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Monitoring water quality through citizen science while teaching STEM undergraduate courses during a global pandemic

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HIGHLIGHTS

• A water quality citizen science project was implemented in 4 undergraduate courses.
• 120 tap water samples from private households and on campus were analyzed.
• The academic background of the participants did not impact the results.
• The results obtained using the different test strips were statistically different.
• Results obtained using the 2:1 and the 5:1 test strips were close to the QA/QCs.

GRAPHICAL ABSTRACT

Due to the COVID-19 pandemic, many universities struggle to engage students while implementing a distance-based teaching/learning approach and to provide hands-on activities to students enrolled in STEM classes. Implementing service-focused activities that can be conducted by the students remotely can overcome these struggles. The goals of this study were to 1) implement citizen science activities focused on water quality using three commercially available low-cost test strips (2:1, 5:1, and 16:1) while teaching four undergraduate engineering courses at the University of Mississippi (UM) during a pandemic event, and 2) evaluate the acceptability and validate the results obtained. Eighty-five undergraduate students (citizen scientists) and five research scientists (control group) collected two water samples (with triplicates) after receiving detailed step-by-step written guidelines and video tutorials. One hundred twenty tap water samples were collected from private households across Lafayette County and its surrounding counties and multiple buildings on campus. Five laboratory fortified blank (LFB) samples were implemented to validate the results. While the academic background of the participants did not impact the results (p>0.05), the results obtained using the different test strips were statistically different (p<0.05). In fact, results obtained using the 2:1 and the 5:1 test strips were close to the LFBs, while, except for the higher concentration of Total Alkalinity (40 mg/L CaCO3), results obtained using the 16:1 test strips were significantly different than the LFBs. Results (in terms of pH, Nitrate, and Total Chlorine) obtained by the citizen scientists using the 2:1 and 5:1 test strips were consistent with those reported in the annual drinking water quality reports from UM and municipalities included in the investigated region. Overall, this activity was well received by the students. Approximately 75% of them agreed that this hands-on activity was a positive experience while struggling to attend face-to-face classes.

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1. Introduction

The emergence and global spread of COVID-19 had and will have a lasting impact on human life. One of the first consequences of the spread of COVID-19 was an abrupt change in education, especially at the university level. Universities were closed for a few days and forced to transition from in-class to remote teaching (Crawford et al., 2020). This rapid move to a distance-based teaching/learning approach represented and will continue to represent a challenge for students as well as for teachers. Laboratory-based classes represent the most challenging class to move to distance-based teaching. The most obvious and inexpensive solution would be to postpone teaching laboratory-based classes until a normal education environment will be restored. However, this solution is not possible within the current approval/accreditation frameworks (Campbell et al., 2020). Increasing the safety of the students by restricting the level of laboratory occupancy represents a valuable alternative. However, in addition to the increased costs, it requires the students to be present on-campus and it creates a challenging environment for students and teachers with pre-existing conditions. Recording the laboratory-based classes represents an inexpensive alternative but it precludes the students of their hands-on experience. Therefore, the approach for teaching these classes needs to be modified.

Following the recommendations provided by the Council on Undergraduate Research (Karukstis, 2004; Kauffman and Stocks, 2004; Wenzel and Karukstis, 2004) and from the National Science Foundation Undergraduate Research (Wenzel and Karukstis, 2004), service-focused activities, including research-based activities, have been implemented during the past two decades in many STEM classes (Tomasik et al., 2013). Students can further improve their critical thinking skills, the efficacy of their civic engagement, and their ability to integrate theory and experience (Tomasik et al., 2014). Through these service-focused activities, the students will see STEM courses, and in particular STEM laboratory, in a context that is compelling to their interests (e.g., environment, sustainability, energy, etc.) (Aubrecht et al., 2015) and engage with their college, university (Donaghy and Saxton, 2012), and local (Jung et al., 2017) communities.

Environmental topics, often used during service-focused activities, enable students to see the connection between their courses and their world and facilitate the conceptual leap from abstract scientific concepts to useful applications (Wenzel and Austin, 2001). Environmental coursework can easily be adapted to existing curricula (Wenzel and Austin, 2001) and teachers can set the level of complexity based on the students’ background (e.g., freshmen vs. senior students) as well as on the available budget. Among the different environmental topics, water quality has been implemented in a few service-learning activities included in analytical and/or environmental chemistry courses during the last decade (Dameris et al., 2019; Jung et al., 2017; Schwarz et al., 2016; Tomasik et al., 2014; Donaghy and Saxton, 2012; Long et al., 2012; Kammler et al., 2012). Most of these activities include the collection and analysis of different water samples. Analysis has been conducted in the field using portable instruments or in the classroom using test kits and/or more advanced instrumentations (Dameris et al., 2019; Jung et al., 2017; Schwarz et al., 2016; Tomasik et al., 2013; Kammler et al., 2012). Due to the extended involvement required (e.g., duration of the sampling and analytical activities, samples’ holding time, etc.), some of these service-learning activities have been offered during the summer (Schwarz et al., 2016).

The main goal of this study was to implement citizen science activities focused on water quality using three commercially available low-cost test strips (2:1, 5:1, and 16:1) while teaching undergraduate STEM courses during a pandemic event. The second goal of the study was to evaluate the acceptability and validate the results obtained by citizen scientists. The students’ reception of this service-focused activity was also evaluated.

To accomplished these goals, students received personalized test kits. While the approach of providing test kits to the participants of water quality monitoring activities has been implemented in citizen science projects (KYW, 2020; Walkenhorst et al., 2020; Ali et al., 2019; Nelms et al., 2017; Peckenham and Peckenham, 2014), it has rarely been used in teaching STEM courses at the university level. Usually, during citizen science projects, citizen scientists (e.g., high school students, volunteers, senior citizens, etc.) receive supplies for collecting and returning water samples to the academic institution involved in the project and/or test strips to measure basic water quality (KYW, 2020; Walkenhorst et al., 2020; Ali et al., 2019). If test strips are provided and data are generated by the citizen scientists, there is still a lack of trust in accepting the data (Ali et al., 2019; Resnik et al., 2015). To overcome this issue, Quality Assurance and Quality Control, QA/QC, samples (triplicated samples and laboratory fortified blanks—LFB) have been implemented.

2. Materials and methods

2.1. Participants and citizen scientists’ pre-activity assessment

The undergraduate students enrolled in four engineering courses, ENGR 100 (Introduction to Engineering), CE 101 (Introduction to Civil Engineering I), CE 405 (Civil Engineering Laboratory III), and ENGR 597 (Water and Wastewater Engineering), at the University of Mississippi (UM) during the Fall 2020 semester represented the citizen scientists involved in the study. A total of 90 participants (85 undergraduate students and five members of the control group) were involved in this citizen science study focused on water quality, primarily in tap water in northern Mississippi. The 85 undergraduate students included 26 freshmen, 15 sophomores, 7 juniors, and 37 seniors. Students enrolled in ENGR 100 and CE 101 were mostly freshmen and sophomore students while senior students were enrolled in CE 405 and ENGR 597. A few junior students were enrolled in CE 101 and ENGR 100. In addition to the citizen scientists, a group of faculty members and post-doctoral researchers with an academic background in environmental topics (e.g., environmental engineering, environmental toxicology, analytical chemistry, etc.) were also involved and are referred to as control group throughout the study.

The pre-activity assessment was conducted using a research-based survey consisting of 1) open-ended questions and 2) questions with five-point Likert scales. Open-ended questions were implemented to assess the academic position of the participants (e.g., highest degree earned, academic status within the university, etc.). Targeted questions (e.g., background knowledge related to water quality, water pollution, water sampling, low-cost water testing, and QA/QC samples) consisted of questions with five-point Likert scales ranging from 1 “strongly disagree/completely unfamiliar” to 5 “strongly agree/extremely familiar”.

2.2. Instructional materials

Four detailed step-by-step written guidelines (text and pictures) describing 1) the content of the personalized sampling kits, 2) how to collect water samples based on EPA guidelines (U.S. EPA, 2016a, 2016b, 2017), and 3) how to analyze the water samples using the three test strips based on the manufacturers’ instruction. In addition to the four step-by-step written guidelines, four step-by-step video tutorials with closed captioning were also implemented. Video tutorials can increase students’ cognitive, affective, and psychomotor learning (Pölloth et al., 2019).

2.3. Sampling

At the beginning of the Fall 2020 Semester, citizen scientists participating in this study (students enrolled in four undergraduate engineering courses) and living on/near campus collected their personalized kits containing sampling bottles, test strips, QA/QC samples, references, and tables for reporting the results from the UM Environmental Engineering
laboratory. Students unable to stop by the laboratory to pick up their personalized kits as well as members of the control group received them separately.

Low-cost test strips implemented throughout the study represent a valuable alternative for obtaining fast, quantitative measurements in the field as well as in the laboratory or in private residences. They are easy to use, disposable, and inexpensive. Three commercially available low-cost test strips (16:1, 5:1, and 2:1) were used to quantify the occurrence of sixteen analytes (Free Chlorine, Total Chlorine, Total Water Hardness, Total Alkalinity, pH, Nitrite, Nitrate, Lead, Fluoride, Iron, Copper, Mercury, Aluminum, Sulfate, Bromine, Cyanuric Acid), five analytes (Free Chlorine, Total Chlorine, Total Hardness, Total Alkalinity, pH), and two analytes (Nitrate and Nitrite), respectively. Results were obtained by placing the test strips in the sampling bottles for a few seconds (e.g., one second for the 2:1 test strips and two seconds for the 16:1 test strips), waiting for approximately one minute (e.g., 30 s for the 2:1 test strips and 60 s for the 16:1 test strips), and by comparing the different pads to the color chart provided. The detailed step-by-step written guideline developed for the 2:1 test strips has been included in the SI.

QA/QC samples implemented during this study included five LFB samples and the use of triplicated samples. LFB samples, reflecting environmentally relevant concentrations of different analytes in northern Mississippi were prepared by diluting a stock solution of each analyte using distilled and deionized water. LFB samples were prepared by adding two concentrations of Nitrate (10 vs. 2 mg/L), Fluoride (5 vs. 2 mg/L), and Total Hardness (40 vs. 10 mg/L CaCO₃), and one pH (7.0) buffer. To prevent a possible non-ethical approach by the citizen scientists, the five LFB samples were labeled as A (Nitrate: 10 mg/L and Fluoride: 5 mg/L), B (Nitrate: 2 mg/L and Fluoride: 2 mg/L), C (pH: 7), D (Total Hardness: 40 mg/L CaCO₃), and E (Total Hardness: 10 mg/L CaCO₃). These samples were used to verify 1) the quality of the results obtained using three different test strips and consequently identify the most suitable test strip for the different analytes and 2) the ability of the students to properly analyze the collected water samples. Each citizen scientist, as well as the members of the control group, collected two water samples. This first sample was a drinking water sample, while the second sample was tap water from a different location, surface water, groundwater, or runoff. Triplicated samples were collected during the second half of September and remotely (e.g., houses, apartments, dorms, etc.) analyzed immediately after their collection using the supplies included in a personalized kit.

2.4. Citizen scientists’ post-activity assessment

The post-activity assessment was conducted using a research-based survey similar to the one implemented during the pre-activity assessment consisting of 1) open-ended questions and 2) questions with five-point Likert scales. Open-ended questions, used to identify the students in order to compare their pre- and post-assessments, allowed the students to provide feedback related to the analytical methods implemented, possible improvements, similarities/differences (e.g., approach, time invested, etc.) compared to previous hands-on activities implemented in other undergraduate STEM courses and/or citizen science projects (if applicable). Questions with five-point Likert scales complemented the pre-activity assessment and ranged from 1 "strongly disagree/no gain/extremely dissatisfied" to 5 "strongly agree/great gain/extremely satisfied." Through these questions, the students 1) assessed their ability to collect and analyze water samples as well as QA/QC samples, 2) identified the most effective method to follow analytical procedures (step-by-step written guidelines vs. video tutorials) and the most challenging test strip (s) used, and 3) assessed the use of service-focused activities in their classes and their applicability in additional classes.

2.5. Statistical analysis

All reported measurements related to the QA/QC samples were used to investigate the impact of the background knowledge (e.g., students with different academic knowledge ranging from freshmen to senior vs. control group) and, indirectly, the quality of the given instructional materials on the results obtained. These measurements were divided based on the academic position of the citizen scientists (e.g., freshmen vs. sophomore vs. junior vs. senior), compared to those obtained from the control group, and statistically analyzed using t-test (SigmaPlot, Systat Software, Inc.). In addition to background knowledge, the reported measurements related to the QA/QC samples were also used to investigate the impact of the analytical method used (e.g., 2:1 test strip vs. 16:1 test strip) on the results. For statistical tests, statistical significance was assumed at $p < 0.05$.

3. Results and discussion

3.1. Implementation and validation of citizen science in monitoring water quality

Overall, results obtained using the 2:1 and the 5:1 test strips were close to the expected values, LFBs (Fig. 1). On the other hand, except for the higher concentration of Total Alkalinity (40 mg/L CaCO₃), results obtained using the 16:1 test strips were significantly different compared to the expected values (Fig. 1c–e and Fig. S1). The 2:1 Nitrate and Nitrite test strips successfully measured both Nitrate concentrations (2 and 10 mg/L) (Fig. 1a–b) while the 16:1 test strips overestimated the lower Nitrate concentration (2 mg/L, Fig. 1a) and underestimated the higher Nitrate concentration (10 mg/L, Fig. 1b). Results obtained using the 5:1 test strips were consistent with the LFBs in terms of pH and Total Hardness (Fig. 1c–e). On the other hand, the 16:1 overestimated pH (Fig. 1c) and the lower concentration of Total Alkalinity (10 mg/L as CaCO₃, Fig. 1e). The 16:1 test strips were extremely inadequate to quantify Fluoride. In fact, regardless of the effective concentration (2 or 5 mg/L), Fluoride was constantly below 0.6 mg/L (Fig. S1). Regardless of the academic background, results obtained by the students were consistent with those achieved by the control group and close to the actual concentration of the five LFB samples. For the five LFB samples, there was no statistical difference ($p > 0.05$) among the results obtained by the participants in the study (freshmen vs. sophomore vs. junior vs. senior vs. control group). This is in contrast with other citizen science studies in which the participants' background impacted the analytical results (e.g., Capdevila et al., 2020; Ali et al., 2019). This different behavior can be attributed to the simple analytical method used (test strips instead of test kits and/or portable probes) as well as to the four detailed step-by-step written and video guidelines that were developed for the participants in an attempt to minimize the impact of the participants' academic background. Providing both step-by-step written guidelines and video tutorials was an effective approach since some of the participants prefer to use written guidelines, while others prefer to follow a video tutorial. Based on the results from the post-activity survey, sophomore (63%) and junior (75%) students preferred video tutorials, while both freshmen and senior (59%) students preferred step-by-step written guidelines (Fig. S2).

In contrast to the participants' academic background, the analytical method used (2:1 vs. 16:1 test strips and/or 5:1 vs. 16:1 test strips) highly impacted the results. Except for higher levels of Total Hardness (40 mg/L CaCO₃), the results obtained using the different test strips were statistically different ($p < 0.05$). The 16:1 test strips, besides being the least accurate among the three test strips, were also the most challenging strips for the students to use. Approximately 80% of the students struggled with the 16:1 test strips (Fig. S3) due to the small size of the testing pad and the color bleeding. Also, a few students were color-blind and using the 16:1 test strip was extremely challenging for them.

3.2. Tap water quality in northern Mississippi

Participants in this study collected two water samples (with triplicates): one tap water sample and one additional water sample (surface
water/groundwater/stormwater or second tap water from a different location). A total of 120 tap water samples were collected across Lafayette County where the UM is located and its surrounding counties (e.g., Marshall, Tate, Panola, Yalobusha, Calhoun, Pontotoc, and Union), from private households as well as from different buildings and dorms on campus. Water in these counties is from wells drawing from the Meridian-upper Wilcox and the lower Wilcox aquifers (Schildhammer, 2019).

Based on the results from the LFB samples, results obtained using a 16:1 test strip were discarded. Nitrate and Nitrite were measured using 2:1 test strips, while pH, Free and Total Chlorine, and Total Hardness were measured using 5:1 test strips. To increase the trust in the obtained results, triplicated samples were collected and analyzed. Results of this study highlighted the overall good quality of the tap water collected (Fig. 2), with the analyzed analytes well below the U.S. EPA maximum contaminant levels, MCL (https://www.epa.gov/dwreginfo/drinking-water-regulations). Approximately 70% of the tap water samples had a pH of 6.8 (6.86 ± 0.43; Fig. 1a). Total Chlorine ranged between below the analytical detection limit and 4 mg/L (0.41 ± 0.54 mg/L). Out of 120 tap water samples collected, only two samples (1.66%) showed a Total Chlorine concentration of 4 mg/L, equal to the Maximum Residual Disinfectant Level (https://www.epa.gov/dwreginfo/drinking-water-regulations). Low levels of Nitrate were anticipated due to the limited agricultural activities in the area. Similar to Nitrate, low levels of Nitrite were anticipated. Nitrite ranged between below the analytical detection limit and 0.67 mg/L (0.02 ± 0.07 mg/L) with 93% of samples having a concentration < 0.1 mg/L (data not shown). Total Hardness ranged between below the analytical detection limit and 180 mg/L CaCO₃ (61 ± 32 mg/L CaCO₃; Fig. 2d). Of the samples collected, 80% had a Total Hardness ranging between 25 and 75 mg/L (Fig. 2d).

Results obtained by the citizen scientists using the 2:1 and 5:1 test strips were consistent with those reported in the annual drinking water quality reports from UM (e.g., UM 2020 and 2019), the city of Oxford (City of Oxford, 2018), where many of the participants live, as well as other municipalities (Mississippi Drinking Water Watch, 2020) in the surrounding areas. For example, Nitrate and Chlorine ranged between 0.46 and 3.04 mg/L and between 0.54 and 2.2 mg/L at UM in 2019, respectively (UM, 2020). Similarly, Nitrate and Chlorine ranged between 0.46 and 3.04 mg/L and between 0.54 and 2.2 mg/L at UM in 2019, respectively (UM, 2020). Nitrate and Chlorine ranged between 0.46 and 3.04 mg/L and between 0.54 and 2.2 mg/L at UM in 2019, respectively (UM, 2020).

Overall, this activity was well received by the citizen scientists (a broad range of undergraduate students) (Fig. 3). Approximately 75% of them, strongly (50%) or somewhat (25%), agreed that this hands-on
activity was a positive experience while struggling to attend face-to-face classes (Fig. 3a). On the other hand, only two students strongly disagreed. However, based on the results from an additional question in the post-activity survey, those two students would like to implement similar activities in other classes. Overall, 67% of the students participating in this activity would like to implement similar activities in other courses (Fig. 3b). An even higher percentage of senior (67%), junior (71%), and sophomore (86%) students would like to implement this hands-on activity approach in other classes (Fig. 3b). Freshmen students (45%) were the least enthusiastic about further implementing this approach (Fig. 3b). Many of them were attending undergraduate courses for the first time and were unsure regarding future courses.

3.4. Future implications

This study highlighted some of the major advantages and disadvantages related to the implementation of low-cost commercially available test strips to conduct a water quality monitoring campaign while teaching undergraduate STEM courses. Major advantages include:

• Minimize the negative impact of switching to remote learning. Students can not only continue to perform hands-on lab activities remotely but also deeply connect to their community by performing water quality testing for multiple sources of water strongly related to their life and community (e.g., tap water, pre- and post-filtered water, recreational water).
• While the proposed approach can successfully be implemented in other STEM courses focused on environmental engineering/chemistry as well as analytical chemistry, it cannot be implemented in all STEM courses.
• By comparing their results with the U.S. EPA standards, students can develop critical thinking about possible environmental concerns related to their communities.
• Undergraduate STEM students with different backgrounds can successfully be used to conduct citizen science studies focused on water quality. In fact, it was observed that the participants’ background had limited to no impact on the results obtained. This was due to the implementation of detailed step-by-step written guidelines as well as video tutorials on how to perform every single step (e.g., sampling collection, handling, and analysis of the samples, etc.) during the study. By reducing the impact of the participants’ background, we were able to compensate for one of the most common limitations of citizen science (Capdevila et al., 2020; Ali et al., 2019).
• The success of any citizen science project is strongly related to the motivation of the citizens involved (Capdevila et al., 2020). Intrinsic drivers (e.g., the personal interest of citizens in advancing

\[ \text{Fig. 2. pH (a), total chlorine (b), nitrate (c), and total hardness (d) values from 120 tap water samples across Lafayette county and its surrounding counties (northern Mississippi).} \]
environmental science and practice, their social commitment, and the promotion to make a difference) and external rewards (e.g., monetary incentives and tokens of appreciation) highly impact the citizens’ motivation and consequently the success of the study (Capdevila et al., 2020). By implementing citizen science projects in undergraduate STEM courses, we can overcome the negative impact related to the citizens’ motivation. Students enrolled in STEM courses are mostly engaged with the topic of these citizen science projects (intrinsic driver) and their final grades are related to their performances in these projects (external rewards).

- The implementation of QA/QC samples (LFB and triplicate samples) increased the trust in the obtained results. The lack of trust in data generated by citizen scientists represents another setback of this approach. However, by providing multiple LFB samples and asking the students to collect and run triplicated samples, we were able to validate the obtained results.
- Test strips are extremely inexpensive (0.08 to 0.40$/strip). Based on the number of students enrolled in the classes as well as on the available budget, more advanced test kits can be implemented. Also, based on the geographic location of the academic institution, different analytes, and consequently different test kits can be implemented (e.g., atrazine test kits can be implemented in an area with intensive agricultural practices, etc.).

On the other hand, limitations related to the proposed approach include:

- Selection of the test strips. Selected analytical methods are based on different pads (e.g., 2, 5, and 16) within each strip changing color and consequently on comparing these colors to a reference scale. This can be challenging for color-blind students. Students can quantify the same concentrations differently due to their perception of different shades of the same color. Overall, the 2:1 and the 5:1 test strips provided valuable results while the results obtained using the 16:1 test strip were unreliable. The poor performance of the 16:1 test strips among the citizen scientists as well as the control group were related to the small size of the testing pad and the colors bleeding.
- Low accuracy at low concentrations. This is related to the relatively high starting concentration (e.g., 1.0 mg/L) of the reference scale used during the study.
- Low accuracy at high concentrations. This is related to the maximum value of the reference scale. If needed, to increase the maximum concentrations tested with the strips, the students will dilute the collected samples using distilled and deionized water. However, by diluting the samples, the accuracy of the analysis will further decrease due to increasing chances to generate errors by the citizen scientists.
- Preservation of QA/QC (e.g., LFB) samples. Due to the stability of the different analytes, it would be extremely challenging to create LFB for all analytes. For example, nitrite should be measured within 48 h; therefore, a nitrite LFB cannot be used by the students. While it would be nice to have LFBs for all investigated analytes, the vast majority of service-learning projects conducted during the past two decades implemented only a few LFBs.
4. Conclusion

Results from our study highlighted the ability to implement low-cost commercially available test strips to conduct a water quality monitoring campaign while teaching undergraduate STEM courses. The proposed approach not only allows the students to be engaged in hands-on activities that can be implemented remotely, but also allows them to be connected with their community. The implementation of QA/QC samples (e.g., LFB and triplicate samples) is essential to enhance the trust in the results obtained by the students. Our study showed that regardless of the academic background of the participants (e.g., students with no to low experience vs. professional scientists), results obtained by the students were consistent with those achieved by the control group and close to the actual concentration of the five implemented LFB samples.

The selection of the test-strips represents a key challenge to the success of the study. In fact, the results obtained using the different test strips were statistically different ($p < 0.05$). The 16:1 test strips, besides being the least accurate among the three test strips, were also the most challenging strips for the students to use. Results obtained by the citizen scientists using the 2:1 and 5:1 test strips were consistent with those reported in the annual drinking water quality reports from UM, the city of Oxford, where most of the participants live, as well as other municipalities in the surrounding areas. Overall, this activity was well received by the citizen scientists (a broad range of undergraduate students). Approximately 75% of them, strongly (50%) or somewhat (25%), agreed that this hands-on activity was a positive experience while struggling to attend face-to-face classes.

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CRediT authorship contribution statement

Matteo D’Alessio: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Project administration, Funding acquisition, Writing – original draft, Visualization, Supervision.

Grace Rushing: Conceptualization, Methodology, Investigation, Data curation, Writing – review & editing, Project administration, Funding acquisition.

Tiffany L. Gray: Methodology, Investigation, Data curation, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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