. We used a mixed-method approach using qualitative and quantitative research methods to assess the impact of the 3D modeling module on students' understanding of the intersection of art and design with science, learning and skills gains, and interests in STEAM subjects and careers. A total of 160 students from eight educational institutions (schools and informal programs) implemented the module. Student reflection questions revealed that students see art and design playing a role in science mainly by facilitating communication and further understanding and fostering new ideas. They also see science influencing art and design through the artistic creation process. The students acknowledged learning STEAM content and applications associated with plant science, 3D modeling, and augmented and virtual reality. They also acknowledged gaining research skills and soft skills such as collaboration and communication. Students also increased their interest in STEAM subjects and careers, particularly associated with plant science. The SADT approach, exemplified by the 3D plant module, effectively integrates science, art, design, and technology, enhancing student literacy in these fields, and providing students with essential 21st century competencies. The module's flexibility and experiential learning opportunities benefit students and educators, promoting interdisciplinary learning and interest in STEAM subjects and careers. This innovative approach is a valuable tool for educators, inspiring new ways of teaching and learning in STEAM education.

**Keywords:** STEAM, 3D modeling, Plant science, Project-based learning, Teamwork, Augmented reality, Virtual reality

## Introduction

To remain a world leader and contribute to science and technological advances, the United States must have a future science, technology, engineering, and mathematics (STEM) workforce with the skills necessary to face 21st century global challenges (Perignat & Katz-Buonincontro, 2019). Developing and implementing successful instructional strategies and approaches to STEM learning is essential. STEM education is a cohesive interdisciplinary approach to learning where academic concepts across disciplines are coupled with real-world lessons to develop student STEM literacy (Tsupros et al., 2008). However, STEM education is often disconnected from innovation and design, where students self-identify as solely scientists, artists, or technophiles, but rarely see the connection between the disciplines (Keefe & Laidlaw, 2013). The integration of arts (A) in STEM education involves the inclusion of art and design principles, concepts and techniques to promote learning in more connected and holistic ways that foster student creativity and innovation through the development of systematic thinking skills that combine the mind of a scientist or technologist with that of an artist or designer (Bazler & Van Sickle, 2017; Meletiou-Mavrotheris et al., 2022). With STEM plus Arts, STEAM education offers an integrated educational approach for scientific-technological, artistic, and humanistic competencies that transcends from interdisciplinary to transdisciplinary (Perales & Aróstegui, 2021). Students see how subjects are integrated through learning experiences that apply to every day developing personal connection and becoming motivated learners, who understand how skills from each subject are needed for future careers (Henriksen et al., 2019; Madden et al., 2013).

STEAM education includes design and design thinking which involves creation, experimentation, and problem-solving, encouraging different perspectives and approaches that promote creativity and innovation while engaging students in STEAM learning (Li et al., 2019; Rolling, 2016). However, in traditional learning school environments, design is usually not emphasized or is limited to engineering and technology-related activities (Li et al., 2019). With the inclusion of emergent technologies such as 3D and multimedia design, the design scope has expanded using digital fabrication tools and 3D visualization for interactive learning (Leavy et al., 2023). Hands-on activities that include designing, developing, and creating students' products, such as 3D models, allow students to gain practical skills, improve visual imagination, and formulate, challenge, realize, and validate ideas (Fu et al., 2022; Leavy et al., 2023). The 3D modeling creative process becomes a medium for project-based learning (PBL), problem solving, and critical and outside-the-box thinking, motivating students to participate and establish connections with their work and promoting the learning of STEAM subjects and careers. Since design is relatively new in STEAM school education, examination of student learning outcomes from design experiences is crucial (Li et al., 2019).

Science literacy in STEAM education is essential as it allows students to comprehend relevant scientific concepts and use science to understand the world around them and address complex challenges (Mansfield & Reiss, 2020; National Academies of Sciences, Engineering, and Medicine, 2021). Exposure to the scientific method empowers students to formulate questions, investigate and draw conclusions, and present results, developing critical thinking and motivation to join the scientific workforce (Arango-Caro et al., 2024; Mansfield & Reiss, 2020; Mastronardi et al., 2020). However, science education is not necessarily a priority, and high-quality, comprehensive learning opportunities are not accessible to many students, particularly from low-income communities, Black, Hispanic, and Indigenous groups, and rural areas (Mansfield & Reiss, 2020; National Academies of Sciences, Engineering, and Medicine, 2021; National Science Board, 2024). By integrating art and design in science teaching, educators can promote scientific literacy and facilitate its access among diverse communities through STEAM education (Liao, 2016; Perales & Aróstegui, 2021).

With the rapid change of technological advances, STEAM educators need to apply innovative strategies to keep pace with new ways of learning. Some emergent technologies have shown potential to improve learning experiences and outcomes through nontraditional educational practices, such as augmented and virtual reality (AVR) and 3D design (Leavy et al., 2023). These technologies, among others, supports self-directed learning, individualized learning, and the learning needs of students with disabilities, while facilitating global interaction and collaboration (Haleem et al., 2022; Mabe et al., 2022; U.S. Department of Education, 2024). Emergent technologies add to the potential for technology to revolutionize education as society has entered the Fourth Industrial Revolution, transforming all aspects of everyday life with an increasing impact on workforce development and demand (Leavy et al., 2023). New professionals will need a strong background in emergent technologies (e.g., artificial intelligence, robotics, AVR), data management, and transversal and soft skills (e.g., creativity, social and emotional intelligence, communication, collaboration, and critical thinking) (Leavy et al., 2023). Immersive experiences through AVR combine the physical world with digital or simulated realities, allowing students to explore inaccessible places, visualize abstract content, travel through time, and face risk safely (Çoban, Akçay, et al., 2022; Çoban, Bolat, et al., 2022; Huang et al., 2016; Pelletier et al., 2021). Immersive AVR experiences can thus facilitate learning of factual and conceptual knowledge, motivate scientific learning and interest in STEM careers, and develop skills in critical and abstract thinking, creativity, and problem solving (Chiu & Li, 2023; Chng et al., 2023; Xu et al., 2022; Zhang et al., 2022). Today’s youth need to be technologically literate and know how to work collaboratively, participate in social networks, negotiate across cultural differences, and navigate contradictory data to be prepared for future jobs (Anderson-Inman, 2009; Keefe & Laidlaw, 2013; Land, 2013). In addition, educational strategies must be devised to reduce the digital use and access divide that arises from some institutions having limited resources including technological education tools (Reich & Ito, 2017; U.S. Department of Education, 2024). Lastly, with technological advances comes the challenge and responsibility of educators to offer innovative learning opportunities that are interdisciplinary and holistic through the STEAM model, as students' 21st century skills lack the integration of the art disciplines (Leavy et al., 2023; Soroko et al., 2021).

Project-based learning in STEAM is an effective means to promote interdisciplinary, self-directed student learning through students working in collaborative teams to create a product (Hawari & Noor, 2020; Markula & Aksela, 2022). The approach of PBL deviates from the teacher-led classroom, making the students active participants and teachers facilitators. When teachers are facilitators, they guide the learning process so that students can learn through experience. Students can explore a problem or topic and devise a solution by planning, investigating primary sources, and using scientific practices (Markula & Aksela, 2022). Students have autonomy and develop leadership skills and project ownership through collaborating actively, performing challenging tasks, and exploring real-world affairs (Hawari & Noor, 2020; Major & Govers, 2014; Nieswandt et al., 2020). Peer-directed group work has a positive effect on student achievement, social interactions, communication skills, and collective responsibility (Détienne et al., 2012; Nieswandt et al., 2020). The ability to express oneself and connect with others is crucial for achieving professional success (Thornhill-Miller et al., 2023). Explaining science to peers is part of cooperative learning that builds character and self-efficacy (Cormier & Langlois, 2022; Kulgemeyer, 2018; Liao, 2016). Communicating skills with scientific or general audiences fosters an understanding of scientific concepts and the process of science. It develops skills to engage with science regardless of whether students pursue science-related careers (National Academies of Sciences, Engineering, and Medicine, 2017; Shivni et al., 2021). A successful PBL-STEAM learning approach allows students to think critically and creatively, work collaboratively, and practice scientific communication.

**Science-Art-Design-Technology (SADT) Approach**

Our project addresses the disconnect between science, art and design, and technology, exploring how high school students can benefit from innovative learning experiences in plant science. High school students need guidance that leads them toward the careers of their interest and exposure to STEM-relevant experiences to help them transition to college and join the workforce (Heise et al., 2020; Murphy et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2021). We use the Science-Art-Design-Technology (SADT) approach, inspired by STEAM pedagogical educational models, to support student learning and interests in STEAM subjects and careers (Fig 1). The SADT approach is characterized by its PBL, which relies on student teamwork and facilitation by educators. This approach is applied through a STEAM educational module where students, working in collaborative teams, develop projects made of four components: 1) investigation of plants under research at a large science research center in the Missouri, USA, 2) design and creation of 3D models of those plants, 3) application of 3D modeling in emergent technology platforms (AVR), and 4) dissemination of project-results. This project is inclusive and diverse, closing the digital use and access divide by bringing these transformative learning and emergent technologies into educational institutions that cannot otherwise access the technology due to limited resources or remote locations and that have high representation of minority groups underrepresented in STEM (e.g., rural students, women, Hispanics, and African Americans) (National Academies of Sciences, Engineering, and Medicine, 2017; U.S. Department of Education, 2024).

This study examines the impact of the SADT approach on high school student's understanding of the integration of art and science, learning and skills gains, and changes in interest in STEAM subjects and careers. The study also aims to contribute to high school STEAM education by sharing lessons learned and best practices to inspire innovative holistic practices with interdisciplinary approaches. This study was guided by the following questions:

1. What do the students understand about the intersection of art and design with science?
2. What are the students' learning and skill gains from using the SADT approach?
3. How does the SADT approach impact students' interest in STEAM subjects and careers?

4. What are the contributions of the SADT approach to STEAM education?

## Methodology

### Student project-based module

A 3D plant modeling project-based module for high school students was developed to integrate science, art, design, and technology into their learning experiences. This module was designed by researchers from the Education Research and Outreach Lab (EROL) at [the institution – blinded] in [the location – blinded], a large non-academic plant scientific research center. The module was facilitated by formal and informal educators and developed by teams of 3-5 high school students in collaboration with [the institution – blinded] education researchers and plant scientists, between the summer of 2021 and the spring of 2024. This module consisted of four components: 1) investigation of the biology and uses of plant species and their importance for scientific research at the [the institution – blinded], 2) creation of 3D models of plant structures from those species, 3) exposure to AVR plant-related immersive experiences to understand the application of 3D modeling in these platforms, and 4) dissemination of project results through handouts and presentations.

*Protocols and 3D modeling software.* EROL researchers created protocols for educators and students to conduct the module and made tutorial videos on learning to use two 3D modeling software systems (Tinkercad® and Fusion 360® from AUTODESK®; www.autodesk.com). The protocols and videos are available for download on the EROL's Education Technology Program website ([the institution – blinded], 2024). Tinkercad® is a user-friendly entry level online 3D modeling program available free of charge to all users. Fusion 360® is free to students and educators. It has more capabilities than Tinkercad® that allow the creation of professional and intricate pieces, making it more suitable to design organic shapes such as plants.

*Facilitators.* We recruited formal and informal high school educators to facilitate the implementation of the module in their institutions. We reached out to educators from Missouri and Illinois within a four-hour drive from [the institution – blinded] to ensure the feasibility of implementation of the fourth component of this module. We announced this opportunity via email using our educators' database, which is continuously updated as educators are identified. After educators expressed interest in this module, they met with researchers to discuss how to implement the module in their educational settings. Facilitators determined if the project would be completed in three weeks or over one or two academic semesters depending on their teaching needs. We introduced the module to the students either in person or virtually. The facilitators provided students with protocols and monitored the different steps involved in developing the teams' projects. Facilitators also distributed online assessments to students before and after the module, collected parent consent and student assent forms, and completed an evaluation of their experience implementing the module (see Assessments section).

*Teams and plants.* The facilitators created collaborative, multidisciplinary teams of self-identified science, technophile, and art students. Each team assigned roles to their members based on their interests and skills (e.g., scientists, designers, artists, science communicators). The teams chose the plant species and structures to model from a selection of plants used by [the institution – blinded] scientists, who volunteered to support the students. Facilitators arranged in-person or virtual meetings between plant scientists and students so that students could ask questions about the species' biology and scientists' research. Researchers also provided specimens for direct observation of plant species and structures.

*Investigation of plants.* The research process was led by student scientists who investigated the plant species' biology, uses, and importance for plant science research. This information was summarized by the students in one-page handouts.

*Creation of 3D plant models.* All students were required to watch tutorial videos created by the research team. Through the videos, students learned how to make Tinkercad® and Fusion

360® accounts and how to create 3D models using both systems (Autodesk Inc., 2023). Students used one or both applications, depending on the time available to conduct the module and the student's experience with 3D modeling. The creative process was led by the student artists and designers who developed the concept art through visual representations of the plant structures using freehand or digital sketches and drawings, reference photos, and plant specimens. Examples of concept art are available in Additional file 1: Supplementary Material A. After the completion of the concept art, students created the 3D models with the option to contact the 3D modeling expert from EROL for help using the software and creating the models.

*Applications of 3D modeling in AVR platforms.* Facilitators coordinated with education researchers to schedule AVR immersive experiences that showcased to students the applications of 3D modeling in AVR platforms. We offered these immersive experiences at educational institutions or at our Center during field trips where students also enjoyed a tour of this state-of-the-art facility. The augmented reality experience consisted of pre-made plant science-related lessons in groups of 1-3 students in the zSpace AIO computers (zSpace, 2024). Using 3D glasses, students had lifelike experiences in a 3D view. The virtual reality experience consisted of an individual experience using Meta Quest 2 head-mounted devices (Meta, 2024). The students visited a virtual world designed by the research team called the "Soybean Saga to Food and Climate Security," where students were able to visit four rooms that showcase information about soybean reproduction and uses, its symbiotic relationship to fix nitrogen, the problems associated with synthetic nitrogen, and soybean research ([the institution – blinded], 2024).

*Dissemination of results.* Students prepared project presentations that were delivered through PowerPoint presentations, hand-made posters, or webpages. The teams decided how their members participated in the presentations.

**Institutions and high school participants**

Here we present results from 160 high school students from eight educational institutions, three public and five private, who participated in this plant 3D modeling experience in both formal and informal settings between fall 2021 and spring 2023 (Table 1). All educational institutions except two were in the St. Louis metropolitan area, MO/IL region. Most of the students participated in this project in a formal classroom setting (Table 1). Institutions A and H had mostly underrepresented Hispanic and African American students, respectively. Student demographics are detailed in Additional file 1: Supplementary Material B. Half of the students were females, a third were males, and the rest preferred not to answer or did not respond. The students were mostly juniors and seniors (82.4%). Forty percent of the students identified as white, with the second largest group being Hispanics/Latinos (21%). Black/African Americans represented 12% of the students and Asians 14%. Four percent represented other race/ethnic groups, and 10% of the students did not respond. In the pre-reflection survey, students were asked to self-identify by subject of interest as art-oriented, tech-oriented, science-oriented, or other. Sixteen percent of the students identified as science-oriented and the other 16% as tech-oriented. Art-oriented students were 24%, 14% of the students identified with other subjects, and 33% did not respond to the question. Students with no previous experience creating 3D models made up 54.3% of the total. Slightly less than half of the students had previous experience with AVR technologies and 3D modeling.

[Location of Table 1]

**Assessments**

To respond to the questions of this research, we chose a mixed-method approach using qualitative and quantitative research methods. Students completed written reflection questions and surveys before and after the module that were administered through Qualtrics$^{XM}$ software (Qualtrics, 2024). We obtained approval from [the institution – blinded] Institutional Review

Board (IRB) ([the institution – blinded]  IRB_2020_1). Only student responses that had student assent, parent consent from minor students, and both pre- and post-responses, if needed, were included in these analyses. Each student's name was assigned with a unique identification number that was the same across all the data collected. Only researchers in the IRB had access to student names. The other researchers in this project that contributed to data analysis, were provided with anonymized data sets with student identifiers.

*Qualitative Analyses*. Students completed open-ended pre- and post-written reflection questions. To assess student understanding of the intersection between science, art and design, the following pre- and post-questions were administered to the students: "How does science play a role in art and design?" and "How does art and design play a role in science?" To assess student benefits from this module, students were asked before the module "What do you hope to learn by participating in this project?" and after the module "Describe any skills or knowledge you developed during this project and whether you feel these will be relevant or applicable outside of the class. How will these be relevant?", "What has been the most important outcome of participating in this project?" To assess student changes in career interests, the students were asked after the module "Has participating in this project changed your interest in science and or art/design careers moving forward? If so, how?"

We used the deductive coding method to analyze student responses. This method uses a top-down approach to systematically categorize excerpts from students' responses based on recurring themes and patterns (Saldaña, 2013). Two coders read the answers and assigned excerpts to codes to build a codebook. The coders compared their codes and adjusted them to create an agreed-upon qualitative codebook (Additional file 1: Supplementary Material C). A third coder reviewed the final codes and standardized and consolidated themes as applicable to summarize the results. Table 2 shows the main themes identified per question with examples of quotes. Frequencies and percentages of students reporting themes and subthemes, were summarized for pre- and post-responses aligned with the reflection questions (Additional file 1: Supplementary Material D and E).

*Quantitative Analyses.* To assess student changes in perceptions towards STEAM subjects and careers, a modified version of the validated STEM Semantics Survey was completed by the students before and after the module (Tyler-Wood et al., 2010). The original instrument has five statements with the first four statements measuring student perceptions towards STEM subjects. Each statement has a similar format: “To me, [science/math/engineering/technology] is:”. Each statement is then followed by five Likert-style range questions: 1. Fascinating to Mundane, 2. Appealing to Unappealing, 3. Exciting to Unexciting, 4. Means nothing to Means a lot, and 5. Boring to Interesting. Each Likert question allows a numerical range of options from one to seven within the two polar choices. The smaller the value in each range, the more positive the perception indicated by the response. For the statement “Boring to Interesting” the values were reverse coded to have the most positive choice align with the smallest value as for the other questions. We added a sixth question to the survey: “To me, DESIGN is:” with the same Likert questions. The last statement of the survey is “To me, a CAREER in science, technology, engineering, art, or mathematics (is):”, with the same five Likert-style range questions as above. Student responses were paired pre/post and analyzed using a paired t-test for each of the six statements using a statistical calculator web application (Statistics Kingdom, 2017).

[Location of Table 2]

## Results

### Products from the implementation of the SADT module

The implementation of the SADT module generated a variety of products and experiences based on its four components: investigation of plants, creation of 3D models of plants, application of 3D modeling in AVR platforms, and dissemination of results.

*Science Investigation.* Teams investigated the biology, uses, and importance of [the institution – blinded] research of fifteen species of plants including crops, native prairie plants, and model organisms (Table 3). For the investigation, the students used scientific articles, websites, photographs, and interviews with [the institution – blinded] scientists as sources. A few teams reached out to the scientists and had in-person or virtual meetings with them (32 students). The results were summarized in handouts, some of which are accessible on the Education Technology Program website ([the institution – blinded], 2024). Furthermore, 41 students visited the [the institution – blinded] and toured the facilities where they saw plant science research first-hand. They visited a molecular lab, the phenotyping facility, and the greenhouses.

*Creation of 3D plant models*. Student teams created thirty 3D models of full plants or plant parts such as leaves, stems, seeds, flowers, stolons, and inflorescences (Table 3). A few models were created using Tinkercad®, while most were created using Fusion 360®. The accuracy of the models varied among teams (Fig. 2). The Tinkercad® models were the least accurate due to the limitation of this program to generate organic shapes (Fig. 2A). Some of the Fusion 360® models were not colored as using the coloring tool requires advanced knowledge of this program (Fig. 2B). The most accurate models were created by students already proficient with 3D modeling software or who had received support from a 3D modeling expert (Fig. 2C). In the case of the common milkweed, one student created the stem, another the flower, and another created the inflorescence, assembled the pieces, and colored the final model (Fig. 2C). The students were resourceful and tried other ways to create plant models in 2D (Fig. 2A) or in intermediate stages between 2D and 3D views (Fig. 2C).

[Location of Table 3]

*Applications of 3D modeling in AVR platforms.* The AVR immersive experiences were implemented at the educational institution or at the [the institution – blinded]. During [the institution – blinded] visits, 41 students experienced augmented reality using zSpaces and an additional 72 students did so in their classrooms. The virtual reality experience "The Soybean Saga to Food and Climate Security" using Oculus Quest 2 was experienced by 137 students. Two schools used the Oculus at [the institution – blinded] (27 students), and four used them at their facilities (110 students). EROL members implemented these activities except at two schools where the teachers implemented the activities. School B has zSpaces, and the teacher runs her own zSpace activities. At school A, the Oculus were delivered to the teacher who was experienced in using the technology. Students from two schools experienced only the zSpace or the Oculus experiences. One school chose not to have these activities due to time constraints in implementing the module.

*Dissemination of results.* Students had the opportunity to develop and practice their communication skills by disseminating team results, creating handouts and presentations, and presenting their projects to an audience. Most of the handouts about the plant species (18) and the presentations of the projects (18) were created digitally using Microsoft PowerPoint or Google Slides. At school E, four students worked individually and created webpages for their projects. In three cases, teams hand-wrote the handouts and created paper posters where some content was digitally written and printed.

Some 3D models and associated handouts that were of high quality went through a further curation process by coauthors in this publication. 3D models were improved for accuracy and color, which were tested for use in the zSpace platform. Handouts were edited to standardize the format style. These products have been added to EROL's collection of plant science educational material and are available on the Education Technology Program website ([the institution – blinded], 2024).

The dissemination of project results was mostly through in-person presentations to student peers. On some occasions, researchers were invited to attend these presentations (school C). Another setting for the dissemination of project results was an open classroom presentation where teachers and administrators stopped by at any given time and heard from the students who were at different stations in the classroom (school E). In addition, students who attended the summer internship at [the institution – blinded] had the opportunity to present their projects during the research center's annual scientific retreat which was virtual that year (2021).

**Students' understanding of the intersections of art and design with science**

*The role of art and design in science.* To assess students' understanding of the intersection of art and science, students were asked to share their thoughts on how art and design play a role in science. The analysis of pre- and post-responses from 60 students revealed five main themes: 1) communication and further understanding, 2) fostering new ideas, 3) bringing ideas to life, 4) bringing science into everyday life, and 5) art and science are complementary (Fig. 3).

Over half of the students recognized that art and design could relate to science through communication and providing more understanding about a concept before the module. Within this theme, visual representations and models were the most cited subthemes. After completing the module, another 30% of the students reported this theme, and 10% of the total students reported a new subtheme for the understanding of scientific concepts (Fig. 3).

The second most common theme was 'fostering new ideas,' which included the subthemes 'create new ideas,' 'creativity,' 'technological advances and tool creation,' and 'aid in problem-solving.' Before the module, over 20% of the students reported this theme with another 10% of the students reporting it after completing the module. The other themes were reported by a few students mostly before the module (Fig. 3). Student counts and percentages per theme are in Additional file 1: Supplementary Material D.

Some quotes from students on the role of art and design in science are:

*“Art and design plays a role in science as it enables individuals to see the separate facets of a plant or organisms and understand their function, individually, rather than just seeing one whole organism or plant.”*

*“Art and design play a role in science because that is how science is able to be communicated. It allows us to better understand scientific concepts through visual representation, and creativity fuels scientific exploration. Art and design allow us to create different tools and technologies in applying scientific knowledge to our everyday lives.”*

*“Being able to visually represent elements of an important scientific model that the average person may not understand under strictly scientific jargon is important for advancing the general public's understanding of science.”*

*The role of science in art and design.* Student reflections from 58 students to the pre- and post-question on how science plays a role in art and design reported five themes: 1) science influences the artistic creation process, 2) similar processes, skills and principles, 3) technological advances, 4) science influences interactions with art, and 5) art and science are complementary (Fig. 4).

The most common theme identified by over 90% of the students was that science influences the artistic creation process (Fig. 4). Several subthemes were identified within this theme, with the most reported being ‘design logistics and specifics’, ‘inspire artistic ideas’, and ‘science creates art’. Over 50% of the students reported this theme before the model and another 45% reported it after completing the module. The other themes were reported by a few students, with the subtheme ‘technological advances’ reported by 10% of the students before and after the module (Fig. 4). Student counts and percentages per theme are in Additional file 1: Supplementary Material D.

Some student quotes on the role of science in art and design are:

*“Science is an inspiration for art.”*

*“Science plays a role in art and design because the scientific method is similar to the creative process, with trial, error, and adjustment.”*

*“Science shapes how art is made and things are designed.”*

**Students learning and skills gained from using the SADT approach**

Responses from 63 students about what they hoped to learn from the module and outcomes gained related to learning and gaining skills revealed several themes (Fig. 5). Before the module’s implementation, students wanted to learn new and interesting things (17.5%) and about the integration of science, art, design, and technology (14.3%). Less than 10% of the students expressed interest in learning science and research skills. After completing the module, few students reported learning about science, but 21% of the students reported learning research skills (e.g., caring for plants, making detailed observations, best lab practices, etc.). Twenty-two percent of the students had hoped to learn about plants. Of those students, 10% acknowledged learning about plants and another 40% of students reported learning about plants only after completing the module. Although few students wanted to learn about technology in general, 38% wanted to learn about 3D modeling. After implementing the module, another 6.3% and 17.5% of the students learned about these respective themes. Some students expressed interest in learning about art and design (14.3%), while another 11% of students expressed learning about this theme at the end of the module. New themes related to soft skills emerged at the end of the module implementation. Students gained skills for teamwork (27%), communication (11.1%), science communication (7.9%), and other skills (14.3%) including perseverance, time management, problem-solving, and leadership (Fig. 5). Student counts and percentages per theme are in Additional file 1: Supplementary Material E.

Some student quotes about learning and skills gained are:

*“Learning more about the applications of plants to human life and the benefits they provide.”*

*“The most important outcome of participating in this project was that I got to work with others. I really did enjoy collaborating with others and each of us having an important role that benefits us and the project.”*

Students were also asked about the relevancy or applicability outside of the class of the skills or knowledge developed. Responses from 35 students were grouped into four ‘relevance’ themes. These themes included relevancy for project and class activities (28.6%), undetermined endeavors outside the class (25.7%), future college areas of study and specific careers of interest to some students (e.g., biology, business, public relations, computer science) (25.7%), and future jobs, job interviews, and life endeavors (62.9%). Specific skills and or knowledge were recorded within themes. Twenty six percent of the students cited science knowledge and research skills as mostly relevant for future jobs and endeavors later in life. 3D modeling skills were cited by 37.1% of the students, mainly for relevance to developing projects and activities in class. Soft skills were cited across the ‘relevance’ themes, with communication (17.1% of students) and teamwork skills (20% of students) mostly cited as relevant for future jobs and endeavors later in life. Student counts and percentages per theme are in Additional file 1: Supplementary Material E.

Student quotes on the relevancy or applicability of outcomes gained are:

*"The experience of presenting and communicating our process and final models to an audience, as well as working in a research-like setting. These skills and experiences will all be useful for my future endeavors."*

*“I believe the experience gained in working with a group and presenting with a group is one of the most important outcomes as it is one of the most common skill in the professional world.”*

**Student interest in STEAM subjects and careers**

Students showed a significant increase in interest in science, mathematics, and design after the module was implemented, based on mean comparisons of responses from 77 students per subject before and after the module (Table 4). Comparisons for technology, engineering, and STEAM careers did not change significantly after the module was completed (Table 4).

**Table 4** Summary of statistical tests for significant differences in interest in STEAM subjects and careers

| Subject | Pre-survey mean (SD) | Post-survey mean (SD)* | t-value | P value | Direction of positive change |
|---|---|---|---|---|---|
| Science | 2.8 (1.5) | 2.6 (1.4) | 3.7 | 0.000 | Significant increase |
| Technology | 2.9 (1.7) | 2.8 (1.5) | 1.3 | 0.2 | No change |
| Engineering | 3.2 (1.6) | 3.2 (1.5) | 0.3 | 0.78 | No change |
| Mathematics | 4.2 (1.8) | 4.0 (1.8) | 2.6 | 0.008 | Significant increase |
| Design | 2.9 (1.7) | 2.5 (1.3) | 4.1 | 0.001 | Significant increase |
| Careers in STEAM | 2.8 (1.6) | 2.8 (1.5) | 1.0 | 0.3 | No change |

* The smaller the mean values, the more positive the responses are. Students responded on a Likert scale of 1-7, with 1 being the most positive choice and 7 being the most negative choice for each of the five statements per question. SD – Standard Deviation. Significant p-values equal ≤ 0.05.

However, students expressed positive changes in interest in STEAM careers based on answers to the post-reflection question "*Has participating in this project changed your interest in science and or art/design careers moving forward? If so, how?"* (Table 5). Answers to this question by 68 students were grouped into two main themes. One theme represents students expressing a positive change in interest in STEAM careers (39.7%). Among these students, seven acknowledge interest in plant science (10.3%). The other theme represents the students who did not have a change in their career interest after the module (60.3%). About 15% of the students were already interested in STEAM careers and another 15% in non-STEAM careers, while the remaining 30% did not provide information on why they did not experience a change in their career interests.

**Table 5** Student counts by themes on changes in interest in STEAM careers after the module

| Themes about changes in interest in STEAM careers | No. students | % |
|---|---|---|
| **Statements expressing positive changes** | **27** | **39.7** |
| More interest in science careers * | 10 | 14.7 |
| More interest in STEAM careers ** | 12 | 17.6 |
| More interest in STEAM careers with other subjects | 1 | 1.5 |
| More interest in design careers | 3 | 4.4 |
| More interest in non-STEAM careers | 1 | 1.5 |
| **Statements expressing no change** | **41** | **60.3** |
| Already interested in science careers | 4 | 5.9 |
| Already interested in STEAM careers | 4 | 5.9 |
| Already interested in art/design careers | 1 | 1.5 |
| Already interested in non-STEAM careers*** | 8 | 11.8 |
| No change with unknown reason | 24 | 35.3 |
| **Total students** | **68** | **100** |

* Six students interested in plant science. ** One student interested in plant science.

*** Three students acknowledged that the module helped them reinforce their interest in non-STEAM careers.

## Discussion

This study addressed the disconnect between science, art, design, and technology by exploring whether a 3D plant modeling learning module for high school students had an impact on students' learning and interests in STEAM subjects and careers, using the SADT approach (Fig. 1).

Integrating art and science through the SADT approach significantly enhanced students' understanding of how these fields intersect. Prior to the module, students primarily viewed art and design as tools for general communication and understanding of science. After participating in the module, a notable shift occurred. Many students reported that art and design facilitate deeper comprehension and communication of scientific concepts, foster new ideas, and bring ideas to life, with 45% acknowledging that science influenced their artistic creation processes. This shift highlights the effectiveness of the SADT approach in fostering an appreciation of the interconnectedness of these disciplines, aligning with the broader educational need for scientists to effectively communicate their work (Segarra et al., 2018). Such integration promotes curiosity and creativity, which are essential for developing positive attitudes toward STEM subjects (Stroud & Baines, 2019).

The module also played a critical role in enhancing students' science knowledge and research skills through hands-on investigation of plant biology, interactions with scientists, tours to the research facility, and dissemination of their findings. Before the module, only a small fraction of students expressed interest in learning about plant science and research skills. However, after completing the module, 40% of the students indicated a deeper understanding of plant science and 21% reported new research competencies. This experiential learning is crucial for students to connect with real-world problems and develop an interest in scientific disciplines that can lead them to future STEM career paths (Arango-Caro et al., 2024; Mansfield & Reiss, 2020; National Academies of Sciences, Engineering, and Medicine, 2021).

The design process is central to the SADT approach as it facilitates the application of knowledge and develops deeper understanding of global literacy (Gess, 2017). Designing and developing products such as 3D models involved cycles of trial-and-error that fostered students' abilities and confidence as they complete their projects (Gess, 2017). Creating 3D models has benefited student development of abstract thinking, creativity, and problem solving, critical in STEAM disciplines and careers (Bicer et al., 2017; Yakman, 2008). Our module followed steps that are known to stimulate creative thinking, including the design of goal proposal, creativity inspiration, design challenges, and presentation and evaluation (Zhan et al., 2023). Creativity was also promoted in our module through the flexibility of implementation, broad range of resources, self-directed learning, and team collaboration (Aguilera & Ortiz-Revilla, 2021; Davies et al., 2013; Markula & Aksela, 2022; Seetoo & Foen, 2022).

Moreover, the SADT approach introduced students to emergent technologies, with over half of the participants gaining skills in the use of 3D modeling and AVR tools. Before the module, many students had no experience with these technologies. The hands-on design experience with digital tools is particularly relevant in today's rapidly evolving technological landscape, where such skills are increasingly necessary (Leavy et al., 2023). Exposure to these technologies broadens students' interests and persistence in STEAM pathways (Bicer et al., 2017; CEOSE, 2024) and aligns with the growing need for digital literacy in education (Lombard et al., 2023).

The module's implementation also fostered the development of essential 21st century soft skills such as collaboration and communication, fostering the development of students' workforce competencies. Students reported significant gains in teamwork skills, appreciating the benefits of collaborative learning over individual work. Our results align with other reported findings that collaborative learning enhances problem-solving abilities and critical thinking (Wang et al., 2023). These experiences provided students with multiple opportunities to understand the benefits of peer and partners collaborations. Communication skills were also notably improved, with students gaining experience presenting their projects and writing about their scientific findings. These skills are vital for professional success and effective communication (Bertrand & Namukasa, 2020; Thornhill-Miller et al., 2023). The ability to convey scientific concepts to peers and general audiences fosters a deeper understanding of science and builds self-efficacy (Cormier & Langlois, 2022; Kulgemeyer, 2018; Ovid et al., 2023; Schinske et al., 2016).

Furthermore, the SADT approach positively impacted students' interest in STEAM subjects and careers. After completing the module, quantitative analyses revealed a significant increase in interest in science, mathematics, and design. Reflection responses indicated that 39.7% of students experienced a positive change in their interest in STEAM careers, with several expressing a newfound interest in plant science. This increase is particularly important given the urgent need to promote careers in plant science and agriculture, which is critical for addressing global challenges (National Academies of Sciences, Engineering, and Medicine, 2021; Niccolai et al., 2022). We know that during the adolescent stage, students develop understanding of work fields and how they are related to them (van Tuijl & van der Molen, 2016). Our module engaged students in hands-on STEAM real-world projects and interactions with professionals, which prepare students for STEM career trajectories and leverages their developmental interest in work fields (CEOSE, 2024; Seetoo & Foen, 2022; Segarra et al., 2018; van Tuijl & van der Molen, 2016).

The SADT approach's innovative framework for enhancing STEAM education integrates science with art, design, and technology, fostering cognitive benefits such as engagement, creativity, and problem-solving skills that will help them navigate 21st century workforce demands (Kang, 2019; Perignat & Katz-Buonincontro, 2019). This PBL module allowed students to engage deeply with multiple disciplines promoting interdisciplinary learning and student ownership of projects through self-directed learning (Gess, 2017; Hawari & Noor, 2020; Rodrigues-Silva & Alsina, 2023).

Educators also benefited from the SADT approach by transitioning from traditional teaching roles to facilitators of learning. This role enabled them to share teaching responsibilities with students, allowing for more personalized and student-driven learning experiences. Facilitators reported professional growth through their exposure to innovative teaching methods, new science content, and emergent technologies, enhancing their teaching practices and confidence (Kang, 2019).

The module's collaborative nature emphasized the importance of teamwork, both among students and between students and professionals. Students worked in teams to complete their projects, valuing their peers' support and shared responsibilities. This collaborative environment promoted critical and creative thinking and gains in skills that facilitate the communication of ideas and shared responsibility which are essential for professional success in STEM fields (Duran & Sendag, 2012; Kerans & Ngongo, 2021; Sanina et al., 2020). Moreover, group work maximizes the autonomy of students fostering project ownership and improving social/relational interactions, by practicing expressing oneself and establishing connections with others (Nieswandt et al., 2020; Thornhill-Miller et al., 2023). Additionally, interactions with plant scientists and education researchers provided students with valuable insights into the collaborative nature of scientific research.

## Conclusion

The SADT approach effectively integrates science, art, design, and technology using the 3D plant modeling module, enhancing student literacy in these disciplines, and providing students with essential 21st century competencies. The module's flexibility and experiential learning opportunities benefit students and educators, promoting interdisciplinary learning and interest in STEAM subjects and careers. This innovative approach is a valuable tool for educators, inspiring new ways of teaching and learning in STEAM education.

This comprehensive approach to STEAM education highlights the potential for interdisciplinary PBL to enhance student engagement, understanding, and interest in STEM fields. By integrating art and design with science and technology, educators can foster a more holistic and effective learning environment that prepares students for the challenges and opportunities of the future.

## Limitations

The study faced limitations due to the incomplete response rate to surveys and reflection questions, potentially affecting the data's comprehensiveness. Variations in module implementation and differences in institutional settings may have also influenced the results.

Future analyses will explore these factors further to understand their impact on student outcomes.

## Abbreviations

AVR: augmented and virtual reality

[the institution – blinded]

IRB: Institutional Review Board

EROL: Education Outreach and Research Laboratory

PBL: project-based learning

SADT approach: Science-Art-Design-Technology approach

STEM: Science, Technology, Engineering, and Mathematics

STEAM: Science Technology, Engineering, Arts, and Mathematics

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**Figure Titles and Legends**

**Fig. 1** The Science, Art, Design, and Technology (SADT) approach

**Fig. 2** 3D plant models created by students

**A.** 3D models with limited accuracy created in Tinkercad® (corn) or Fusion 360® (2D model of volvox). **B.** Models with limited accuracy created in Fusion 360®. **C.** Detailed 3D models created in Fusion 360®.

**Fig. 3** Student understanding of the role of art and design in science

Number and percentage of students who responded to the questions "How does art and design play a role in science?" before, before and after, or after the implementation of the module

**Fig. 4** Student understanding of the role of science in art and design

Number and percentage of students who responded to the questions "How does science play a role in art and design?" before, before and after, or after the implementation of the module

**Fig. 5** Student learning hopes and learning and skills outcomes

Percentage of students who reported their learning hopes and learning and skills outcomes before, before and after, or after the implementation of the module

**Table 1** Information on participating educational institutions

| Educational Institution | No. Students | Type of Institution | Educational Setting | Community Type | Educational Practice | Location | Module Period |
|---|---|---|---|---|---|---|---|
| A | 28 | Public | Formal | Urban | Co-ed | Chicago, IL | Spring 2023 |
| B | 44 | Public | Formal | Semi-rural | Co-ed | Springfield, MO | Fall 2022 |
| C | 24 | Public | Formal | Urban | Co-ed | St. Louis, MO | Fall 2021 |
| D | 22 | Private | Formal | Urban | Only females | St. Louis, MO | Fall 2022 |
| E | 4 | Private | Formal | Urban | Co-ed | St. Louis, MO | Spring 2022 |
| F | 17 | Private | Formal | Urban | Co-ed | St. Louis, MO | Spring 2022 |
| G | 7 | Private | Informal | Urban | Co-ed | St. Louis, MO | Summer 2021 |
| H | 14 | Private | Informal | Urban | Co-ed | St. Louis, MO | Spring 2023 |
| **Total students** | **160** | | | | | | |

*These institutions serve students from underserved communities with a majority of Hispanic students (A) and African American students (H).

**Table 2** Survey questions and associated main themes and example student quotes

| **Survey Question (codebook numbers associated with main codes are in parenthesis) *** | **Main Themes** | **Example** |
|---|---|---|
| **Q2.** How does art and design play a role in science? (Pre/post) (1.1.1. - 1.1.10) | Communication and furthering understanding | "Art and design play a role in science because that is how science is able to be communicated. It allows us to better understand scientific concepts through visual representation, and creativity fuels scientific exploration" |
| | Foster new ideas | "Art gives you inspiration and imagination to try out new things and you have to design how you are going to do that." |
| **Q1.** How does science play a role in art and design? (Pre/Post) (1.2.1. – 1.2.9.) | Science influences artistic creation process | "science plays a role in art and design because it describes or says what to draw or show" |
| **Q3.** What do you hope to learn by participating in this project? (Pre)<br><br>**Q4a.** What has been the most important outcome of participating in this project? Describe any skills or knowledge you developed during this project. (Post)<br><br>(2.1. – 2.11.) | Learning new/interesting things | "I hope to learn many new things" |
| | Learning about the integration and connection of art, design, science, and technology | "I hope I can learn more about how to use technology to create art while connecting it to science" |
| | Learning about science | "I learned more about the plant I was researching" |
| | Learning about the use of technology | "I was able to improve my skills in 3D modeling and how to model a lot more properly." |
| | Learning about design/art | "3D art making skills" |
| | Learning soft skills | "I developed better presenting skills and more skills on how to work with other people and as a group on a project that can contain some pretty individual opinions" |
| **Q4b.** [What has been the most important outcome of participating in | Relevance for projects/classes | "I developed being able to create a 3D model and can now do that in future classes or projects." |

| | | |
|---|---|---|
| this project? Describe any skills or knowledge you developed during this project] and whether you feel these will be relevant or applicable outside of the class. (Post) (3.1. – 3.5.) | Relevance for endeavors outside of class | “A skill that I developed during this project are more stronger communication skills…This is a skill that will be applicable and relevant outside of class…” |
| | Relevance for future college or careers | “…the experience of working with a researcher will help me in the future when I participate in undergraduate research in college.” |
| | Relevance for jobs/job interviews/endeavors later in life | “Working in teams definitely helped my communication skills, which are very important in work environments.” |
| **Q5.** Has participating in this project changed your interest in science and or art/design careers moving forward? If so, how? (Post) (4.1. – 4.3.) | Statements expressing positive change | “I think that it has increased my interest in going into a science career, because I really enjoyed working on the models.” |
| | Statements expressing no change | “I was already interested in careers in the scientific community” |

* In parentheses it is indicated if the question was administered before, before and after, or only after implementing the module and the codebook numbers associated with each main theme.

**Table 3** 3D plant models created by students

| Plant Type | Common Name | Species Name | 3D model (plant parts) | Institution |
|---|---|---|---|---|
| Forb | Common milkweed | *Asclepias syriaca* | Plant | G |
| Small weed | Barrel medic | *Medicago truncatula* | Leaf | B, D |
| Green algae | Chlamydomonas | *Chlamydomonas reinhardtii* | Cell | C, G |
| Green algae | Volvox | *Volvox carteri* | Colony | G |
| Grass | Big bluestem | *Andropogon gerardii* | Spikelet pair | E |
| | | | Inflorescence | D |
| Grass | Fox millet | *Setaria viridis* | Plant - 3 life stages | G |
| Grass | Indiangrass | *Sorghastrum nutans* | Spikelet | E |
| Grass | Little bluestem | *Schizachyrium scoparium* | Spikelet pair | E |
| Grass | Seashore paspalum | *Paspalum vaginata* | Stolon | D |
| Crop | Alfalfa | *Medicago sativa* | Stem and leaves | C |
| Crop | Barley | *Hordeum vulgare* | Inflorescence | B |
| Crop | Cassava | *Manihot esculenta* | Female flower | D |
| Crop | Maize (corn) | *Zea mays* | Male flower | E |
| | | | Female flower, germinated kernel | D |
| | | | Leaf, seed | E |
| | | | Stem, leaves, female and male inflorescence | C |
| Crop | Oat | *Avena sativa* | Flower | D |
| Crop | Soybean | *Glycine max* | Plant and seed | B |

Figure 1



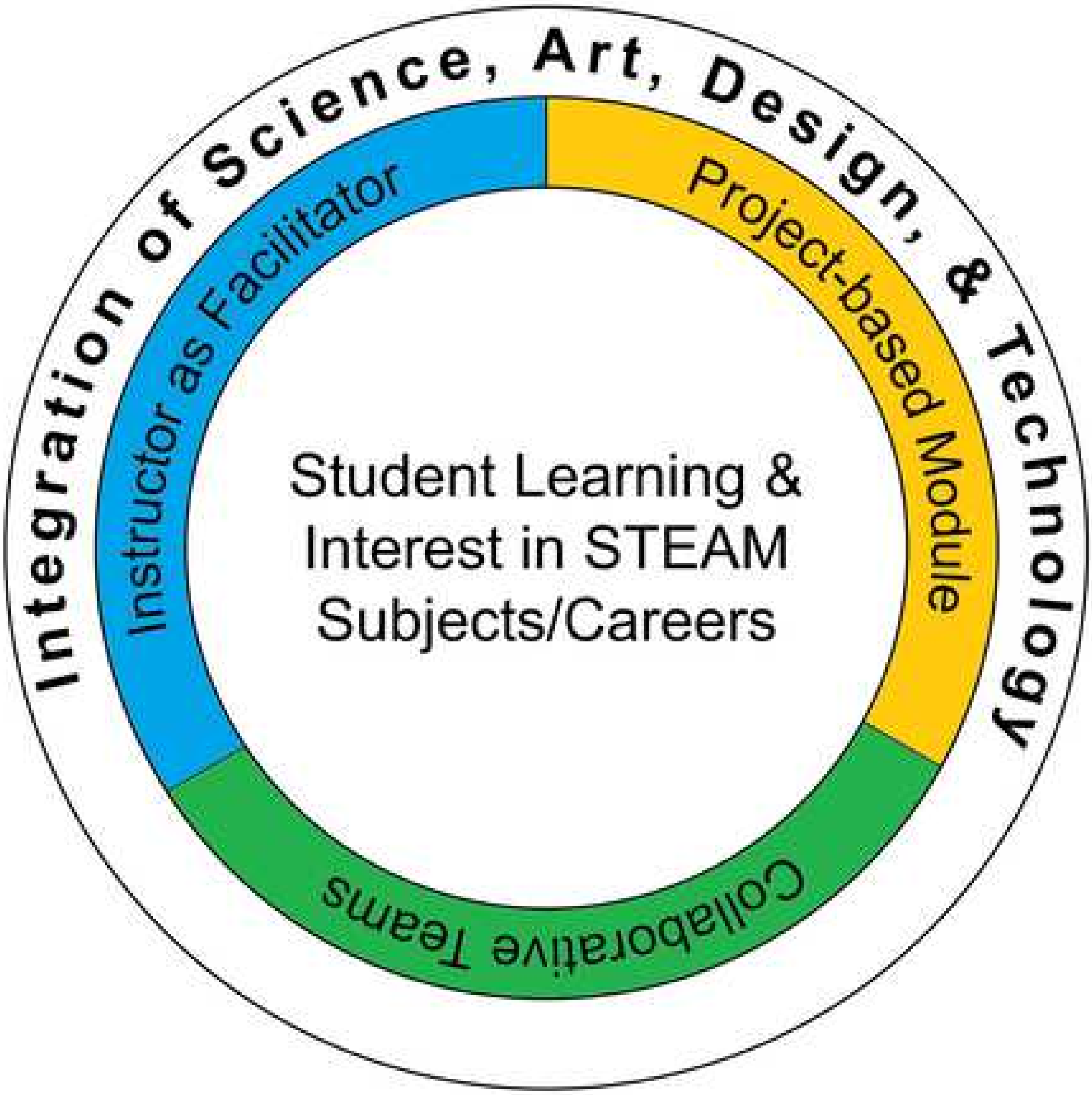
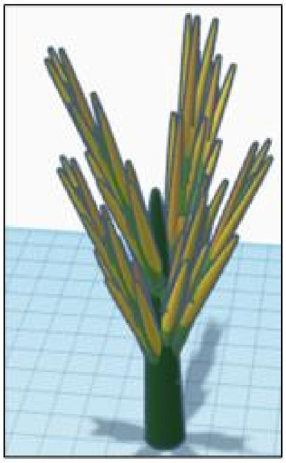
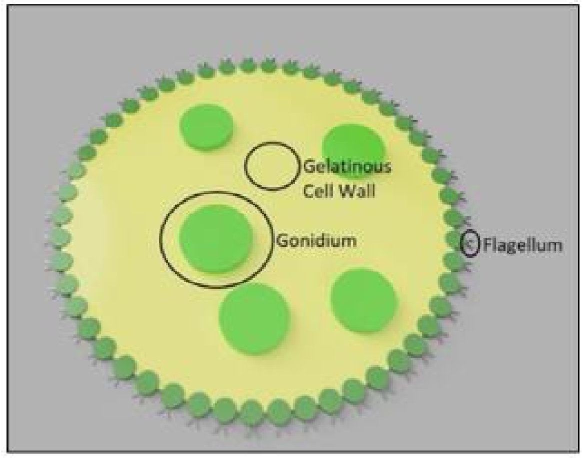

Integration of Science, Art, Design, & Technology
Instructor as Facilitator
Project-based Module
Collaborative Teams
Student Learning & Interest in STEAM Subjects/Careers

Figure 2 Click here to access/download;Figure;Figure 2. 3D models.docx

**A**

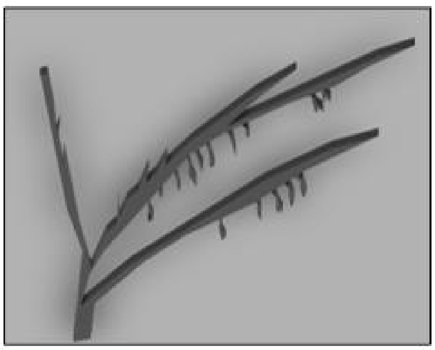


Corn (*Zea mays)* male inflorescence

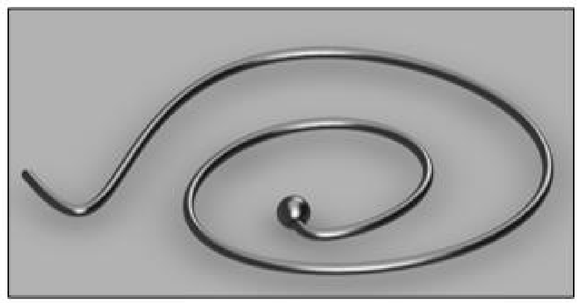



Reproductive phase of Volvox (*Volvox carteri*)

**B**



Big bluestem (*Andropogon gerardii*) inflorescence



Corn (*Zea mays*) female flower

**C**

Common milkweed (*Asclepias syriaca*)

Big bluestem (*Andropogon gerardii*) spikelet

Chlamydomonas (*Chlamydomonas reinhardtii*)

Figure 3



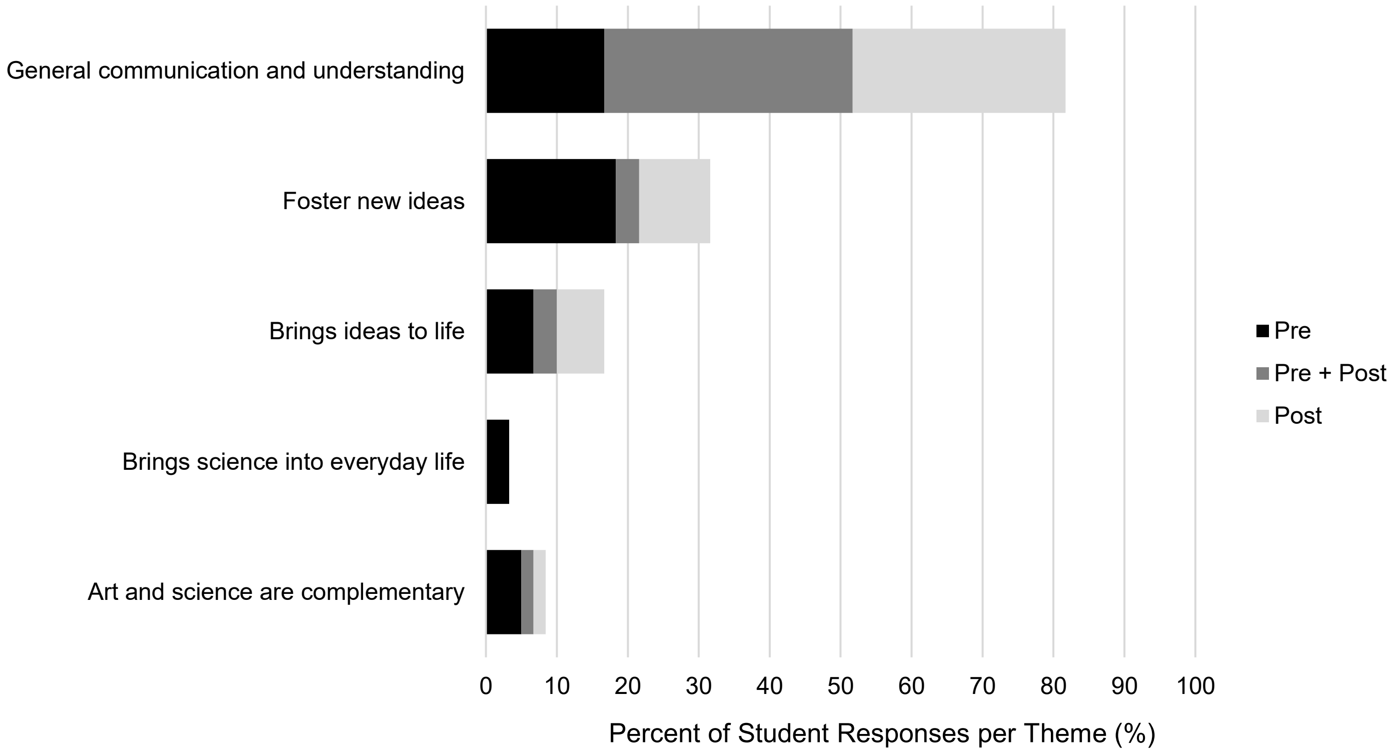

General communication and understanding
Foster new ideas
Brings ideas to life
Brings science into everyday life
Art and science are complementary
0
10
20
30
40
50
60
70
80
90
100
Percent of Student Responses per Theme (%)
Pre
Pre + Post
Post

Figure 4

Click here to access/download;Figure;Figure 4. Role of science in art and design.docx

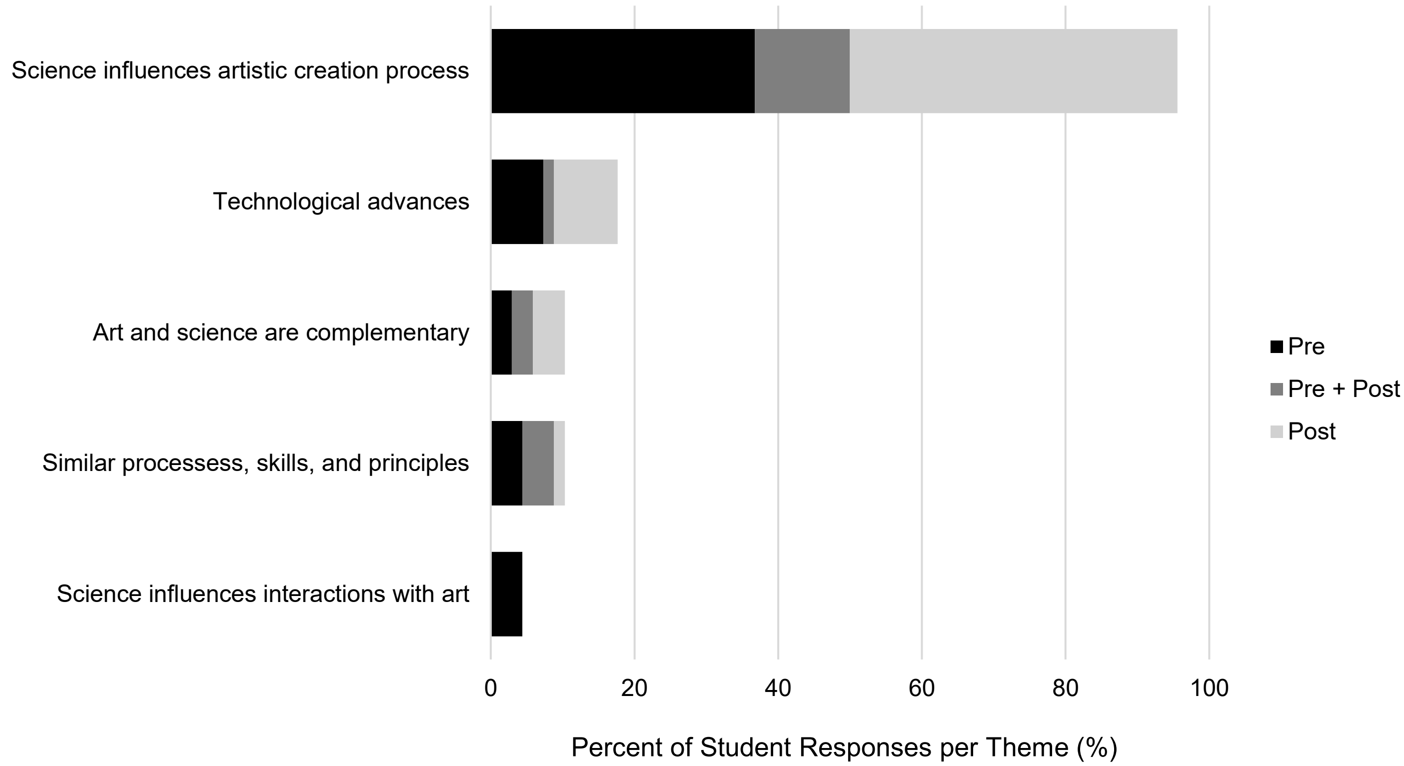
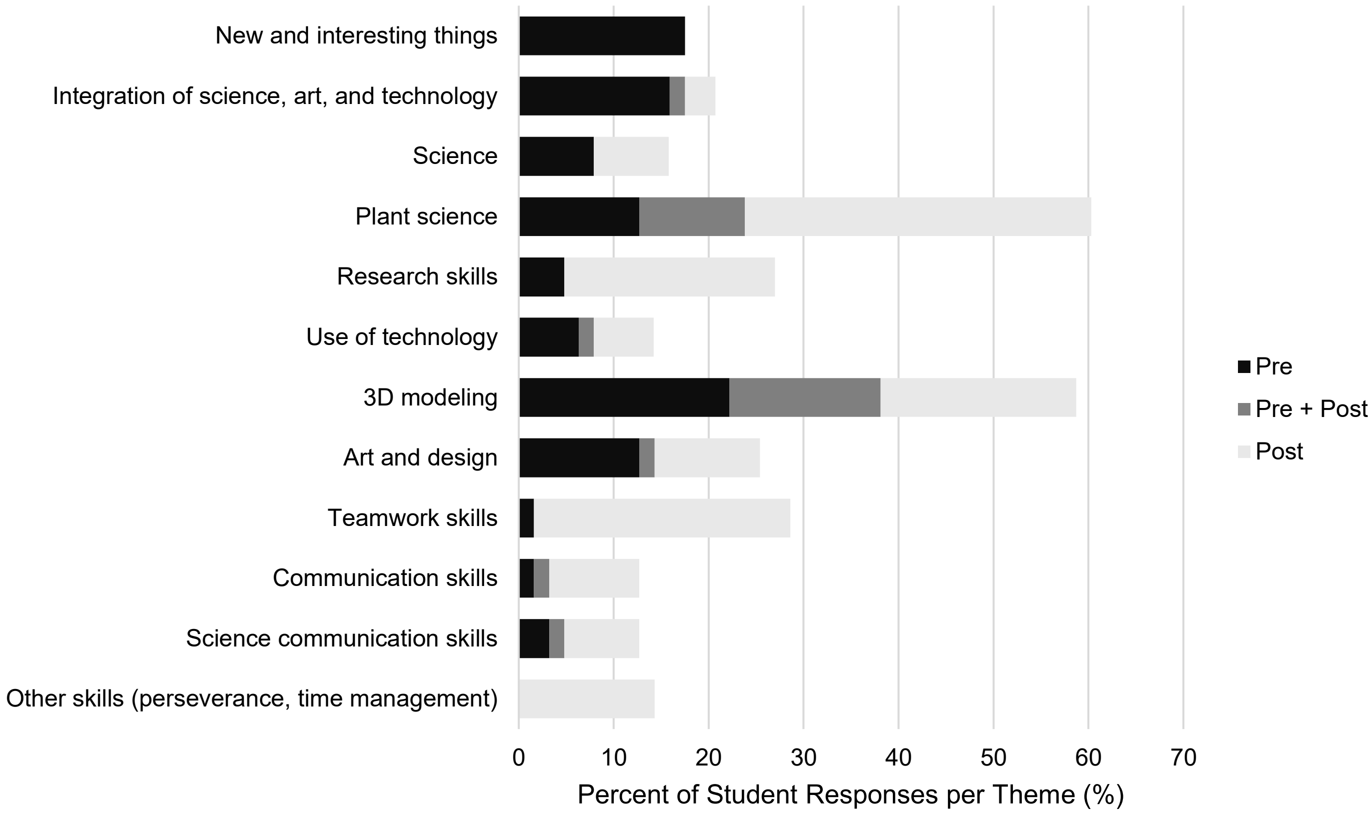


Figure 5

Click here to access/download;Figure;Figure 5. Learning and skills outcomes.docx



supplementary materials

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# 3D plants: The impact of integrating science, design, and technology on high school student learning and interests in STEAM subjects and careers

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## Declarations

### Availability of data and materials

Data will be made available on reasonable request.

### Competing interests

The authors have no competing interests to disclose.

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### Authors' Contributions

SAC directed the project, analyzed the data, and was the primary author of the manuscript. TL wrote sections of the manuscript and assisted with data analysis. KY and MA assisted with data analysis. NL created the tutorial videos, was the 3D modeling expert who advised students and curated the models. CB provided external project advice. KCD oversaw the project and assisted with data analysis. All authors reviewed versions of this manuscript.

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