CITIZEN SCIENCE:
THEORY AND PRACTICE

Maggot Menageries: High School Student Contributions to Medicinal Maggot Production in Compromised Healthcare Settings

CASE STUDIES

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ABSTRACT

This case study describes how high school students can participate in research, development, and testing of real-life solutions for society's most intractable problems. In modern warfare, civilians make up most of the casualties, and conflict-affected communities are often isolated and have only limited access to healthcare. Most surviving casualties have limb wounds from injury or surgery, and many of these become infected and require long-term treatment or amputation. In 2020, MedMagLabs and the Queensland Virtual STEM Academy partnered to engage high school students to co-develop and test methods and training resources that empower people in conflict-affected communities to produce medicinal maggots for highly efficacious and affordable wound care. Maggot therapy is the treatment of wounds with living fly larvae to remove dead tissue, to control infection, and to promote wound healing. As opposed to most citizen science, which mainly focuses on data collection and/or educational and awareness-raising outcomes, this project focused on the co-creation of knowledge and the delivery of tangible research outcomes. The measure of its success was the development of end-user friendly medicinal maggot production methods and training resources. The study explains how citizen scientists and researchers collaborated with one another to achieve this objective. Project execution was largely in line with The Ten Principles of Citizen Science. Further review of project outcomes and self-reflection by the research team highlight important lessons for such collaborative studies, which have been summarised in five recommendations specifically relating to research collaborations with schools and student citizen scientists.

INTRODUCTION

Caring for chronic wounds can be very difficult in modern healthcare settings. It is even more challenging in compromised healthcare settings where hospitals have been destroyed; where doctors, nurses and aid workers are attacked and flee from violence; and where there are no effective antibiotics to treat infection. This is the situation in many of today's conflict zones (Loy 2019; Moussally 2019). To make matters worse, civilians are increasingly the target of hostilities or become caught in the crossfire (Yero et al. 2014). Such conditions also make viable early piloting of treatments challenging or costly. Consequently, there is a need to improve general medical care and wound care that is fit for these settings. However, research and development (R&D) is made extremely difficult because most researchers have no access to conflict-affected communities because of the security situation. This requires innovative approaches to such R&D. In this case report, we describe how citizen scientists residing in Australia have been instrumental in the development of wound care supply solutions for isolated communities in conflicts as far afield as Syria, Yemen, and Afghanistan.

Maggot therapy is the treatment of wounds with living fly larvae (maggots) to remove dead tissue, to control infection, and to promote wound healing (Sherman and Pechter 1988; Cazander et al. 2013). Maggots have the potential to be particularly effective in austere and low-resource healthcare settings such as in war and disasters (Stadler, Shaban, and Tatham 2016). Moreover, maggot therapy does not require surgical expertise. This means that even lay carers can administer the maggots with relatively little guidance (Mirabzadeh et al. 2017).

The goal of our Maggot Menageries project, which is the focus of this case study, and its parent research project at MedMagLabs, was to provide conflict-affected communities with the knowhow, rather than the equipment and materials, required for medicinal maggot production and maggot therapy. Methodology must be developed and tested that utilises basic everyday resources. These methods and procedures need to be clearly communicated to the end users who may be from diverse ethnic and language groups, and diverse socioeconomic and educational backgrounds. The use of visual multilingual communication tools is critical. Finally, before such production and treatment manuals can be released for use, they need to be tested for their accessibility and utility. The present case study reports on this R&D process. We focus in particular on the role citizen scientists have played in the development and testing of medicinal maggot production methods and training resources.

We first reflect briefly on the traditional citizen science (CS) approach and its bias toward data collection activities and educational and awareness-raising outcomes rather than co-creation of knowledge and delivery of tangible R&D outcomes, as was the focus of this project. The materials and methods section then explains the nature of the project and how citizen scientists and researchers collaborated with one another. The objective of this CS project, and therefore the measure of its success, was the development of end-user-friendly medicinal maggot production methods and training resources. Consequently, as far as reporting of results is concerned, we have been preoccupied with our achievements and where we encountered problems. However, in the discussion section, we not only take stock of the technical outcomes, but also benchmark our project against The Ten Principles of Citizen Science (Robinson et al. 2018), and provide some self-reflections on the outcomes of the collaboration itself and its limitations. Important lessons were learned that will be invaluable to other teams of professional and citizen scientists. Therefore, we conclude our case report with five recommendations specifically relating to research collaborations with schools and student citizen scientists.

BEYOND TRADITIONAL CITIZEN SCIENCE

Tidball and colleagues advocated for a greater role of CS in disaster and crisis preparedness and response because it facilitates data collection and encourages the affected communities to participate in research that leads to better solutions, greater buy-in, and increased resilience (Tidball et al. 2012). However, there are few self-identified CS projects in health research, let alone in the contexts of conflict, aid, or therapeutic goods, all of which apply to this study of medicinal maggot production in compromised healthcare settings. Rather, the field of CS is dominated by biological, conservation, and ecological investigations, as well as geographic information research and investigations in social science and epidemiology (Kullenberg and Kasperowski 2016). A systematic review of CS-related research published between 1997 and 2014 found that of 888 publications that met the inclusion criteria, only 9 were concerned with medical topics, the first of which was published in 2011 (Follett and Strezov 2015).

There are only a few avenues for the general public to contribute to the betterment of the lives of people living in conflict-affected communities and other compromised healthcare settings. For example, one may support organisations such as Médecins Sans Frontières (MSF), but direct engagement through in-country volunteerism is not possible for obvious security reasons. In our case, CS provided a platform for young citizens to get more intimately involved beyond donations and to make an active contribution. Likewise, researchers who investigate conflict issues and develop solutions that benefit conflict-affected communities are often not able to operate in conflict zones. Consequently, it is difficult to work with affected communities to co-create and execute research and develop end-user-informed solutions. The research objectives of our study arose from a need to develop such user-informed solutions that assist isolated communities to produce limb- and life-saving medicinal maggots. Without access to affected communities, MedMagLabs partnered with Grade 9 and 10 high school students from rural Australian schools and their supervising teachers. The aim was for students to be intimately involved in the co-creation and testing of maggot production solutions for rapid implementation and real-life impact.

In contrast, it is all too often the case that when students are given the opportunity to become citizen scientists, the motivation to do so is skewed toward education, the promotion of science, the raising of awareness regarding certain issues, and the learning of skills (Ruiz-Mallén et al. 2016; Aivelo and Huovelin 2020; Hahn et al. 2020; Harlin et al. 2018). Research outputs are often of secondary importance, even though young citizen scientists can do much more. For example, twelve youth from the Karuk Tribe of northern California received research training and subsequently conducted a survey and assessment of community health and food choices (Kim et al. 2020). The findings of that study were adopted by the tribe, and a range of lifestyle interventions were implemented in line with cultural values. Our case report provides further evidence that student citizen scientists can make meaningful research contributions with direct and beneficial impact on society.

MATERIALS AND METHODS

There are four parts to the materials and methods section. The team composition and collaborative approach to this research project is presented first, followed by the materials and methods employed by the Fly Keeper and Lab Tech research teams. Finally, we describe how the overall project outcomes, including the citizen scientist collaboration, were evaluated.

TEAM COMPOSITION AND COLLABORATIVE APPROACH

This CS project was a collaboration between MedMagLabs from Griffith University (*www.medmaglabs.com*), the Queensland Virtual STEM Academy (*www.qvsa.eq.edu.au*), and four participating rural Queensland high schools: Isis District State High School (Isis), Roma State College (Roma), Thuringowa State High School (Thuringowa), and Nanango State High School (Nanango). The Isis Shire was named after the local Isis River, which was in turn named by colonial surveyors after the Isis River in Oxfordshire, England (Centre for the Government of Queensland 2018).

The Queensland Virtual Science, Technology, Engineering and Mathematics (STEM) Academy (QVSA) is an initiative of the Department of Education in Queensland, focused on connecting, engaging, and challenging highly capable rural and remote students from Grades 5 through 9 in STEM. The QVSA provides virtual enrichment and enhancement programs focusing on current, real-world STEM to more than 100 schools in regional and rural Queensland, offering optimal conditions for engaging student citizen scientists and maximising outreach to rural settings. The Maggot Menageries project was framed within a problem-based learning pedagogical framework, constructed by STEM teachers in collaboration with MedMagLabs. This ensured students developed the skills and understanding in biological sciences to enable deep engagement and alignment of learning to the Australian Curriculum, which is crucial when engaging with schools.

The program was divided into two ten-week periods, a Fly Keeper project and a Lab Tech project. The former focussed on the development of fly colony rearing solutions for conflict-affected communities, while the latter was concerned with the production of medicinal maggots in such challenging environments. At Isis, five Grade 9 students conducted the Fly Keeper research and five Grade 10 students the Lab Tech research. In total, across the four teams, 31 students participated, and of these, 61% were Grade 9 and 39% were Grade 10 students. Only 19% of all students were male, 81% were female.

The geographic spread of collaborating organisations meant that the program had to be delivered from a distance out of both the Gold Coast Griffith University Campus, where MedMagLabs was located, and Brisbane, where QVSA headquarters are situated. Face-to-face interactions with Isis, Thuringowa, and Nanango students occurred via the virtual classroom teaching platform iSee (*www.iseevc.com.au*). Team meetings with Roma students and their teacher were conducted via Zoom (*www.zoom.us*). MedMagLabs communication with students followed Queensland Department of Education guidelines with a teacher present for all online sessions. All other communication was passed via QVSA staff from students to MedMagLabs and vice versa. Students were supervised directly by QVSA, and in their schools were supervised by teachers supportive of this project. Unlike students, teachers had the opportunity to interact directly with MedMagLabs. To participate in this program, students had to commit to 1.5 hours per week outside the regular classroom and had to be willing to invest some extra time for homework research tasks. By conducting this program outside of regular class hours, students did not miss regular teaching, and there was no danger they would suffer adverse consequences. This also freed up teachers and allowed them to work with the students.

This case report presents mainly the CS research process and outcomes involving the Isis team because there is a sensible limit to authorship for a paper of this nature. The research outputs of Roma, Thuringowa, and Nanango students have been used and included in this paper to triangulate and validate the results reported by the Isis team. The collective effort of all four teams provided ample data for the improvement of MedMagLabs training material.

THE FLY KEEPER PROJECT

Students were initially introduced to the R&D work conducted by MedMagLabs as well as the humanitarian background regarding the wound burden and wound care in conflict and other compromised healthcare settings. Under the guidance of the QVSA, the students then researched the biology of flies before being given MedMagLabs draft infographics (e.g., ***Figure 1***). This preliminary research provided students with the background knowledge the teachers believed necessary to allow deeper understanding of the requirements and specifications for fly colony maintenance as outlined in the infographics. With this information at hand, the students explored the resources

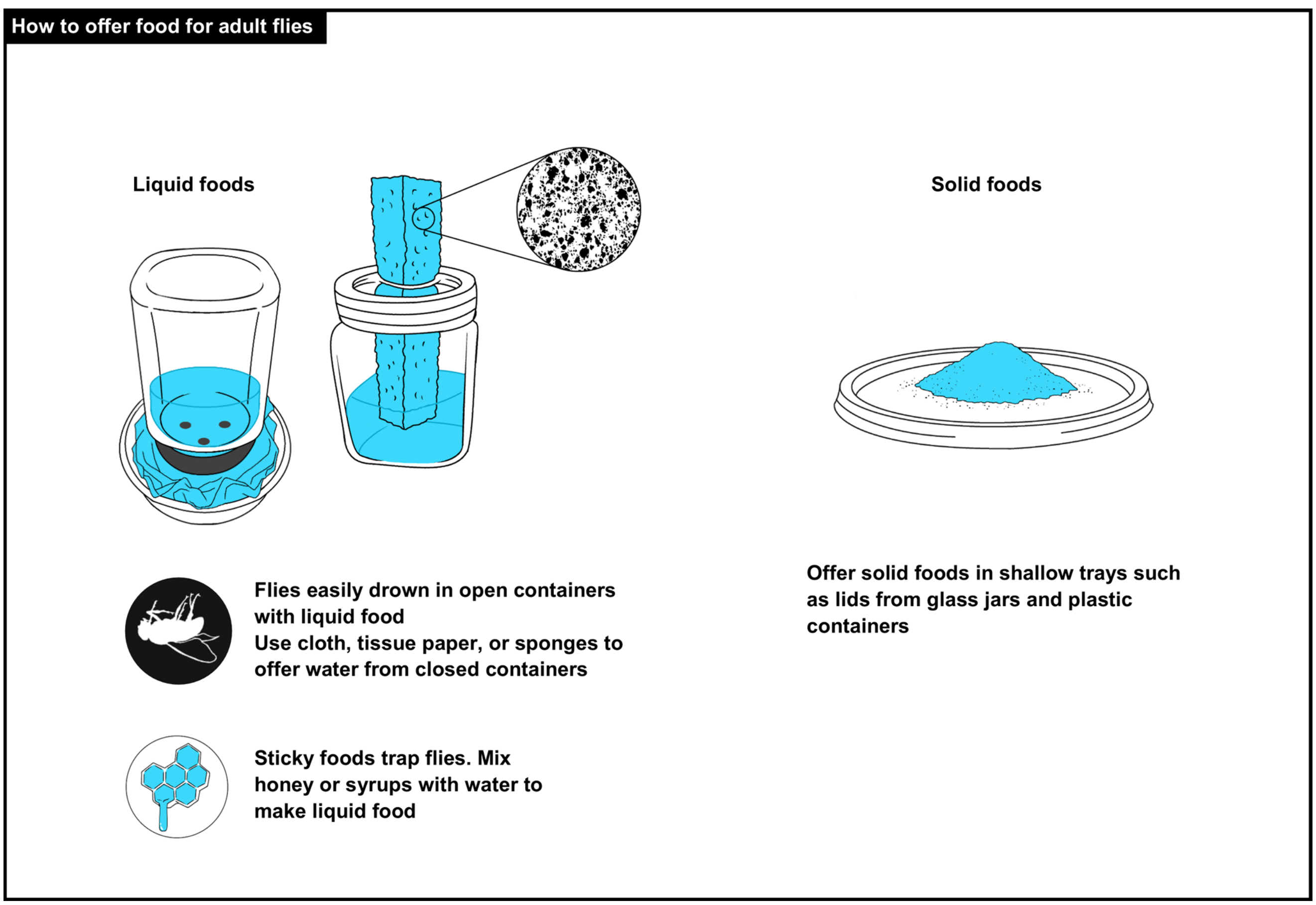

Figure 1 Example of an infographic provided to the students explaining how to offer food to adult flies.

that would be available to conflict-affected communities and designed their own caging and husbandry solutions on the basis of the guidance provided. Cage designs were sketched out in group work and further refined with the help of design proposal templates provided by QVSA. The most promising designs were chosen and built.

MedMagLabs then sent *Lucilia sericata* fly pupae to stock the newly built cages. The Isis team monitored both environmental conditions and fly performance. Temperature and humidity were measured and graphed over time, and notes were kept on the daily behaviour of flies. When flies started to reproduce, eggs were harvested and reared in a maggot rearing setup developed according to the infographic guidance provided by MedMagLabs.

THE LAB TECH PROJECT

The R&D approach for this part of the program involved less ideation and co-development of solutions than was the case for the Fly Keeper project. There was insufficient time for students to engage creatively with the challenges of sterile procedures in low-resource settings. Instead, the students were provided with guidance on how to disinfect medicinal fly eggs and rear young maggots aseptically and fit for medical treatment. Tasks included the construction of a clean workbench out of cardboard boxes; the construction of simple incubation vessels for disinfected eggs; and procedures for egg harvesting, separation, disinfection, and incubation. The students then tested these procedures, the accessibility of the instructions, and the practicality of given solutions in low-resource settings. To test whether the disinfection process produced sterile eggs, the students were also provided with ready-to-use Fluid Thioglycollate Medium in vials for sterility testing as per Therapeutic Goods Administration guidelines (TGA 2006). The disinfection and sterility testing manuals given to the student scientists included textual information and illustrations explaining key steps as well as examples of a laminar flow cabinet and a homemade low-resource clean work bench. The students reported the results of the Lab Tech component of the program along with Fly Keeper results in a final project report, including visual documentation of solutions and work undertaken.

PROJECT EVALUATION

The scientific outcomes of the project were benchmarked against current best-practices in medicinal fly husbandry and medicinal maggot production because the aim was to develop low-resource solutions that ensure accessible guidance for the reliable production of safe medicinal maggots. The CS collaboration as well as learning and teaching outcomes for student citizen scientists were evaluated on the basis of project outputs and a team meeting to discuss the research process and findings. Teachers were also given the opportunity to reflect on the project's administration and educational outcomes, and on the students' experience overall. These insights are presented in the Discussion and Conclusions sections of this paper.

At all times, MedMagLabs and QVSA encouraged the student citizen scientists not to be afraid of failure, indicating that mishaps and failures offer unique learning opportunities that are highly valued because they permit the improvement of maggot therapy services to be provided to conflict-affected communities.

RESULTS

Corresponding to the three main activities of this research project, we present first the results of our fly husbandry work, which included the development and testing of low-resource fly maintenance methods and maggot breeding setups. This is followed by the results of our medicinal maggot production and quality control efforts.

ADULT FLY COLONY MAINTENANCE

Students engaged in an iterative design approach with MedMagLabs and QVSA teachers. This process led to the development of four designs, one building on the principles of the other, but continuously improving upon its predecessor. The final prototyped version was made from three round 15-litre water bottles commonly used in office water dispensers. They were connected chain-like and end to end (***Figure 2a***). This modular design was developed with dangerous war conditions in mind. The students argued that the modular design provides some redundancy; meaning that if one compartment gets damaged in a bombardment, for example, not all fly stock is lost. The Isis team designed this cage using resources they believed were available in Afghanistan.

The Fly Keepers documented that the bottle cage performed well and provided the flies with enough room and ventilation, allowing flies to live up to eleven weeks. The makeshift nature of the cage that was constructed with basic materials threw up its challenges when bottle joints and access sleeves came loose and permitted flies to escape. Students learnt that these challenges are part of prototype design and testing in research, and they came to understand that end users in compromised healthcare settings would improve the design over time. The students also used sand as a substrate in the adult fly cage, although not required and only necessary to provide pupariation substrate for maggots in the maggot rearing setups. Similarly, the students erroneously applied

Figure 2 Cages for adult flies designed and built by the four student teams. **(a)** Isis District State High School, **(b)** Roma State College, **(c)** Thuringowa State High School, and **(d)** Nanango State High School.

the space requirement of 110 cm^3 per fly to the maggot cage design. This highlighted that improved guidance for end users needs to take into account the tendency of users to confuse the husbandry requirements of different life stages.

The cage designs varied among the other three citizen scientist teams (***Figure 2***). Roma's design was equally innovative, using plastic bottles to make tubing for the cage frame. Lots of sticky tape was used to hold everything in place, resulting in flies getting stuck on the exposed sticky surfaces of the tape. Moreover, the team struggled with the structural integrity of the cage, which required ongoing strengthening and modification. In comparison, the cages made by Nanango and Thuringowa appear very conservative and in their design reflect the availability of a school woodworking workshop. However, more sophisticated designs and construction do not necessarily translate into better performance. For example, the Thuringowa team struggled to keep flies alive owing to a combination of insufficient water provisioning, which resulted in dehydration, and insufficient ventilation leading to overheating when they placed the cage outside in the sun.

Although educational attainment may be similar, students lack the life experience found in older people from conflict-affected communities. The lack of pragmatism that comes with youth and inexperience has been apparent in the citizen scientists' approach to cage design. For example, it is unlikely that an elaborate interlocking multi-container cage system for adult flies as built by Isis would have been the first choice for a more mature lay breeder of flies. However, what matters to the Maggot Menageries project is not the elegance of the design but whether it achieved its purpose.

High fly mortality on two occasions coincided with a weekend period during which students were not able to attend to the needs of the flies. The feeding dishes (***Figure 3***) were not providing enough food and water for the number of flies, which led to starvation, dehydration, and premature death. Adult flies consume large amounts of carbohydrates, which means that in captivity, flies need to have *ad libitum* access to sweet foods as well as plenty of water. MedMagLabs provided visual instructions for how to construct simple feeding stations that provide liquid food for several days (***Figure 1***). If the students had adopted this mode of feeding, the high losses could have been avoided. Interestingly, adequate feeding of flies has been a problem for all four citizen scientist teams. Throughout, small feeding dishes without food reservoirs were used (***Figure 3***). This meant that food was consumed and exhausted too soon, water evaporated quickly, and flies drowned at times in dishes with liquid food. In addition, students offered protein-rich food such as raw meat and dog food continuously rather than temporarily. This led to increased odour and the tendency to move cages outside, as in the case of Thuringowa, exposing the flies to unfavourable environmental conditions. In the end, inadequate feeding regimens and poor temperature control were the main reasons for repeated colony declines. It emerged that some students struggled with the visual instructions via infographics as they were accustomed to more elaborate teacher guidance and more familiar school scaffolding of work instructions. Whether this is a universal problem also facing end-user communities in compromised healthcare settings is uncertain, but it highlights the need for more explicit guidance on the nutritional needs of flies, the types of food that are appropriate, the amount of food that is expected to be consumed by adult flies over time, and the importance of feeding stations that provide food over longer periods of time and in a safe manner that prevents flies from drowning.

MAGGOT REARING

The Isis team reared successfully a second generation of medicinal flies with a maggot rearing setup they designed and built themselves with commonly available materials (***Figure 4***). There was some consideration for maggot rearing among the other Fly Keepers, but that did not extend beyond providing the pupariation substrate and maggot diet dishes inside the adult fly cage, which should be avoided. However, successful breeding of new flies was not reported. Across all four teams, bad

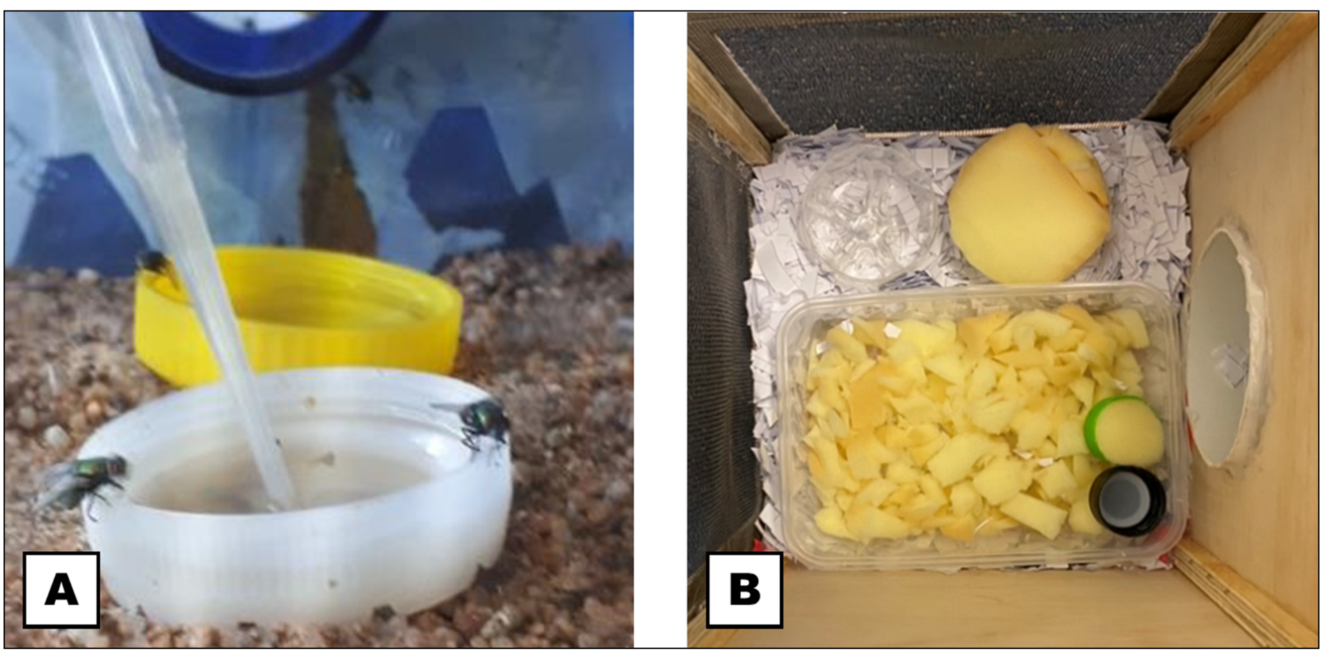

Figure 3 Feeding stations offered to adult flies for liquid foods (either water or honey water). **(a)** Isis District State High School and **(b)** Nanango State High School.

Figure 4 Construction overview for the maggot rearing setup designed and trialled by Isis students. Inside the outer container **(a, b)** a smaller container held meat diet for maggots to eat. The sand substrate **(c)** in the outer container supports pupariation of maggots once they have finished feeding. The lid construction **(d, e)** prevents maggots from escaping while permitting air exchange.

odour emanating from meat diets used in adult flies and maggot rearing was perceived as off-putting and unpleasant in the school environment. Fortunately, the Isis team were able to manage this impact, while a lack of acceptance and suitable infrastructure to manage bad odour in the other three schools resulted in none attempting to prototype maggot cage setups and to breed maggots. In addition, the short life span of the flies kept by these teams meant that flies were not maturing enough to lay eggs.

Medicinal maggots can be reared on meat-free diets (Tachibana and Numata 2001), but it is much easier for isolated communities to source low-quality meat for this purpose, which is why our guidance is limited to this feeding regimen. It stands to reason that odour is less of a barrier where there are poorly treated wounds, and maggot therapy can make a real difference to patient outcomes by saving limbs and lives. The same need has not been experienced by the communities of participating schools, which explains the intolerance to the odour and the lack of motivation to solve the odour problem.

MEDICINAL MAGGOT PRODUCTION AND QUALITY CONTROL

A prerequisite for high-quality and safe medicinal maggot production is a clean working environment that minimises the contamination of disinfected medicinal maggots. For this reason, the collaborating teams were encouraged to build a low-cost clean workbench. All four groups came up with designs and prototypes that varied in their practicality and likely performance (*Figure 5*). User-generated dust must be avoided, which is difficult in the prototypes from Isis and Thuringowa. Although the fabric curtain installed by Isis further reduces airflow in the workbench, it also rubs against the users' arms and clothing, which liberates dust (*Figure 5a*). Similarly, round access holes for users in the Thuringowa prototype (*Figure 5c*) would also rub against clothing and arms. Except for Nanango's prototype (*Figure 5d*), the internal surfaces of the clean benches were not lined with plastic that can be easily wiped and disinfected and does not generate dust. Only Isis was able to test the clean workbench for user friendliness and sample safety. Learnings from all four groups helped MedMagLabs

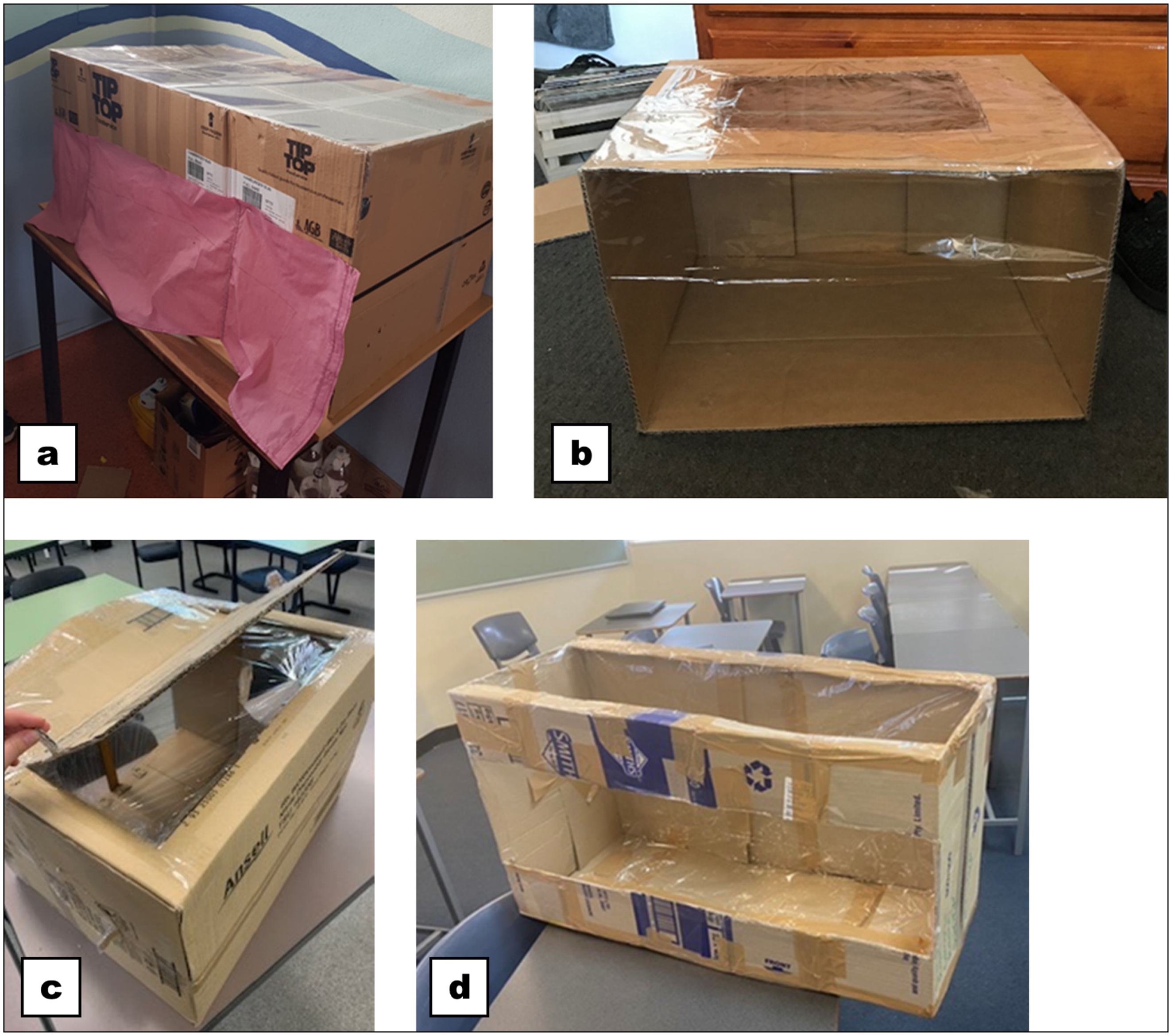

Figure 5 Low-cost clean bench constructions to provide an aseptic environment for disinfection of medicinal maggots in compromised healthcare settings. **(a)** Isis District State High School, **(b)** Roma State College, **(c)** Thuringowa State High School, and **(d)** Nanango State High School.

to develop a highly visual construction manual for a low-resource clean workbench.

When Isis trialled the production of medicinal maggots, the blended textual and visual guidance provided by MedMagLabs was mostly interpreted correctly. However, the students appeared to struggle with the limited room available inside the workbench, and with sterile work practices. For example, sterilised equipment used inside the clean workbench was moved out and then back in, potentially compromising sterility. Also, the egg yolk used to incubate the disinfected eggs was not directly transferred from the eggshell to the incubation jar, which increased the chance of contamination. Nevertheless, the students successfully put fly eggs through the disinfection procedure and reared from these medicinal maggots (***Figure 6***). Quality control testing showed contamination for only one out of three samples of disinfected eggs (***Figure 6e***). Consequently, the students achieved, if not complete sterility, then high levels of product disinfection with modest resources. This confirms that with a little more practice and improvement of workflow procedures and techniques, disinfected medicinal maggots of high quality can be produced by lay producers such as high school students and communities in conflict and elsewhere. The student experience highlighted the need for more accessible instructions, resulting in the development of a step-by-step visual instruction manual for medicinal maggot production.

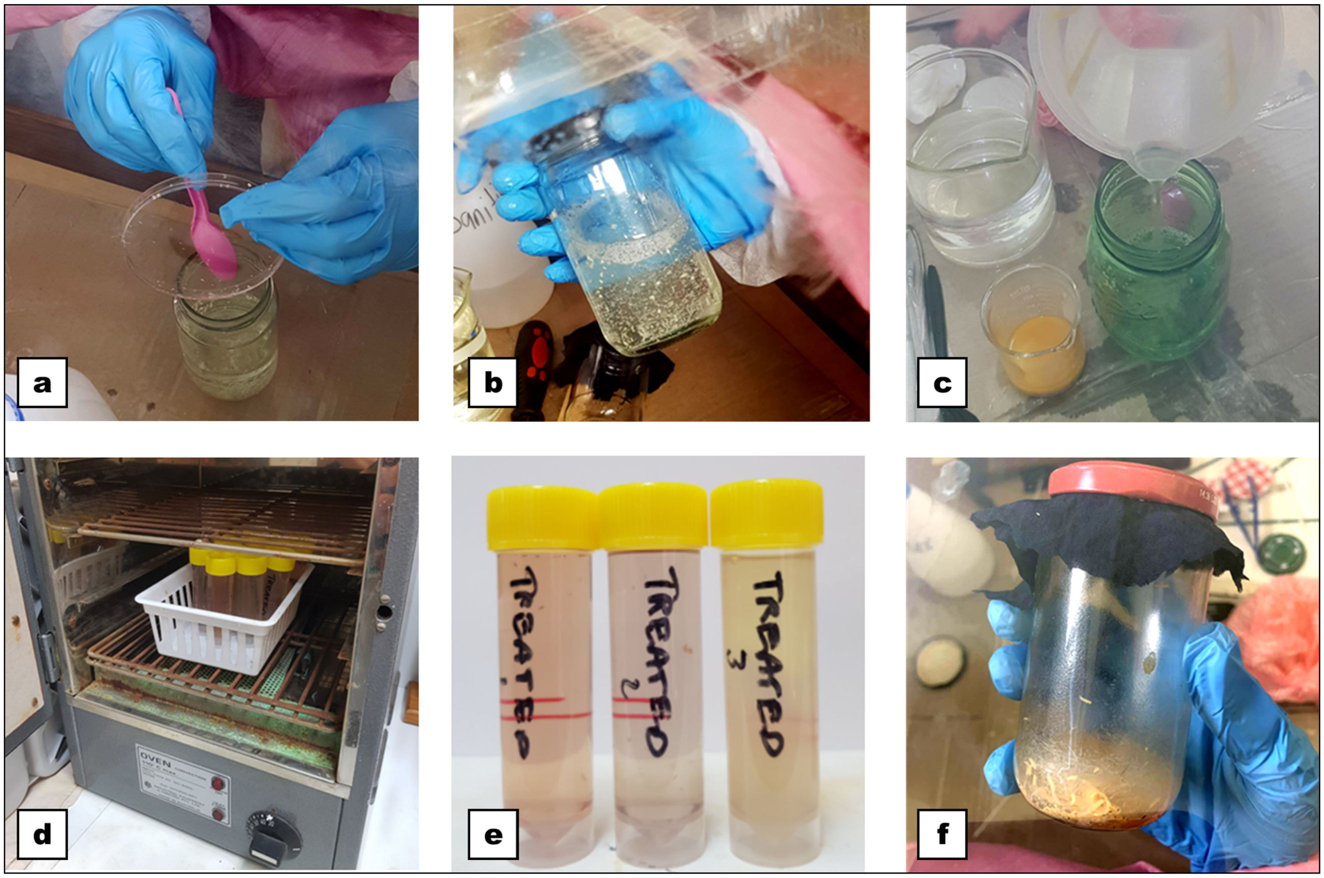

Figure 6 Fly egg disinfection process and quality control steps performed by Isis. Images illustrate **(a)** the separation of eggs that are usually stuck together as an egg mass, **(b)** disinfection of eggs with sodium hypochlorite solution, **(c)** washing of eggs prior to inoculation on chicken egg yolk, **(d)** incubation of sterility test samples in an incubator, and **(e)** results of testing after 48 hours of incubation at 32–37^{o}C. Only Sample 3 (*far right*) exhibited signs of contamination. Image **(f)** shows successfully reared young maggots from disinfected eggs.

DISCUSSION

The objective of our research project was to co-develop workable solutions for low-resource medicinal maggot production in compromised healthcare settings, and to test whether conflict-affected communities could establish and maintain medicinal maggot production systems with local resources. Our partnership with Grade 9 and 10 citizen scientists from four rural Queensland high schools was invaluable, as they became proxies for conflict-affected communities. With regard to the research objective, the results presented in this case study clearly demonstrate that it is possible to construct effective and workable medicinal maggot production infrastructure including adult fly cages, maggot rearing setups, a laboratory clean bench, and medicinal maggot incubation containers from commonly available everyday objects found anywhere, including in war-torn countries.

Although we demonstrated that student citizen scientists can contribute meaningfully to research beyond mere data collection, it is difficult for us to make predictions as to which other research fields would most benefit from student citizen science collaboration, partly because of the disciplinary position of our project and the general characteristics of student scientists. Maggot therapy supply chain management occupies an interdisciplinary domain at the crossroads of supply chain management, medical goods manufacturing, medicine, microbiology, and entomology. Moreover, our research partnership was productive because the co-development of workable production solutions in conflict-affected communities required partners with equivalent average educational attainment and lack of entomological expertise, comparable to the end-user groups in conflict. The important take-home message is that student citizen scientists, when given proper support, encouragement, and resources, can make meaningful contributions across a range of disciplines. This capacity to contribute will necessarily increase with increasing age and maturity of the citizen scientists involved.

REFLECTION ON CITIZEN SCIENCE OUTCOMES AND LIMITATIONS

It is helpful to reflect on the project outcomes as they relate to CS with the help of The Ten Principles of Citizen Science, which define good practice in CS (Robinson et al. 2018) (***Box 1***). Principle 1 is the most fundamental as it requires active involvement of citizens in research, as contributors, as collaborators, or as project leaders. Thirty-one students from four rural Queensland high schools collaborated with QVSA and MedMagLabs in the Maggot Menageries research project. Principle 2 calls for a genuine science outcome, which was the motivating objective behind the engagement of citizen scientists in this research. Project planning and execution ensured that the benefits of participation were shared between professional and citizen scientists (Principle 3). The student citizen scientists have been participating in multiple stages of the scientific process (Principle 4). For example, Fly Keeper teams both designed and prototyped fly production solutions, tested their prototypes, and evaluated the data. Lab Tech teams tested disinfection protocols and analysed the generated data. All teams contributed through their reports and documentation to the communication of results. The need to provide citizen scientists with feedback is enshrined in Principle 5. It was explained to all participants that the results of the Maggot Menageries project would feed directly into and improve the medicinal maggot production solutions for compromised healthcare settings. During the first interactive research meeting, MedMagLabs introduced the students to the Grand Challenge and the project objectives. Principle 6 points out that CS is one of many research approaches and has its own limitations that need to be considered. While the Maggot Menageries research project has generated very useful insights, there is no doubt that it also suffered from significant limitations, which are explained shortly. Publication of the Maggot Menageries research outcomes satisfies Principle 7, which calls for project data to be made publicly available, ideally in open access form. Moreover, project-related publicity has raised and will continue to raise awareness beyond the participating schools (Holmstrom 2021). Likewise, the research findings will be used to improve medicinal maggot production innovations that will also be made public via open platforms, as required by Hope in Conflict:

Box 1 The Ten Principles of Citizen Science (Robinson et al. 2018)

1. Citizen science projects actively involve citizens in scientific endeavour that generates new knowledge or understanding. Citizens may act as contributors, collaborators or as project leaders and have a meaningful role in the project.
2. Citizen science projects have a genuine science outcome. For example, answering a research question or informing conservation action, management decisions or environmental policy.
3. Both the professional scientists and the citizen scientists benefit from taking part. Benefits may include the publication of research outputs, learning opportunities, personal enjoyment, social benefits, satisfaction through contributing to scientific evidence, for example, to address local, national and international issues, and through that, the potential to influence policy.
4. Citizen scientists may, if they wish, participate in multiple stages of the scientific process. This may include developing the research question, designing the method, gathering and analysing data, and communicating the results.
5. Citizen scientists receive feedback from the project. For example, how their data are being used and what the research, policy or societal outcomes are.
6. Citizen science is considered a research approach like any other, with limitations and biases that should be considered and controlled for. However, unlike traditional research approaches, citizen science provides opportunity for greater public engagement and democratisation of science.
7. Citizen science project data and metadata are made publicly available and where possible, results are published in an open-access format. Data sharing may occur during or after the project, unless there are security or privacy concerns that prevent this.
8. Citizen scientists are acknowledged in project results and publications.
9. Citizen science programmes are evaluated for their scientific output, data quality, participant experience and wider societal or policy impact.
10. The leaders of citizen science projects take into consideration legal and ethical issues surrounding copyright, intellectual property, data-sharing agreements, confidentiality, attribution and the environmental impact of any activities.

A Humanitarian Grand Challenge. Any such communication of results includes, of course, the acknowledgement of the work contributed by the four student citizen scientist teams (Principle 8). This paper is co-authored by the Isis team, and the students from the other three schools are listed in the acknowledgements. While it is too early to fully evaluate the Maggot Menageries program as requested in Principle 9, an important first step is the publication of this case study. Further evaluation of research outcomes, including societal and policy outcomes, will be conducted by MedMagLabs as part of the parent research program under the Hope in Conflict: A Humanitarian Grand Challenge. Finally, Principle 10 raises the importance of legal and ethical issues. When working with minors it is particularly important that their welfare is protected. Engagement with students was therefore conducted under the supervision of QVSA staff and local teachers. Because there was no qualitative research with third parties and no vertebrate animals were used, there was no need for institutional human or animal research ethics approval. However, the premature mortality of many flies during the research project raises serious concerns around the use of invertebrate animals in a CS context. Exemption from animal ethics regulation does not per se justify the destructive use of insect experimental animals, and such experimentation should be reconsidered if there is a high likelihood of unnecessary distress and death of experimental animals.

Even though the primary goal was to contribute to R&D in the context of a real-life challenge, the CS collaboration had to also enrich the learning of the participating Grade 9 and 10 students. At Isis, the Australian syllabus is taught with particular focus on increasing opportunities for students to experience science as a human endeavour. Indeed, Science as a Human Endeavour is one of the three key strands of science central to the Australian Curriculum. Having the chance to participate in a meaningful scientific endeavour, such as the Maggot Menageries project, helped Grade 9 and 10 students to meet curriculum descriptors such as: "values and needs of contemporary society can influence the focus of scientific research;" "scientific understanding, including models and theories, is contestable and is refined over time through a process of review by the scientific community;" and "people use scientific knowledge to evaluate whether they accept claims, explanations or predictions, and advances in science can affect people's lives [...]" (ACARA 2017). The Maggot Menageries project also aligned closely with the Australian Grade 9 achievement standard for science, which includes student competencies such as control and accurate measurement of variables, systematic collection of data, ethics and safety, and data analysis (ACARA 2017).

Students who participated in the Maggot Menageries project developed science inquiry skills, which also form a key component of the Australian Curriculum for science. These skills include planning and conducting an investigation; processing and analysing data and information gathered; as well as processing, analysing, and evaluating data and information; and communicating findings through presentations and written reports. In addition, students had the opportunity to develop skills in project management, teamwork, leadership, and strategizing for real-world problem solving. Perhaps most important for students was the sense of contribution and involvement in a real-life research project with tangible benefits to vulnerable people in conflict. Whether this has had a formative impact on students' career development or inclination to participate in future citizen science programs remains to be seen, but on the basis of the positive student feedback, the possibility should not be underestimated.

On the downside, the extracurricular Maggot Menageries program was perceived by some students as too long, especially for those students that participated in both the Fly Keeper and Lab Tech challenges. The work also competed with other teaching at the schools, which meant that students were required to catch up on regular teaching time they had missed. Although this, too, was a learning and growth opportunity as it required students to develop time-management skills and take responsibility to ensure they kept up with their class work.

RESEARCH COORDINATION

The collaborating organisations including MedMagLabs, the QVSA, and the four schools were geographically dispersed across Queensland, Australia. QVSA has information technology systems in place to work remotely with students. However, the iSee virtual classroom software and the Griffith University IT system were incompatible, which prevented login from campus and thus required the MedMagLabs researcher to work from home for scheduled meetings. This was not always possible, and some meetings were therefore missed. Following the Department of Education child protection process, MedMagLabs staff could contact and communicate with students only via QVSA staff, which impeded collaboration and the exchange of information. This influenced project outcomes and made trouble-shooting more difficult, especially for the three teams that had problems with fly maintenance.

As an extracurricular program, students had 1.5 hours per week of school time to conduct the research, and not all students were able to invest extra time. However, it is pleasing to see how much was achieved in such a short time, and to reflect on what might be achieved with more time and better communication.

CONCLUSIONS

We have demonstrated how the involvement of student citizen scientists added valuable insights to MedMagLabs' research under the Hope in Conflict: A Humanitarian Grand Challenge initiative. This research has led to the improvement of methodology and user manuals developed for the production of medicinal maggots in conflict and other compromised healthcare settings. For the students, the CS collaboration with QVSA and MedMagLabs was an invaluable learning opportunity that provided firsthand experience of the role science plays in the real world, a sense of achievement, and the opportunity to develop important science skills. It also helped some of the students (mostly the Grade 10 students) to refine or decide their areas of interest for career and/or subject pathways. Finally, the project made an important contribution to the wider school community as it engendered a sense of pride in participating schools, which is a particularly important outcome for small rural schools.

The lessons that have been learned from this collaborative research endeavour can be summarised in the following recommendations for future CS collaborations involving high school students.

1) To maximise research collaboration, there must be direct lines of communication between the professional researchers and the student citizen scientists. This may require researchers to obtain education department clearance to work with children prior to commencing the research.
2) Communications IT such as virtual meeting software needs to be compatible with the IT systems used by collaborators and must be accessible across the entire research team.
3) Student citizen scientists must have enough time to conduct the research and keep detailed records. This will require negotiation with teachers, parents, and students. Researchers need to consider the competing demands on students and adjust their objectives accordingly, and students must be prepared to invest additional homework time.
4) Researchers should collaborate closely with teachers to prepare information material and research-related tasks for students using instructional language and formatting in line with the school curriculum. This will ensure familiarity and minimise confusion.
5) Research that requires students to care for live invertebrate animals must be carefully considered. Even though in most jurisdictions, such as Australia, ethics protocols and approvals are not necessary for research with invertebrate animals, their welfare must be protected, and safeguards must be put in place to minimise animal distress and unnecessarily high mortality.

DATA ACCESSIBILITY STATEMENTS

All relevant data has been provided in this paper. The activities and outcomes of the MedMagLabs Humanitarian Grand Challenge R&D project, which includes the Maggot Menageries study, can be accessed at *www.medmaglabs.com*.

ETHICS AND CONSENT

The students on the team were co-researchers and not study subjects. Therefore, there was no need to conduct a human or animal research ethics review. However, guardian permissions were sought for publication of photographs of student work or of students themselves. Permission was also given to list student authors' full name and school affiliation.

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COMPETING INTERESTS

At the time of publication MedMagLabs has been a non-commercial informal Griffith University School of Medicine research lab led by Frank Stadler. It is the expectation of Hope in Conflict: A Humanitarian Grand Challenge that the solutions developed by MedMagLabs are commercialised and/or implemented in conflict-affected communities and other compromised healthcare settings. This may or may not apply to the work reported in this publication. The other authors have no competing interests to declare.

AUTHOR CONTRIBUTIONS

FS conceived the Maggot Menageries program, supervised the scientific components of the program, and drafted the manuscript. FS, AL, and GB co-developed the Maggot Menageries project. AL coordinated the engagement with students and supervised research sessions. GU, KG, and MS co-developed the low-resource sterile work practices and provided students with sterility testing kits and guidance. The students from Isis (SO, JW, MC, CB, JF-G, ZZ, AR, BW, TS, TA) conducted the R&D work reported in this case study including the construction of prototype fly rearing and disinfection equipment, testing of this equipment and related procedures, and the microbiological quality control protocols. Their findings were complemented and triangulated by the findings of the Nanango, Roma, and Thuringowa students who are listed in the acknowledgements section. Research reports prepared by all four participating teams formed the foundation of this publication. AB and KH were the supervising teachers at Isis and MH at Nanango, providing in-school support to students and contributing to the evaluation of the program. PB visualised production and disinfection guidance and illustrated the infographics. MM co-supervised the preparation of illustrations.

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