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Forming bonds between molecules and communities through Project M

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Calcium carbonate is a compound that is well-recognized and very prevalent in daily life e.g., chalk, mussel shells and limescale. However, scientists still have many questions about its formation mechanisms, the different crystal forms it takes, and how we can control and direct this formation to produce this material with different properties. Project M was a chemistry citizen science project for UK secondary schools exploring the synthesis of samples of calcium carbonate under different reaction conditions and analyzing them at Beamline I11, an X-ray diffraction laboratory at the Diamond Light Source synchrotron. Science communication played a crucial role in the success of the project, connecting different communities to the science and creating unique opportunities to center and empower the Project M Scientists.

KEYWORDS

chemistry, citizen science, science communication, calcium carbonate, youth

Introduction

Citizen science in the classroom creates practical opportunities to engage the youth in scientific enquiry (Makuch and Aczel, 2018), to improve their scientific literacy and science capital (Bonn et al., 2018) and to give them agency in their education (Ballard et al., 2017). Examples specifically for chemistry citizen science in the secondary/high school domain include monitoring the physiochemical parameters of coastal water quality (Araújo et al., 2022b), evaluating global medicine quality (Bliese et al., 2020), recording radon tests in their homes (Tsapalov et al., 2020), and comparing the bacteria resistant performance of non-fouling polymer hydrogels (Hansen et al., 2022). Teachers have also perceived added value for their own chemistry teaching practices through the use of citizen science (Araújo et al., 2022a). However, meaningful science communication with youth (and adults) is so much more than the act of providing or creating an opportunity for engagement in/with science (Petrie et al., 2006; Archer et al., 2015; Dawson, 2017; Murray et al., 2022b).

Citizen science has a plurality of definitions (Haklay et al., 2021) but within this work, we use the following definition: "*the active participation of non-professional scientists in the generation of new scientific knowledge*" (Perez et al., 2023). Our focus on citizen science in the classroom puts Project M in a context that is studied by at least three research traditions under their lead concepts of participatory research, science communication, and science education. Through participating in citizen science activities, students work not only on fake exercises but on actual and current research questions. Their participation, framed by the power and control they have in this endeavor, thus constitutes an involvement in science or participatory research (Cornwall and Jewkes, 1995). At the same time, this involvement in science is mediated through activities and communicative formats that address a particular public of science (usually non-professional scientists). In this way, citizen science in the classroom can be seen as a science communication activity (Horst et al., 2016). To express this connection, Metcalfe et al. have proposed to understand citizen science as participatory science communication (Metcalfe et al., 2022). Finally, citizen science in the classroom is not limited to just scientific and communicative purposes but can also have a particular educational function. In this way, such activities can be regarded as science education (Lewenstein, 2015).

Science education is typically distinguished into formal, non-formal and informal learning opportunities. Formal STEM learning is generally considered as happening in the classroom during routine class times based on educational curricula and studied under the concept of science education (Lewenstein, 2015). Non-formal learning is defined by UNESCO as "*organized and sustained educational activities that do not correspond exactly to the definition of formal education [and] may or may not confer certification*" (UNESCO, 1997). Informal STEM learning is a much wider domain that covers all other educational opportunities, for instance in the park, at a museum or at home (Morris et al., 2019). Due to the diversity of formats, functions and aims of non-formal and informal STEM learning opportunities, the latter can be described with the concept of science communication, which Horst et al. define as "*organized, explicit, and intended actions that aim to communicate scientific knowledge, methodology, processes, or practices in settings where non-scientists are a recognized part of the audience*" (Horst et al., 2016). Although science communication extends well beyond educational activities - it also covers mass-media communication of science and science fiction for example – capturing non-formal and informal STEM learning in this way has the advantage of defining it according to its function (communicating science), and not according to what it is not (formal education).

By considering citizen science in the classroom as participatory science communication in non-formal learning settings, we gain an important framing for the study presented in this paper. First, Metcalfe's emphasis that participatory science communication should incorporate different forms of knowledge and experiences (2022) creates space for students to practically implement their own conceptualizations in a real-life situation. This sensitizes our analytical view for how they can individually or collectively apply the theory from their textbooks to a meaningful scientific question, but also how they might communicate it. In turn, Bucchi (2008) highlights that science communication is a responsive process, rather than a tool for a prescribed form of event. Therefore, the students' success and the success of the citizen science project fundamentally relies on multiple layers of effective science communication between all of the relevant stakeholders. Here we describe how science communication bridged this gap between different communities to connect them to a real chemistry research question through Project M. We particularly highlight how co-creation and communication with our citizen scientists and our community were fundamental to the overall success of the project and share learnings from our experience.

Context

Project M was a citizen science secondary school project in 2017 investigating the structure of calcium carbonate. Calcium carbonate has three main forms or "polymorphs": vaterite, calcite, and aragonite, which have the same chemical composition but a different crystal structure (arrangement of atoms) (Deer et al., 1967). Directing polymorph formation is important for being able to control material properties and is often done through the use of additives. Nature is already an expert in exerting this control, using proteins and organic molecules (acting as additives) to form the different polymorphs of calcium carbonate that make up for example the shells of sea creatures such as mussels and oysters (Lowenstam and Weiner, 1989; Mann, 2001). This so called biomineralized calcium carbonate has many favorable properties such as greater toughness and fracture resistance, created in part by the role of the additives in controlling polymorph and crystal structure. Inspired by this approach there has been much research using amino acids (that make up protein chains) as additives in calcium carbonation formation (Pokroy et al., 2006; Gilow et al., 2011; Kim et al., 2011; Borukhin et al., 2012; Green et al., 2016). Project M expanded on this work by synthesizing and analyzing a large number of powdered samples with different amino acid additives and concentrations, to reveal the effect of the additive on the polymorph and crystal structure.

Diamond Light Source is a synchrotron, a type of particle accelerator, that accelerates electrons to produce intense beams of X-rays. It has an experimental laboratory called I11 that uses these X-rays to perform diffraction experiments on powdered samples and analysis of the patterns that are produced provides information on the 3D arrangement of atoms in the sample. This technique gives valuable insights in the structural composition of the powdered samples. I11 can carry out very fast diffraction experiments on powdered samples – <10 s per sample (Thompson et al., 2009, 2011). This technique provides valuable insights in the structural composition of the powdered samples. Automation of these experiments has been made possible through a robot, which minimizes the time lost in changing samples manually (Thompson et al., 2011) and allow automation of the experiment data collections. By using variables like additive concentration in the calcium carbonate synthesis at various specified concentrations, 1,100 samples were planned. The combination of the robot and the fast diffraction experiments at I11 meant all of the Project M samples could be collected in a 24-h experiment.

Project setting

Audience, materials, and methods

Students (13–18 years old), teachers, teaching assistants and laboratory technicians were our target audience. We refer to them as the "Project M Scientists" to intentionally convey their meaningful contribution and define them with power in their role. This directly builds on from important conversations in the citizen science field (Shirk et al., 2012; Gadermaier et al., 2018). The Project M Scientists made powdered samples of calcium carbonate using different types and/or concentrations of additives to influence which polymorph formed. The protocol to make the samples was first sketched out in consultation with teachers, with a focus on trying to use resources and equipment available in schools and to convey key information on the science behind our experiment. The results from Project M were intended to be scientifically relevant to the research in the field so this also guided some of the experimental design. It was split into two stages to cover the making the samples ("sample synthesis") and the loading of the samples into small capillaries ready for analysis ("sample preparation"). This protocol was updated following frequent conversations and *in situ* tests with the Project M Scientists, ensuring each of the two stages for the experiment fit within a typical lesson timeframe (45 min) and complied with the relevant risk assessments. The final protocol was also converted into a video to provide a visual point of reference. In parallel with this, software for the Project M Scientists to access the data was developed. Once the optimal protocol was established and the feasibility was proven by tests with some of the Project M Scientists, the project was promoted via press releases and support from various networks and school mailing lists to identify secondary schools interested in participating. The time required to carry out the experiment and the fact the necessary resources would be provided were clearly communicated during this promotion. One hundred and ten schools were selected through the application process, located across the UK and with a focus on ensuring schools from underserved areas were represented. Each school was sent a box of resources, equipment, and chemicals (see Table 1), with the only variables per box being a chemical as the additive and unique sample codes for identification. Each set of experiments for the individual additive was repeated 4 times by different schools.

Communication

The social media platform Twitter provided an important communication avenue for mutual exchange as well as for broader engagement with interested parties within and outside the project. It is widely used to share scientific results and insights including through humor (Su et al., 2022), and indeed creates opportunities for secondary science communication, whereby audiences share the messages within their own online communities (Hu et al., 2022). Schools were encouraged to share their experiences online via Twitter. This approach meant that the schools could individually assess the situation to ensure their own compliance with the relevant General Data Protection Regulation (GDPR) (European Union, 2016). We shared the project stages online using the @DLSProjectM account via tweets, photos (including re-tweeting those of the Project M Scientists) and short videos and we also used @DLSProjectMLive (an automated account) during the 24-hour experiment to share live results via the Twitter API. In total we had 66,000 impressions on this account between January and April 2017 in the run up to the experiment, with most of these impressions (27,900) occurring in April before and during the experiment. We also used @DLSProjectMLive during the 24-h experiment to share results live on Twitter. The Project M website was used to share the science and to provide resources for the schools (Project M, 2017). The website also included a blog written by Alice Richards, an undergraduate intern, to share the process of analyzing data. Many of these interactions created science communication opportunities with the schools as well as with external audiences (Figure 1).

Access to data

Following the 24-h diffraction experiment, all schools were contacted to inform them that their data could be accessed. Access was a particularly tricky topic when working at a facility like Diamond Light Source: over 14,000 facility users create terabytes of data every year, so there are understandably strong security restrictions on who can access data and how. However, as a counterbalance, our Project M Scientists were now our users and had the right to see their data and the right to engage with it in a format that they could understand. A secure web interface was therefore created to enable the Project M Scientists to access their data, compare it with relevant data from other Project M Scientists and carry out analyses to identify what they had made. We also created a resource to provide details on the analysis and questions for discussion. To address security issues, sample codes and passwords were issued to each school, with a master code provided for teachers to give them an overview of their class's samples.

Discussion

The communication flows within our citizen science project (presented in Figure 1) were shaped by multiple science communication opportunities. To structure our discussion, we are focusing on those opportunities centering around the audiences, the communities, co-creating the protocol, and the communications in and around Project M.

Audience

A key question in science communication and citizen science fields is that of audiences and publics, with increasing reflection on the often-exclusionary nature of these practices (Pandya, 2012; Streicher et al., 2014; Dawson, 2018; Judd and McKinnon, 2021; Mahmoudi et al., 2022). We were particularly keen to reach Project M Scientists in underserved areas, so ensured this was a clear aim in selecting the schools through the use of established indices of deprivation (Ministry of Housing CLG, 2015). For the scale of our project, the obvious route was to promote via established routes that are already working, rather than expecting people to come to us (Humm and Schrögel, 2020). This meant tapping into pre-existing networks for Chemistry teachers via the Royal Society of Chemistry, Physics teachers via the Institute of Physics, teachers and students already interested in scientific research via the Institute of Research in Schools, Scottish Schools Education Research Center and schools already signed up to the Diamond Light Source Educational mailing list. We also sent out press releases to local and national press, as well as promoting it on Twitter and the Diamond Light Source website. However, we acknowledge the act of applying was by self-selection, so not all schools were able to do this. Future work may include working directly with underserved schools to support them with experiments like this and to facilitate wider participation from different communities.

Building communities through science communication

An important consideration for citizen science projects is the fact that you might have to build a community of practitioners around a project from scratch. This heavily relies on science communication as a way of communicating to this community how their work contributes to and enables the implementation of citizen science, and why this matters (Halpern and O'Rourke, 2020). For us this included our own colleagues as we were working with a technical and communications team of more than 15 people who were mostly unfamiliar with citizen science or chemistry. It was therefore essential to bridge this gap to unite the team behind the same goals. We explored options to achieve this via science communication, such as presenting in internal site wide

TABLE 1 Project M box contents list.

Item	Quantity	Item	Quantity
$CaCl_2.2H_2O$	2 x 25 g	Sheets of Blue Paper	10 (1 per sample)
Na_2CO_3	1 x 50 g	Master sample sheet for teachers, with all barcodes, logins and additives concentrations for their calls	3 copies
Additive	1	Student sample information sheet with the barcode, login and additive concentration for their sample	3 copies for each of the 10 samples
Large funnels	10 (1 per sample)	Teacher handouts with scientific background detailed instructions for setting up and running the experiment	3
Filter paper	1 Packet	Student handout on the science behind project M	30
Kapton capillaries	20 in a small bag (2 per sample)	Student instructions	30
Glue	1	Student worksheets	30
Vials + Lids	10	Materials safety data sheet	1
Electric toothbrush	1	Example risk assessment	1
Tweezers	2	Stamped addressed returns envelope	1
Small plastic bags	10 (1 per sample)	USB sticks	2
Large plastic bags	10 (1 per sample)	Diamond pens	1 pack for the class
Unique Sample Barcode Labels for Small Plastic Bags	10 (1 per sample)	Diamond literature	

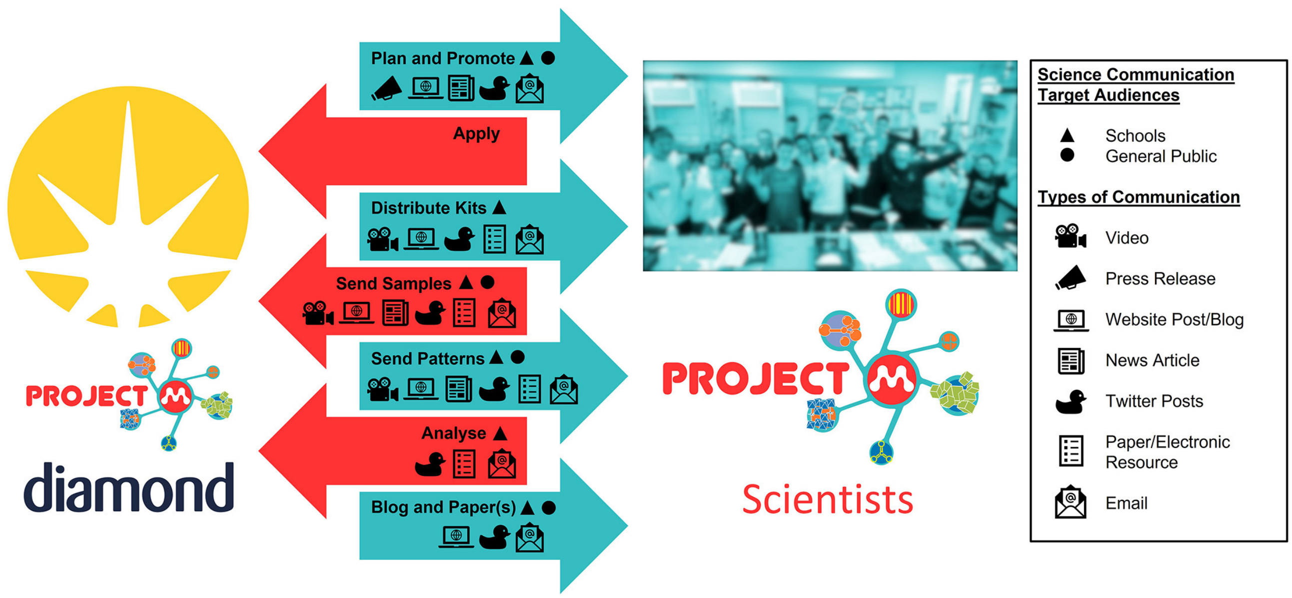

FIGURE 1
Opportunities for and types of science communication used throughout the different stages of Project M.

meetings, sharing the project aims at regular points as reminders in meetings and having local conversations. The latter proved to be particularly important, as it simultaneously enabled us to build relationships and empower our team to connect with the science of calcium carbonate. We also conveyed the role of each part of work to the overall product, which resulted in cross-fertilization of ideas to create the Twitter account @DLSProjectMLive. The additional bonus we noticed was that our team had a strong sense of ownership around their work in Project M, regularly asking follow-up questions on their own initiative about progress of both the project and the science and responding enthusiastically to requests for support.

This interest extended to the broader community of colleagues at Diamond Light Source, who were not directly involved in the project. We actively engaged in internal dissemination opportunities to reach them (such as the internal site wide meetings) and intentionally created opportunities for visibility and engagement with the science and the citizen science. A clear example of the latter was the 8-h box packing marathon that took place in the Diamond Atrium, where our colleagues were able to see the packs being assembled and chat with us as we worked. Many of these staff volunteered their time of their own accord to help prepare the boxes for the Project M Scientists, asked follow-up questions about progress throughout the project, and promoted the project to their local schools.

Lots of the Project M Scientists used Project M as an opportunity to build their own community and communicate science in school. Whether doing Project M as part of regular school classes or in after-school science clubs, informal feedback from teachers involved in Project M highlighted that students attributed value to their contribution, similar to the feedback from youth citizen scientists working with Ballard et al. (2017). We are aware of one example of two schools using Project M to build a community between younger and older students (in middle school and high school respectively). Older students gained valuable experience in mentoring and younger students had unique opportunities to share their ideas and discuss science outside of standard classroom structures. Teachers were very enthusiastic about participating, with many commenting on their excitement about the opportunity to do real chemical research with their students and some requesting citizen science chemistry projects just for teachers.

Co-creating the protocol

The starting point for any protocol is understanding what it sets out to achieve and the context in which it is to be deployed. The framing of science communication as social conversation (Bucchi and Trench, 2021) provides an important reflection point here: in co-creating a citizen science project with schools, we need to open ourselves to the relationship with our citizen scientists. Fundamentally, this means we as citizen science practitioners should truly listen and acknowledge their perspectives before starting (Hecker, 2022). Institutional barriers or lack of materials/links to curricula are major barriers for teachers to engage their students in citizen science (Kloetzer et al., 2021). The context of structure within the ecosystem of co-creation was therefore very important for us in order to successfully achieve our aim to create a valid and robust scientific methodology for Project M (Kaletka et al., 2016; Eckhardt et al., 2021). We actively sought to include teaching staff early in the project development process to address this. They are experts in science education in their classrooms and in their curricula, so acknowledging this and the context of role here is very important.

In Project M, conversations with teaching staff directly impacted the protocol and the strategy, where they shared the need for connections to the curriculum and science education learning outcomes (Kelemen-Finan et al., 2018; Scheuch et al., 2018; Roche et al., 2020; Aristeidou et al., 2022). The division between science education and science communication in the classroom and in research can imply that they have little in common, when the reality is that they fundamentally share the common goals of education, entertainment and engagement in and about science (Baram-Tsabari and Osborne, 2015). The curriculum is therefore not intended to limit or restrict the potential areas of research that school citizen scientists can engage with. However, early conversations with teachers quickly identified synergies with the curriculum for Project M and they highlighted positively the opportunity to connect the practical skills and ideas delivered in class to a real-life situation. These conversations were very helpful for making these connections and for ensuring the gap between what is known and what is not known can be bridged within the time allocated.

For the project methodology, we started by seeking initial feedback on the average school laboratory resources through conversations with teaching staff from a local school. Using this information, we created the protocol, which was tested with a small group of local students and teaching staff (ca. 10 students and three teaching staff). We observed them doing this first pilot and had discussions afterwards to refine and improve the methods. The refined methodology was taken to a second school, who had not participated in any of the initial testing (and were therefore completely fresh to the project). Twenty students and three teaching staff participated in the second iteration and shared their input. We had follow-up conversations with teaching staff to assess the final protocol and addressed all feedback before finally scaling the project out to all schools. This iterative process was time-intensive, as with the challenge of resourcing most co-creation citizen science projects (Gunnell et al., 2021).

The co-design process was also used in the creation of instructions and handouts for all of the Project M Scientists. Language shapes the intent and purpose of an interaction and is frequently used as a way of asserting power. It can be completely impenetrable due to jargon (Bullock et al., 2019) or performative (Kueffer and Larson, 2014) when it is delivered in a corporate or academic way to people outside formal institutions. We wanted to make our resources accessible to students so they could use them with minimal support, but we also wanted to introduce them to new vocabulary. The co-design process meant we could identify problematic terms or phrasings and ensure we used terminology in use in the classroom – e.g., most UK secondary schools used deciliters (dL) as opposed to the research lab standard of milliliters

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FIGURE 2
Tweets from various schools sharing their experiences loading capillaries.

(mL). In cases like this where we knew many laboratory technicians, teaching assistants and teachers would be preparing the materials for and sharing the protocol with their class, we wanted to minimize their burden. The protocol was therefore designed to be easy to follow, to provide learning opportunities, to share good practice (e.g., wearing safety spectacles) and to ensure it was reproducible and consistent for the scientific credibility of the results.

The contents of the supply box that was sent out to schools outlined in Table 1 were selected for a combination of scientific and practical considerations, most of which only became obvious after conversations with teaching staff to understand their local contexts and needs. As mentioned above, a central focus was to minimize work for the teaching staff, so multiple copies of instructions were printed with copies for students and more detailed copies for teaching staff to support them in preparing for the experiment. We also provided two back-up USB drives containing all documents and videos in case extra copies were required or in case internet access was not possible. Carrying out risk assessments is an essential part of laboratory chemistry, but it is not possible to write a universal risk assessment that would legally cover the schools. We therefore provided an example risk assessment to support school staff with this, but explicitly stated that each school needed to do their own. Scientific consistency in methodology is important in the context of building trust in citizen science data (Burgess et al., 2017), but discussion with teaching staff highlighted the different filter paper and filter funnel sizes available in school laboratories, as well as varying amounts. This would induce a serious variable in terms of filtering time across difference schools and would limit the number of samples that could be made simultaneously. We therefore provided the same size funnel and filter paper to ensure all samples could filter at same rate and so the 10 samples could be made within the same class period. Petri dishes were also provided as schools reported not having access to enough of these for the number of samples we planned – every sample needed to dry for 1 week in a petri dish.

We provided all chemicals apart from the solvents to ensure the same standard and quality, and this even included ensuring all samples were from the same batch. Sending solvents by post is not possible in the UK, due to the high risk of flammability. However, discussions with teaching staff revealed some variability in what was available to them, but acetone, for example, was a commonly available solvent. Some items in Table 1 were specifically included for the loading of the capillaries, which included the spatula to load the powder into the capillary, the tweezers, and the electric toothbrush to facilitate the packing of the powder, as well as the glue to seal the capillaries. From our visits to the two schools who piloted the protocol, we saw that many workbenches were light gray or white, which would not provide a strong enough color difference to see the white calcium carbonate powder. The sheets of blue paper were therefore included to provide contrast for the capillary loading. The final practical items were barcoded vials and lids for the remaining sample not used in the capillary loading, barcoded small bags to hold the capillaries, barcoded larger bags to hold the vial, and a stamped addressed envelope for returning the samples. The barcoding enabled us to track samples and identify them throughout the experiment.

Frequent reality checks are critical to ensure what you are proposing is possible for the target audience. There is often a gap between what people sign up for and what they think they are signing up for, as well as a gap between the expectation and reality of resource and time availability in schools (Aristeidou et al., 2022). This is particularly true when thinking about school laboratories/equipment or access to computers or printers. We intentionally built the project to be achievable within a secondary school chemistry laboratory – ensuring for example, that the weights we were requesting were within resolution of the weighing balances available (informal feedback from teaching staff highlighted that generally the minimum is 0.01 g) and using conical flasks rather than beakers as more schools use these. In the UK, many teachers have a limited printing budget and computers are a limited resource, so we printed out everything for the schools to ensure they did not have to use their own budget on our activity. These materials/resources often have lifetimes beyond the project, which teachers appreciate (Araújo et al., 2022a). We provided individual instructions and reporting sheets for each Project M Scientist (plus spares) to ensure everyone had their own copies enabling them to input their own results. This was also important in promoting good lab practice and consistency across the participating schools, as it ensured Project M Scientists could follow the same lab protocol independently.

Communication resources to support learning

To support learning needs *in-situ* in the laboratory, we recorded three videos: (1) Introducing the science of calcium carbonate, the diffraction experiment, and Diamond Light Source, (2) the synthesis of the samples and (3) the loading process for the capillaries. For (2) and (3) we recorded videos of ourselves performing each stage of the experiment. These two videos were scripted to ensure our language matched the language of the protocol and to ensure our version of the protocol was exactly the one described in the materials we were sending to schools. These videos provided additional opportunities to share the science behind the project and to connect with our Project M Scientists. From looking at the samples, we have the impression that schools were more exposed to scientific practice and process. The capillary loading process is tricky (as communicated to us by the schools in tweets shown in Figure 2), and many experienced scientists find this quite difficult. It is also quite challenging to describe the steps in a written document, so the video was an opportunity to demonstrate best practice and techniques for doing this. The (often sticky) powder must be packed without gaps inside a 0.5 mm Kapton tube, which can be a delicate process. The consistency of the packing of the loaded capillaries across samples from a school was therefore an interesting insight into whether they had watched the video to pick up the skills involved.

Awareness of the variety of IT security protocols and software available in schools led us to develop a custom web interface to enable facile visualization and analysis of the data, circumventing requirements for specific software packages or requirements for software to be downloaded. However, access extends beyond the act of getting the data to also include the act of engaging with the data, which is where science communication comes into play. A resources pack was built to accompany the web interface to convey how to carry out analyses of the samples (Project M, 2017). This built on concepts that had been introduced in the initial pack and provided prompts for critical thinking around the scientific process (e.g., sources of errors) with links to real world problems.

FIGURE 3
A collage of tweets demonstrating the communication on Twitter from the Project M Scientists and the @DLSProjectM account.

The intellectual tools developed through critical thinking provide important foundations in problem solving, decision making and in interacting with others (Vieira et al., 2011). These prompts therefore provided opportunities for the Project M Scientists to gain an understanding of the chemical composition of their individual samples but also to reflect on and rationalize how real-life experiments work.

Communicating Project M

The act (and art) of communicating about science usually involves multiple modalities. In our case, we had multiple communities involved including the Project M scientists, chemists and synchrotron users and our own colleagues. This translates to varying information and engagement needs for this broad community of people doing and interested in the science. The authors and the communications team at Diamond Light Source communicated the science of Project M via big press releases to national media (Diamond Light Source, 2016, 2017), interviews with TV and radio stations, conference talks, social media and more, as detailed in Figure 1. These experiences combined with the creation of the videos for the Project M Scientists enabled the team to develop skills and confidence in media work and in communicating science to different audiences via different forms of media, e.g., the key talking points with a science journalist for print media need to be delivered differently to a live radio interview on a local morning show. The Project M blog was also a useful way of demystifying the scientific process and sharing initial results (Project M, 2017), and some updates were shared with schools via emails. Simultaneously, our Project M Scientists were also busy doing their own science communication: tweeting their experiences, writing articles for school newspapers, presenting at school assemblies, and doing interviews with local press (Figure 3) (Campbell, 2017; UnknownReporter, 2017). In learning about this, additional resources should be planned for and shared with citizen scientists to ensure they have a variety of options for how to share their experiences and the project outcomes.

The use of only one social media platform prevented us from engaging with a wide variety of people, with clear limitations to the potential audience on Twitter (Robson et al., 2013; Tancoigne, 2019). We know that many of our younger Project M Scientists were not able to engage with us or indeed do not use Twitter. Even considering the engagement we had, algorithms limit who engages or even sees your tweets. However, interacting with youth within the important legal framework of GDPR has its own challenges across all social media. By sharing the account @DLSProjectM and the hashtag #DLSProjectM with the schools, they had the power to assess their own compliance with GDPR. We still received quite a few interactions from schools, with many sharing feedback or photos and one school even video streamed their experiment live via the Periscope service (see Figure 3). One school also shared how their students would use Project M to work toward their bronze CREST award, which is an optional STEM accreditation that UK students can work toward (also Figure 3).

A surprising audience that we were not expecting to draw in via Twitter was the scientific research community who were not involved in Project M. Citizen science is not super common in chemistry (Motion, 2019), crystallography or in synchrotron science. A recent survey of European Citizen Science projects highlighted that only 0.6% of projects count as "chemistry" (Hecker et al., 2018). This meant that many of our scientific colleagues within and beyond Diamond Light Source were curious about what was going on. An important point to note here is that this meant our Twitter accounts @DLSProjectM and @DLSProjectMLive were simultaneously communicating science to two very different key groups: the Project M Scientists (mainly teaching staff who were running school or department accounts) and the scientific research community. This required science communication about the science and science communication about citizen science, with both groups being interested in one or both, whilst also ensuring we centered the Project M scientists and their work. Sharing live results and the scientific process online was therefore one small way of building different dimensions of trust (Brondi et al., 2021) in Project M and citizen science.

Challenges

An important reflection on the protocol is to consider the completion rate. A total of 80% schools returned samples, although not all are a complete set (Figure 4). We believe this is a good completion rate given the high workload involved in making and preparing the samples. Some issues reported by teaching staff via email were curriculum pressures and staffing problems, which in turn meant reduced time for the experiment or that only a few samples could be made. Variations in class timing or in science club timing and the fact two sessions were required may also have affected the completion rate. Whilst budgetary restraints and having enough samples for statistical significance are important considerations, options such as designing a shorter experiment, reducing the number of samples per class, or providing more detail on what would be involved so they can think about logistics when signing up could be explored to address this as there is clearly interest in this type of project. Some of the issues were also due to our own inexperience at running projects at this scale or to experimental challenges. However, the latter unexpectedly provided an important reflection point: a teacher shared positive feedback on the power of citizen science to demonstrate to their students that real science doesn't always work. Negative results and/or failures are not well communicated in formal academic journals, let alone in science communication, but this is an important and welcome way of humanizing science that should not be underestimated (Zaringhalam, 2016; Murray et al., 2022a). Another consideration in retrospect is that although many teaching staff were busy, there was a lot of enthusiasm and good will from them. There would have also been an interesting opportunity to build a community for the teachers involved in Project M, such as through collective conversations, an online forum or targeted further dissemination, which is an important factor for future work.

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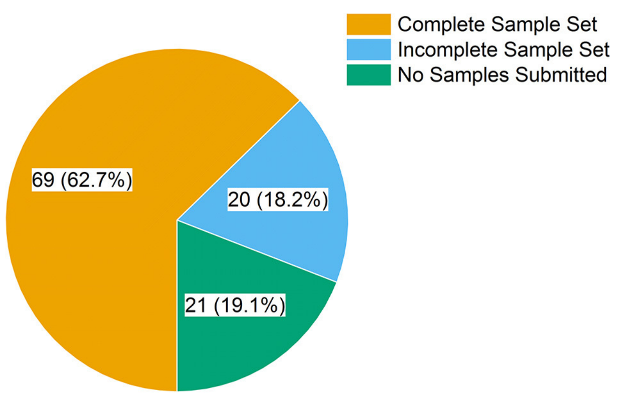

FIGURE 4
The completion rates for the submission of samples sets for Project M, where each school applied to carry out experiments for one full sample set. The number of sample sets is therefore directly equal to the number of schools.

Conclusion

Chemistry citizen science projects in the classroom create unique opportunities for research, for youth agency and skill building in their education, for professional development for teachers, teaching assistants and lab technicians, in addition to building communities at different scales. In the case of Project M, the community of people involved started as a small team within Diamond Light Source, but quickly grew to include the Project M Scientists, other colleagues at Diamond, various stakeholders, and the broader science community. The science communication methods we deployed at different layers were fundamental to the establishment and growth of the communities. This required careful consideration and challenging of assumptions about factors like language, facilities, equipment, access, time, and resources, which all directly affected the success of the project. Ignoring these factors or assuming what was possible would have disempowered the Project M Scientists by creating more work for them to participate equitably. Science communication was therefore crucial to bridge the theoretical expectations and the practical reality of citizen science for Project M and enabled opportunities for the Project M Scientists to engage and participate in real research in a meaningful way.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Ethics statement

Teachers who signed up on behalf of their school to participate were informed of the aims of the research, including its publication goals, prior to consenting to take part. Separate consent beyond the consent obtained during the sign-up process was not necessary. Further ethical review and approval was not required for this study in accordance with the local legislation and institutional requirements.

Author contributions

CM and JP conceptualized the paper, wrote, and reviewed the article. LH and RO'B contributed to the implementation and reviewed the paper. All authors contributed to the article and approved the submitted version.

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Conflict of interest

RO'B was employed by the Wellcome Trust.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor YG declared a past collaboration with the author CM.

Publisher's note

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