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Evidence-based studies on the benefits of integrating STEM into the arts are limited; however, some suggest that it can lead to improved scientific literacy and new approaches for artistic scholarship. Unfortunately, undergraduate education often creates disciplinary silos where the two are not integrated. Here, we discuss a unique collaboration between professors in the art and biology departments. Our goal was to integrate science into art courses using an agar art activity. We hypothesized that art students could effectively learn microbiology laboratory techniques and use them as novel tools for artistic practice. The activity was integrated into two to four sessions of introductory and advanced art courses over four semesters. After learning aseptic technique to culture bacteria, the students were supplied with a variety of media and bacterial strains and tasked with recreating a famous artist's drawing or using their own artistic concept. Student learning was assessed using a rubric to evaluate their art and demonstrate that the learning outcomes were met. Improvement in aesthetic, conception, and technical proficiency in handling the bacteria were demonstrated when comparing their first attempt at creating agar art to their second. Advanced art students earned higher scores than introductory students; however, the average scores for all students were "proficient" or above suggesting that the learning outcomes were met. The art was externally evaluated through American Society for Microbiology's (ASM's) Agar Art Contest and each time, at least one of our student artworks was chosen as a finalist for the People's Choice Award, providing validation of the success of our collaboration.

KEYWORDS agar art, aseptic technique, microbiology, drawing, interdisciplinary curriculum, arts and sciences, teaching collaboration

INTRODUCTION

The higher education curriculum within the United States has transitioned from a broad overview of the arts, sciences, humanities, and religion to "silos" which focus on a highly specialized course of study (1). It is well documented that educational silos are not preparing today's workforce with the skills to solve complex global challenges (2). Solving these challenges requires learners to be multi-disciplinary, ethical, and creative problem-solvers that can function in multicultural, multilingual, and collaborative environments (3).

Historically, science and art were not always divided. Albrecht Dürer, considered the greatest German artist of the Northern Renaissance, and James Audubon, famed Haitian American watercolorist and ornithologist, both produced masterpieces with enduring influences on the natural sciences (4, 5). Additionally, the scientist who discovered penicillin in the 1920s, Alexander Fleming, was also known for creating works of art using microbes on agar (6). In 2015, the American Society for Microbiology (ASM) continued this tradition and created a contest calling for microbiologists and artists to "paint" works of art using bacteria on any agar medium "canvas." Scientists and artists alike took to the challenge and cultured bacteria on top of agar plates into a multitude of shapes and colors. The contest went viral as people from around the world admired the beauty of something not normally deemed as appealing to the eye. After such a successful outcome, ASM continued to carry on the tradition annually. Therefore, creating innovative curricula and outreach programs that embrace science and art is important not only to restoring the historical relationship that has been diluted by disciplinary division in academia, but also to nurture competencies essential for preparing future students to enter an advanced workforce.

STEAM (science, technology, engineering, arts, mathematics) is a global educational strategy aimed at creating integrative

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courses and programs. The benefit of incorporating the arts in STEM for current and future scientists is well documented (7–9). However, evidence-based studies on the benefits of integrating STEM into the arts are limited (1). Studies suggest it can lead to improved public scientific literacy and new approaches for artistic scholarship (10). In fact, if it were not for the scientific developments of different mediums and technologies like paints, solvents, transportable tools, mathematical ratios, archeology, architecture, and the camera, artists would not have the ability to experiment, get out of their comfort zone, and create new things.

In this article, we discuss our unique collaboration between the arts and sciences, where students taking art courses were brought to the microbiology lab to learn how to use agar as a canvas and bacteria as the paint to create agar art in hopes of broadening scientific awareness while restoring an interdisciplinary relationship that is necessary for advancement in a modern society. Some of the students had never been in a lab before and were hesitant to work with bacteria due to fear and lack of knowledge of microbiology. However, as they worked with the different types of agar and the distinct species of microbes, they also learned that many bacteria can be commonly found in and on our bodies and do not harm us. Student learning was assessed by using a rubric to evaluate their final artworks to determine if the learning outcomes (in both art and science) were met. The students showed improvement in both aesthetics and technical proficiency when comparing their first attempt at creating the art to their second. Advanced art students earned higher scores than introductory students; however, the average scores for all students were "proficient" or above suggesting that the learning outcomes were met. Several of the student's agar arts were submitted into ASM's Agar Art Contest and each time, at least one of our student artworks was chosen as a finalist for the People's Choice Award. This provided an external evaluation of student learning and validated the success of our collaboration. Together, these data demonstrate the contribution of science in the development of art and provide a template for educators to implement learning experiences that support education initiatives such as the Vision and Change which focus on scientific literacy and interdisciplinary communication (11).

Intended audience

This activity was developed for undergraduate students that are non-science majors, specifically art majors or minors.

Learning time

The activity can be executed in a minimum of two class periods with a total of 4 to 6 hours in class. The microbiology professor will need additional time (~4 h) outside of the class period to grow the bacteria and prepare the media.

Prerequisite of student knowledge

No prerequisite knowledge in art or microbiology is required.

Learning objectives

Upon completion of this activity, students will:

1. Demonstrate an awareness of aesthetic and material concerns through visual choices.
2. Apply the principles of design to the creation of agar art.
3. Illustrate an understanding of the cultural morphology of the distinct species of bacteria on various types of agar.
4. Demonstrate proficiency handling bacteria using aseptic technique.

PROCEDURE

Materials

A list of materials can be found in Appendix I in the supplemental material.

Student instructions

Students will learn basic microbiology laboratory techniques and apply them to making agar art. Students will be required to follow all safety guidelines, including dressing appropriately for laboratory work. A handout with student instructions can be found in Appendix I in the supplemental material.

Faculty instructions

It is recommended to start planning the agar art activity *at least* one semester prior to implementation.

This activity requires that an interdisciplinary collaboration be formed between a microbiology professor and an art professor; therefore, the first step is to identify a collaborator. If you are unfamiliar with the professors in the art department at your institution, you could arrange to meet with the chair of the art department to solicit recommendations for the collaboration. Alternatively, you could review the course catalog to determine which art course would be a good fit for this activity and then reach out to the professor of record for the course.

Once a collaborator is identified, the logistics for the course need to be addressed. Coordinate your teaching schedules to determine the dates the agar art activity will be implemented. The laboratory will need to be reserved for the specified dates. The syllabus should be adjusted to include the logistics for the activity.

Laboratory supplies will need to be ordered for this activity; therefore, you will have to determine which department will

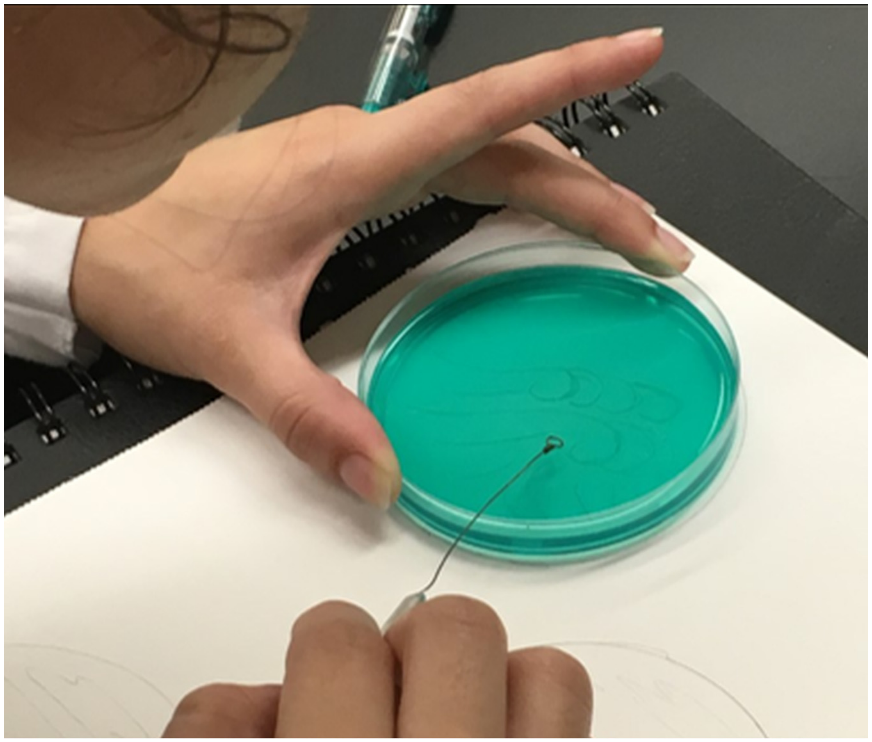


FIG 1. Student using an inoculating loop with bacteria to trace drawing onto the agar plate which is placed on top of a sketch drawn within a petri dish-sized circle on a sketch pad.

cover the expenses. Universities typically encourage interdisciplinary teaching and may provide funding opportunities for such endeavors. Refer to Appendix I in the supplemental material for a list of materials needed for this activity.

A few days prior to the scheduled date of the agar art activity, the media should be prepared according to the manufacturer's directions. The amounts of each type of media will be determined by the number of students in the course and the number of plates each student will be allocated. Plates should be dried overnight at room temperature before storage at 4°C. The bacterial strains should be grown 1–2 days prior to class by streaking onto nutrient agar and incubating at the proper temperature. One set of plates should be made for each lab table for the students to share.

Prior to the scheduled class, the art students should be notified of the proper attire required for laboratory work and to bring lab coats if they own one. Extra lab coats of varying sizes should be available for students who do not own their own.

Prior to the scheduled laboratory session, art students should be exposed to artists who merge the scientific process with artistic concerns such as Kiki Smith, Steve Kurtz, and Maria Peñil Cobo. Teachers in advanced art courses should also lead a discussion about the "borrowed" significance that comes with the use of certain materials for artmaking and the conceptual value added to artworks by such materials (or processes). For example, in "Rare Death from a Common Friend" a student explained the choice of bacteria to paint a skull when they wrote "The bacteria, *Staphylococcus aureus*, is the most dangerous type of *Staphylococcal* bacteria, yet it is a common bacterium found on healthy human skin." In art history, the skull is an often-used symbol called memento mori, a reminder of the unavoidable persistence of death as an urge to live one's life at the fullest (12). In this case, the bacterium lands its own ubiquity as a memento mori for this artwork. The commonality of *S. aureus* paired with its deathly ability are "borrowed" meaning called signifiers in semiology (13). Similarly, students should be asked to sketch concepts they would like to explore during the lab sessions that take into consideration the significance of the material they are using and the context in which they operate. Which bacterium is this? Where can it be found? What does it do? Is the laboratory context something that gives meaning to your process culturally or historically? Can you think of imagery that would build upon the intrinsic nature of this material and location, beyond its aesthetic beauty (color and texture), to create a deeper meaning for your artwork?

Once in the laboratory, the microbiology professor should first review laboratory safety protocols. A PowerPoint is available in Appendix II in the supplemental material to use as a teaching tool. It covers the basic background information regarding the bacteria and media to be used, including expected colony morphologies, and proper aseptic technique. Each student should receive a copy of the instructions in Appendix I in the supplemental material entitled, "Agar Art: Finding the Beauty in Bacteria." The professor should include a demonstration of proper aseptic technique and bacterial inoculation of the agar plates. The agar plate should be placed on top of a sketch as a depicted in Fig. 1 and the image traced using the inoculating loop with the bacteria. Inform students that pressing too hard on the surface will break the agar. Remind students that the bacteria will not be seen on the plates and requires incubation to grow and be visualized. If bacteria are seen on the plate during inoculation, this indicates that too much bacteria have been used because only streak marks left behind by the inoculating loop should be seen prior to incubation. Students should label the lids of the plates with their names, dates, and bacteria used. Once they have completed making their agar art, seal each plate with parafilm and incubate with the plate inverted at the appropriate temperature for 24 h to 48 h. For example, *Serratia marcescens* should be incubated at room temperature to achieve bright red growth. The plates can then be stored in the refrigerator until the next class meeting.

During the second agar art session, the students can view and photograph their results. The professors can lead a discussion on the final outcomes and whether they met the students' expectations. Discussion on media choices, bacteria/agar combinations, amount of bacterial growth visualized, and contamination issues could be discussed by the microbiology professor. The composition and conceptual imagery can be discussed by the art professor. It is important to discuss how the image can be altered to express the feeling the student is looking to communicate. Optionally, once students have become familiar with handling bacteria, they could determine the modifications needed and be allowed another attempt at making the agar art to improve their final outcomes. This would require a third class meeting to view the results.

Lastly, students may opt to submit their agar art to the annual ASM's Agar Art Contest as participation in the contest may increase student motivation.

Suggestions for determining student learning

To assess the student's agar art, the grading rubric in Appendix III in the supplemental material can be used. The rubric includes criteria that are linked to both the art and science-based learning outcomes.

Sample data

Sample data is provided in the "Evidence of student learning" section of the Discussion.

Safety issues

The ASM Guidelines for Biosafety in Teaching Laboratories should be followed for this activity with the same considerations used for a microbiology lab course. The bacteria used in this exercise require BSL-1. Because this activity is geared toward non-majors with little to no laboratory experience, it is recommended that the laboratory safety protocols are reviewed prior to starting the activity. Students must be reminded to wear the proper attire prior to the scheduled class, i.e., lab coats, long pants, and closed-toe shoes. Long hair must be pulled back. Lab coats should be provided for students who do not have their own.

DISCUSSION

Field testing

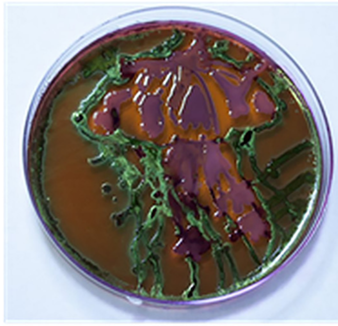
We have conducted this agar art activity for four semesters with approximately 50 students, the majority of which were art majors or art minors. The agar art activity was integrated into an introductory drawing course for one semester and into an advanced materials and methods art course for three semesters. For the drawing course, students had to research a historical artist and choose an image as reference or as inspiration to recreate one of their works as agar art. The advanced art students were asked to imagine an artistic concept that would benefit from the intimate relationship between humans and bacteria, utilizing the principles of design they are familiar with to create agar art. We treated the first class session as practice and allowed students to experiment with different agars and bacterial strains, while the second session was used to create their final agar art piece. Students were given feedback and exchanged tips during a group discussion after their first attempt and using the rubric on their second attempt. A third session was sometimes included to allow students to assess their creations and make modifications as needed. Advanced students were also asked to provide an artist statement explaining their conceptual approach to the assignment. Additional time was spent outside of the class periods photographing the art, writing an artist's statement and submitting them to ASM's Agar Art Contest. Showing the students images of past winners helped inspire them. Participation in the contest motivated them to try their best to create a winning piece.

Some of the students had never been in a lab before and were hesitant to work with bacteria, at first, because they were afraid that it was harmful. However, as they worked with the different types of agars and the varied species of microbes, they were taught that many bacteria can be commonly found in and on our bodies and do not harm us. They quickly became comfortable and proficient with handling the bacteria in the lab.

Evidence of student learning

Examples of graded student work are shown in Fig. 2. The final agar art was evaluated using the grading rubric in Appendix III in the supplemental material. Learning outcome (LO) 1 was assessed using the "Visual Communication" and "Concept" categories of the rubric; LO 2 was assessed by the "Aesthetic Quality" category; LO 3 was assessed by the "Media Choice" category; and LO 4 was assessed using the "Technical Proficiency" category. A score of "proficient" or higher suggested that the learning outcomes were being met. The artistic properties of the artworks submitted for grading were based on the understanding of the principles of design as demonstrated by their composition (including contrast, balance, emphasis, proportion, hierarchy, repetition, rhythm, pattern, white space, movement, variety, and unity). Furthermore, the conceptual value of the artworks submitted were graded based on the topic illustrated (either the selection of an historical

A

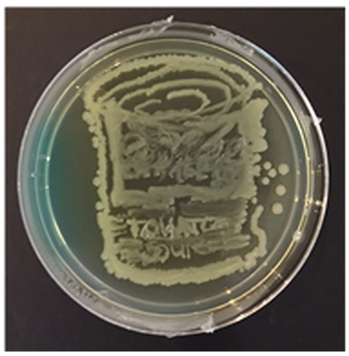


Category	Score
Visual Communication:	Above Expectations (17)
Concept:	Exemplary (20)
Aesthetic Quality:	Exemplary (20)
Media Choice:	Exemplary (20)
Technical Proficiency:	Proficient (15)
Total Score:	**92**

B

Category	Score
Visual Communication:	Proficient (15)
Concept:	Above Expectations (17)
Aesthetic Quality:	Proficient (15)
Media Choice:	Exemplary (20)
Technical Proficiency:	Above Expectations (17)
Total Score:	**84**

C



Category	Score
Visual Communication:	Needs Improvement (13)
Concept:	Below Expectation (11)
Aesthetic Quality:	Needs Improvement (13)
Media Choice:	Needs Improvement (13)
Technical Proficiency: .	Proficient (15)
Total Score:	**65**

FIG 2. Three examples of graded agar art using a rubric that assesses whether the learning outcomes were met (A to C).

artwork to reinterpret for the intro students or the development of a personal concept intrinsically linked with the nature of the bacteria used in the art submitted for the advanced courses.) Note that it is difficult to judge the full value of a concept without historical and sociological contexts. For that reason, this component should be graded using an open critique with oral participation from the class or via a written artistic statement that establishes the background. For example, "What artist was used as an inspiration and why?" is a question that the introductory-level students should be able to answer. "What is the link between the material and the subject matter illustrated in the work?" is a question that advanced students should be able to clearly articulate, and their answer should be obviously linked with the artwork presented. A discussion guide was provided in Appendix IV in the supplemental material and examples of written artistic statements were provided in Appendix V in the supplemental material.

In Fig. 2A, the student effectively mirrored the illustrated jellyfish's bioluminescent abilities with the green metallic glow of the *Escherichia coli* when grown on an EMB agar plate, resulting in an "exemplary score" for media choice. A score of "proficient" was assigned for "technical proficiency" due to too much bacteria being used in some areas, causing it to overgrow and spread around the perimeter of the plate. Furthermore, the student emphasizes texture, an essential element of design, by layering two bacteria and capitalizing on their growth pattern. It displays a unique and creative interpretation of the subject matter with the use of a variety of bacteria to create color contrast and engage with the audience. The artist wrote an artist statement that clearly communicated a relevant concept with the material and the image created and demonstrated a successful integration of scientific literacy (Appendix V in the supplemental material). In addition, the artwork demonstrated an understanding of the principles of design with the use of asymmetrical balance, variation in line work, a complementary color scheme, and implied texture. The use of these elements created by the bacteria engages the audience.

In Fig. 2B, the design demonstrates a somewhat creative approach to a not-so-unique but relevant concept. It effectively links bacteria's fundamental link to human life with the skull still-life iconography historically associated with the concept of *memento mori*, Latin for "remember the eminence of death"

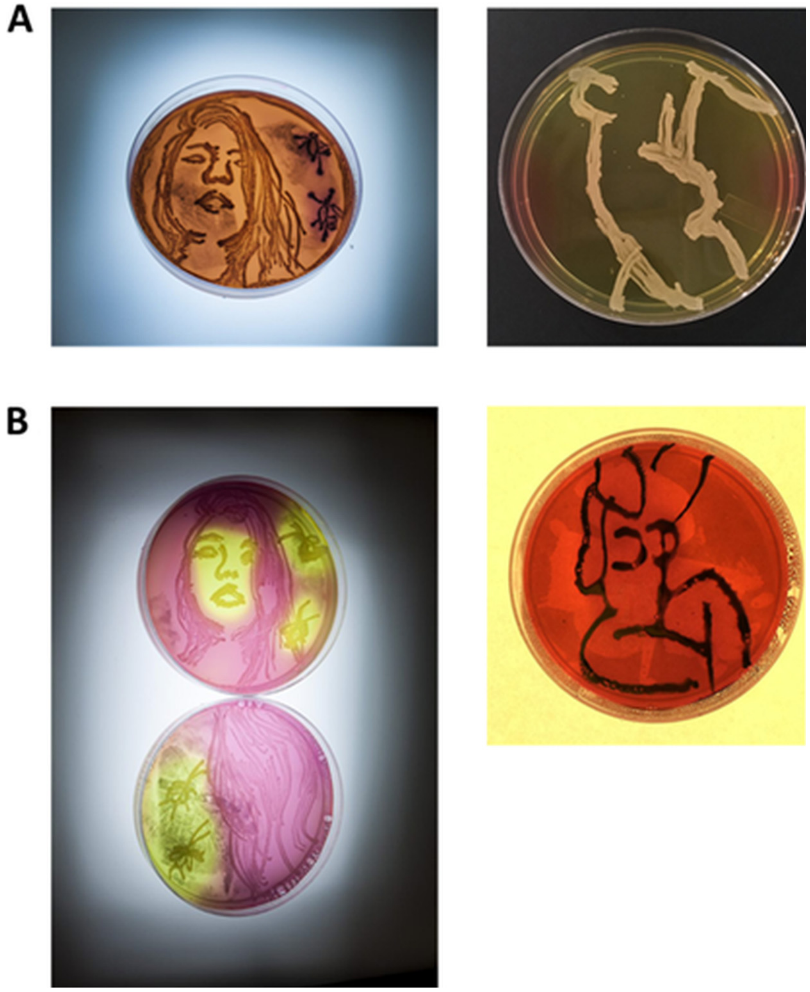


FIG 3. Evidence of student learning through comparison of first agar art attempt (A) to second attempt (B). The images to the left were created by a student in an advanced art course while the images on the right were created by a student in an introductory drawing course. Both students show improvement from their first to their second attempt.

and was graded "above expectations" for the concept. However, the composition is off-centered and does not take the round canvas into account. Furthermore, the color use and other elements of design were simple, but also proficiently demonstrated through line, repetition, and texture (visual communication and aesthetic quality). The choice of starch agar was considered "exemplary" because it was appropriately used with iodine to give the skull a black and white appearance like an x-ray. A score of "above expectations" was assigned for "technical proficiency" due to the presence of a few colonies growing outside the streak lines.

Although it can clearly be linked to the Andy Warhol soup can artwork from which it is inspired, Fig. 2C's central composition is not engaging nor its interpretation original which is why this artwork needs improvement with its visual communication. Furthermore, the line and color choices do not reflect the pop art style selected (concept: below expectation), nor does it demonstrate clear mastery of the principles of design by being quite messy (aesthetic qualities: needs improvement). This piece needs some work with its visual and conceptual quality. The conceptual message is not too clear, and the bacteria chosen does not help with the communication of the concept. The image demonstrates some level of understanding but it is not at a mastery level. The elements of design are not used to the best of their abilities. This student should have chosen strains and media with more vibrant colors to reflect Andy Warhol's work, therefore, "needs improvement" was assigned for "media choice." Although the soup can is distinguishable, there are colonies seen outside of the drawing area while other areas are overgrown with bacteria, therefore, a score of "proficient" was assigned for "technical proficiency."

Overall, Fig. 2 demonstrates the students' abilities to apply the principles of design to the creation of agar art. By choosing a combination of bacteria and agar that were appropriate for their artwork, they illustrated their understanding of cultural morphology. All the students demonstrated proficiency with handling bacteria using aseptic technique, as little to no contamination was observed and the bacterial growth was mainly within the streaked areas.

When the agar art activity was extended to allow students to create a second agar art after evaluating their first attempt, improvements were observed. In Fig. 3, two agar

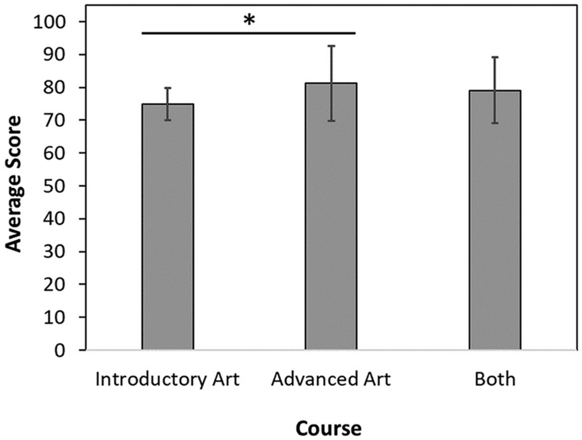


FIG 4. Average scores of the final agar art pieces created by students in an introductory and/or advanced art course. A rubric was used to assess the final agar art pieces from all students (N = 50). A comparison of agar art scores of students in the introductory art course versus the advanced art course is shown. On average, the advanced students earned higher scores. The single asterisk indicates a statistically significant difference (P = ≤ 0.05).

art creations from the same student are compared from both the advanced (on the left) and introductory (on the right) art courses. The images on the top are the students' first attempts while the images on the bottom are the students' second attempts. When comparing their first agar art attempts to their second, better choices for media/bacteria combinations were made. Better technical proficiency is detected with better control over the amount and placement of the bacteria. Getting more comfortable with the laboratory tools, students were also able to demonstrate more motor precision in their drawing; drawing with invisible ink is indeed not an easy task, it requires practice! Through observation, they were also able to anticipate the texture through growth pattern and color dispersion more accurately. Finally, like with all art projects, through open critique and exchanges between artists, students were able to develop more intimate concepts related to the process and materials they were using. Seeing what combinations worked well for their peers helped nurture their creativity on the next attempts. Only their final agar art pieces were assessed using the grading rubric. The advanced art students earned higher average scores than the introductory art students and this difference was statistically significant (P = ≤ 0.05) (Fig. 4). The average overall score for the assignment for students in both courses was 79. Comparing the average scores for each rubric category revealed that the advanced students scored higher on "media choice" than introductory students (Table 1). This statistically significant (P = ≤ 0.05) difference could have been attributed to the nature of the advanced art course which focused on exploring various artistic media, techniques, and processes to create art, while the focus of the introductory art course was drawing. Averages for each category on the rubric were 15 or above, regardless of whether the students were introductory or advanced (Table 1). These data suggest that the learning outcomes are being met, since the average scores for each category were "proficient" or above.

TABLE 1
Means and standard deviations of scores in each rubric category for agar arts made by introductory and advanced art students[a]

Rubric category	Introductory art (N = 17)		Advanced art (N = 33)		*P* value
	Mean	SD	Mean	SD	
Visual Communication	15.12	1.50	16.09	2.47	0.14
Concept	15.00	1.22	16.24	3.32	0.14
Aesthetic Quality	15.00	1.41	15.88	2.42	0.18
Media Choice	15.00	1.00	16.58	2.72	0.03*
Technical Proficiency	15.12	1.65	16.21	2.36	0.09

[a]N, # of students; SD, standard deviation. *, $P < 0.05$.

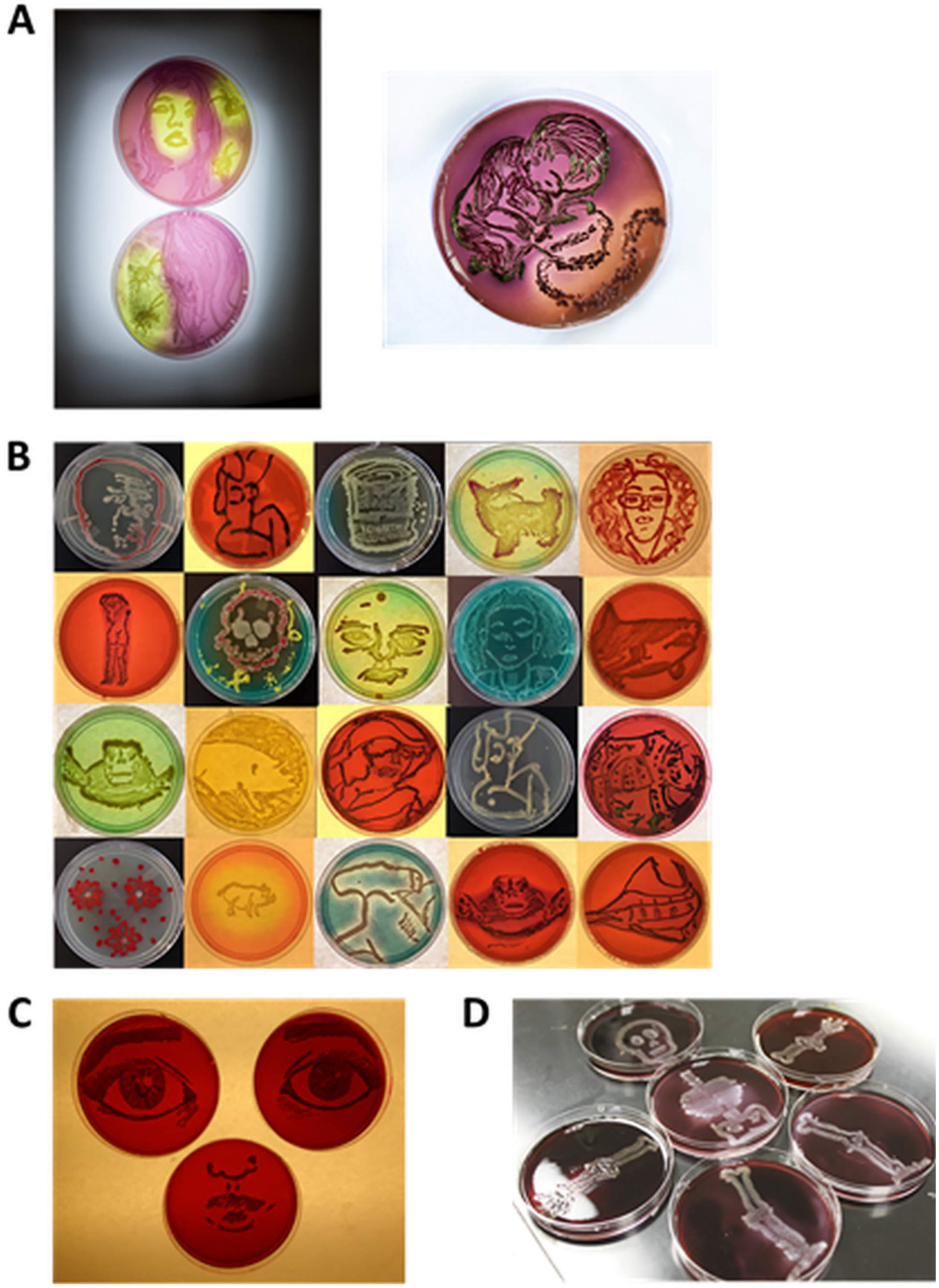


FIG 5. Student agar arts selected as People's Choice Award finalists in ASM's Agar Art Contest in (A) 2016, *Grotesque Beauty* (left) *and Bacteria at Birth* (right); (B) 2017, *Inspired*; (C) 2019, *Emotion*; (D) 2020, *Dem Bones*. Of the hundreds of entries from all around the world, only the top 50 submissions are selected by the judges for consideration for this award. This serves as evidence of the learning outcomes being met as the high quality of our students' agar art was recognized by external reviewers.

Each semester, the students' agar artworks were submitted to the ASM's Agar Art Contest. The art was evaluated by external judges assigned by ASM which consisted of both scientists and artists. The judging criteria included creativity, design, presentation, and communication. Our students participated in this contest on four separate occasions and each time, at least one of our students' artworks was chosen as a finalist for the People's Choice award (Fig. 5). This serves as evidence of the learning outcomes being met as the high quality of our students' agar art was recognized by external reviewers.

Possible modifications

Alternative timelines to conduct the activity over three class periods as opposed to two are recommended as this would allow students to repeat the activity after they have learned from their mistakes.

Other agars and strains of bacteria could be used based on their availability. We have used blood agar, DNA agar, and "blue/white screening" agar (Luria broth agar with ampicillin, arabinose, and x-gal) with *E. coli* + pUC19 (blue) and *E. coli* + pUC19-MTCR (white).

Submitting to the ASM Agar Art Contest is an optional addition to this activity. It is recommended to include this option as the possibility of winning a contest tends to motivate students to do their best. However, the timing of the contest may not always line up with your course schedule. In this case, you could stay connected with your former students and encourage them to enter the contest once it is open for submissions.

In terms of the art assignment, there are many alternative themes that could be used. For example, students could explore implied versus actual texture, two- dimensional design using art principles to create a compelling piece that communicates a specific message, or they could research a contemporary scientific artist like Carol Prusa, a biology/chemistry major turned artist, and create a piece inspired by that artist's style.

Additionally, students could create posters, similar to a research poster, to present their art in the context of the science that was used. A couple of our students created poster presentations that were presented at local STEM symposiums.

This activity could also be done in reverse where instead of the microbiology professor teaching the art students, the art professor could teach the artistic aspects of making agar art to the microbiology students. Either way, the goal of integrating science and art is achieved.

A possible extension of this project could include an exploration of the broader impacts of the experience on the students. Pre- and post-surveys could be used to determine whether the non-science majors who participated in the agar art activity demonstrated an increased understanding of microbiology, an improved attitude toward science in general, and an increased awareness of the relevance and impact of science on art and vice versa.

SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

SUPPLEMENTAL FILE 1, PDF file, 2.1 MB.

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We declare no conflicts of interest.

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