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"The Gems of Water": a co-created *scientist-citizen* approach for water quality monitoring

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To better understand local water quality pollution by organic contaminants and how it affects communities around the world, "The Gems of Water" project aims to build a co-creative global *scientist-citizen* approach, actively engaging citizens and connecting them to scientists and to advanced water monitoring tools. The project applies the Stir Bar Sorptive Extraction technique with an advanced wide-screening method, used to assess the occurrence of agrochemicals, industrial compounds and pharmaceuticals in surface and groundwaters. In collaboration between Coral Conservation and the Joint Research Centre (JRC) of the European Commission, a study was conducted to identify contamination patterns which could be affecting the coral reef by investigating water quality in local rivers in the south Caribbean region of Costa Rica, an area characterized by agricultural activities linked to bananas production. Coral Conservation is a youth-led non-governmental organization focused on activities for the conservation and protection of the coral reef. Sampling locations for the study were jointly determined with members of the Coral Conservation group and included 13 sampling points from 3 different rivers and 2 wells. The pilot study allowed evaluation of the workflow for *scientist-citizen* collection of water quality data, whereby participants from the local community conduct sampling and extraction activities, while the wide-screening analysis of about 230 contaminants is performed at the JRC Water Laboratory. Considering the lessons learned through the Costa Rican pilot case, in this paper we discuss the elements required for successful *scientist-citizen* projects. Challenges are described and outlooks provided to improve citizens' engagement projects and others participatory water quality monitoring activities. "The Gems of Water" project contributes to data collection of rarely monitored compounds in rural and remote areas through a *scientist-citizen* approach, addressing knowledge gaps on water quality and building bridges between science and society. The outlook is for such an innovative approach to support bottom-up management actions which can lead to alternative solutions in water quality management.

KEYWORDS

water quality monitoring, citizen science, Costa Rica, Stir Bar Sorptive Extraction, wide-screening, pesticides

1 Introduction

Worldwide expansion of industrial agriculture from the 1990s has been accompanied by a 50% increase in pesticide consumption (FAO, 2022). Pesticides are used to kill unwanted pests or vectors of disease,[1] but their occurrence in the environment is concerning, due in most part to their toxicity, persistency, and tendency to bioaccumulate (Metcalfe et al., 2022). The increased use of pesticides and their known negative effects on human health and the ecosystem highlight the need for a greater understanding of chemical pollution and in parallel, for strengthening monitoring of environmental compartments, especially water (Giordano et al., 2009). In most cases, monitoring water quality remains sporadic and based on target-screening, not allowing for a broader and quicker quantification of a variety of pollutants and not keeping up with the speed and extent of contamination (Johansson et al., 2022). Constraints on consistent water quality monitoring can be attributed to a lack of human capacity and expertise, the unavailability of technical equipment and logistical and economic challenges (Kirschke et al., 2020). Pesticide contamination sources include disposal from industrial processes, leakages and improper maintenance of treated wastewater discharges, urban and agricultural runoff, where type of produce, local climatic conditions, and application times play a relevant role (Gikas et al., 2022). Based on a global analysis, the Americas' use of pesticides increased over time, making it the region with highest levels applied in cropland (in hectares) on average per year (2.83 kg/ha/y) between 1990 and 2020 (FAO, 2022). In 2020, the Americas was the biggest importer of pesticides worldwide (FAO, 2022). Within Central America, Costa Rica records a pesticide use above average for tropical regions, with an average application of pesticides active ingredients in cropland of 14.7 kg a.i/ha (Rodríguez-Rodríguez et al., 2021). In banana plantations, which represent one of the major export markets for the country, reported pesticide active ingredients applications in cropland reach peaks of 76 kg a.i./ha/y (Echeverría-Sáenz et al., 2018). In Costa Rica, a country at the forefront of environmental awareness, pesticide contamination in surface waters has been widely reported by independent academic researchers, but there are no coordinated and ongoing monitoring programs (Mendez et al., 2018). Additionally, the Costa Rican regulatory framework is vague, with limit values for pesticides in water defined only for cumulative concentrations of organochlorine and organophosphate compounds (Mendez et al., 2018).

Various studies have investigated pesticide occurrence (screening up to 260 compounds) along with their eco-toxicological assessment in rivers nearby banana and pineapple plantations in the Northern Coast of the Caribbean (Arias-Andrés et al., 2018; Echeverría-Sáenz et al., 2018; Mendez et al., 2018), and agricultural fields along the Pacific coast (Rodríguez-Rodríguez et al., 2021; Weiss et al., 2023). Frequently detected pesticides reported in these studies include the fungicides azoxystrobin and other azole fungicides along with insecticides cypermethrin, chlorpyrifos, diazinon, endosulfan and the herbicide diuron. Land-use, but also historical and unauthorized use, distribution of the streams network and methodology contribute to explaining the type of compounds detected (Rodríguez-Rodríguez et al., 2021). Considering these factors is therefore important when setting up a monitoring program that should provide insights into local water quality contamination and characteristic.

The need to expand monitoring capacity and to provide wide-eyed solutions to human and ecosystems health issues highlights the need for alternative approaches to water quality monitoring. To respond to this need, from a technical point of view, wide-screening monitoring methods can guarantee a wider grasp on water contamination, while citizens' science represents an alternative data source, which can extend monitoring to a wider time and spatial scale, enriching opportunities of cooperation between scientists and citizens (Carvalho et al., 2019). Citizen scientists can attain data with a space and time resolution, which would not normally be obtained at higher national and international levels and can be more relevant to local community issues. Furthermore, inclusion of society in scientific water research and data collection through citizen engagement can help to achieve a sustainable and respectful management of water (Fritz et al., 2019), beyond political discontinuity that characterizes national and international institutions (Gawlik et al., 2018).

This paper illustrates the application of the "The Gems of Water" project as an alternative co-created *scientist-citizen* approach for water quality monitoring. "The Gems of Water" seeks to reverse the traditional citizen-science relationship, by promoting the role of scientists as "supporters" of citizens in understanding water quality issues they might identify as concerning. Applying a wide-screening method based on the Stir Bar Sorptive Extraction (SBSE) followed by GC–MS analysis of 230 organic compounds, mainly belonging to the class of pesticides, "The Gems of Water" connects citizen science to wide-screening, a novelty in respect to traditional citizen science analysis of physico-chemical (pH, nitrates and phosphates, conductivity, turbidity) parameters through the deployment of field-kits (Shupe, 2017; Thornhill et al., 2017; Zhang et al., 2017; Hegarty et al., 2021; Yevenes et al., 2022). Indeed, to our knowledge, only The Pesticides Detectives, a national citizen science project in Australia, used wide screening to detect pesticides in sediments.

The Stir Bar Sorptive Extraction involves magnetic stirring of a stir bar in a water sample (Campanale et al., 2021). The stir bar is a small glass magnet, covered with an absorbent layer of polydimethylsiloxane (PDMS), which targets adsorption of hydrophobic organic compounds, such as pesticides, industrial chemicals and pharmaceuticals. After extraction, the stir bars are thermally desorbed at high temperatures (300°C) in the injector port of a gas chromatograph, allowing identification and quantification of large numbers of organic compounds when applied in combination with Mass Spectrometry (GC–MS) detection (Ochiai et al., 2011; David et al., 2019). SBSE has successfully been applied in extraction of organochlorine and pyrethroid pesticides in surface waters (Serôdio and Nogueira, 2005; Ochiai et al., 2011). Furthermore, the technique has been widely praised for its inexpensive, easy, ecological, and fast analyte extraction (Posada-Ureta et al., 2016). Such adjectives refer to the great reduction of solvent used in comparison to traditional extraction methods, and to the streamlining of the sample preparation to one step stir bar conditioning. The limited use of solvent and its simplicity make the SBSE suitable for citizen science and extends participation of citizens to sample extraction, beyond collection of water samples. Lastly, performing SBSE close to the sampling site significantly streamlines logistics, eliminating the need for water

1 https://www.who.int/news-room/questions-and-answers/item/chemical-safety-pesticides

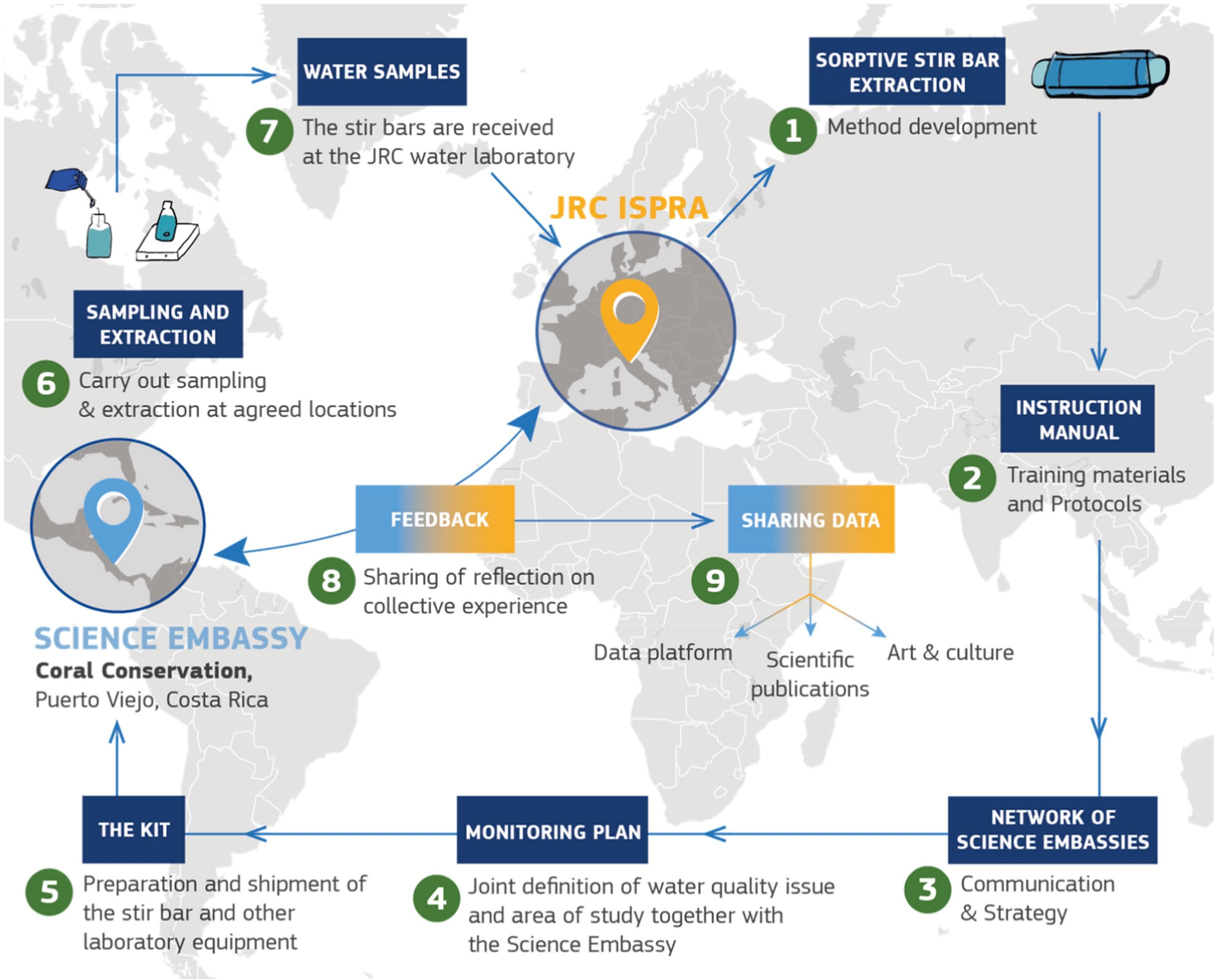

FIGURE 1
"The Gems of Water" *scientist-citizen* workflow description from the development of the scientific method (1) to the sharing of data (9).

sample shipments, thereby ensuring improved stability and facilitating easier logistics. While the use of grab sampling permits a controlled and small sample volume compared to other sampling and extraction methods, its ability to detect temporal contamination is nonetheless constrained by the frequency of sampling collection (Posada-Ureta et al., 2016).

This paper describes the project potential to establish a framework of dynamic *scientist-citizen* collaboration based on co-creation, transparency and acknowledgment for water quality monitoring. In Costa Rica, "The Gems of Water" approach has been trialed for the first time in 2023 in collaboration with NGO Coral Conservation[2] and citizens of the community of Puerto Viejo, Limón (Figure 1). There are community concerns about the impact of agricultural runoff from banana plantations on coral reefs in the Caribbean Sea. Indeed, international research carried out overseas has identified pesticide runoff from agricultural activity as a non-point source of pollution for corals. Chronic exposure to such pollution can significantly degrade coral health (Davis et al., 2014). This community implemented the use of Stir Bar Sorptive Extraction (SBSE) samplers combined with an advanced wide screening method to investigate the occurrence of pesticides in surface waters during March 2023.

2 Materials and methods

2.1 "The Gems of Water" *scientist-citizens* workflow

"The Gems of Water" workflow comprises various steps from the development of the analytical method to sample analysis, as described in Figure 1. The first step in the workflow is the identification and development of an analytical method applicable in the context of citizen science under operational safety conditions. The sampling strategy, the stir bar extraction method and the analytical method for organic compounds in surface, ground and drinking water was designed and optimized at the European Commission Joint Research Centre (Cacciatori et al., 2023), based on Lerch et al. (2018). Step 2 involved the development of protocols for sampling and extraction. These were written and collated in an instruction manual, including generic background

2 https://coral-conservation.org/

information on water quality, monitoring and its importance (Cacciatori et al., 2023), targeted at the citizen participants of the project. The instruction manual was enriched with videos accessible by QR-code, to increase approachability to the content. A meeting was organized to explain procedures and present the instruction manual, after which participants were invited to consult the videos and materials and raise any questions or doubts. Step 3 is focused on Engagement with individuals and groups interested in water quality, herein termed *science embassies*, was established mostly through the network of the Social Engagement Platform of the World Water Quality Alliance,[3] which brings together communities from around the world on the topic of water quality. During the initial 6 months period, monthly meetings were organized with *science embassies*, to ensure the establishment of a co-creative environment of trust, after which frequency was decreased to bi- or tri-monthly online communication. Step 4 involves defining the local water quality issue of interest. Working together, scientists and the community, identify and define the local water quality problem, plan the monitoring campaign, share scientific and technical information and agree on roles and responsibilities. Once the components of step 4 are agreed upon, during step 5 a kit (Section 2.3) is prepared and shipped to the engaged *science embassy*. During step 6, the community members are invited to carry out sampling and extraction, while step 7 involves the shipping of stir bar samples back to the European Commission JRC where they are then analyzed by Gas Chromatography – Quadrupole Time of Flight – Mass Spectrometry (GC-QToF-MS). Step 8 in the workflow is a feedback survey. Participants provide feedback on the process and on their experience to allow learning and improvement (Data Sheets 1, 2, 3, Supplementary material). The last step in the workflow is step 9 which involves evaluation and sharing of data and acquired knowledge. The results are shared through online meetings followed by discussion around sharing and application of the data.

2.2 Study area

The case study was conducted in the Southern Caribbean area of Costa Rica (Figure 2). Water samples were collected from Estrella, Carbon and Sixaola rivers and groundwater from 2 wells, in the area of Puerto Viejo, Limón. According to investigation work conducted by Coral Conservation, two main banana plantations are located along the Estrella River basin. The Sixaola River, shared with Panama, has banana plantations managed with sustainable practices in its upper catchment, while conventional intensive banana plantations are present all along the lower catchment. The Carbon River runs parallel to the coast connecting the two villages of Cahuita and Puerto Viejo and is surrounded by banana plantations in its downstream region. The wells surveyed were a private well located near a banana plantation and a governmental distribution well of potable water near the village of Cocles. Both these wells are used to supply drinking and household water to local communities.

3 https://wwqa.info/ (Accessed December 13, 2023).

2.3 The kit

Participants in "The Gems of Water" project are provided with a kit containing all equipment, consumables and instructions needed to complete sample collection and extraction. Kits are prepared and shipped by the JRC Water Laboratory. Each kit contains printed copies of the instruction manual and sampling document, to be filled out during sampling, in both English and the language most appropriate for the collaborating community. Amber glass sample collection bottles (100 mL), a sample bottle holder to assist sample collection, pre-made labels and personal protective equipment (PPE) such as gloves and lab coats were also included in the kit. For sample extraction, conditioned stir bars are supplied in individually sealed vials, plus 5 magnetic stirrer plates with power adaptors, glass pipettes and a magnetic stick. Lastly, vials containing internal standards are provided for quality control purposes.

For the case study, the NGO Coral Conservation received in their sampling and extraction kit; instruction manuals in English and Spanish, 35 amber glass bottles (100 mL), 35 conditioned stir bars and 35 internal standard vials as well as the other components listed above.

2.4 Sample collection and extraction

Fifteen grab samples (100 mL) were collected in duplicates in brown glass bottles over the 8th and 9th of March 2023 by the 4 citizens and 4 core members of Coral Conservation (Figure 3). The sampling was performed during the dry season. The extraction procedure using the stir bars was modified based on Lerch et al. (2018). In short, stir bars were pre-conditioned at the JRC Water Laboratory under nitrogen flow for 3 h at 310°C. One pre-conditioned stir bar was placed into each amber glass bottle containing 100 mL of site collected water sample using the magnetic stick. Internal standard solutions (trans-Nonachlor_C13) were prepared in acetone (1 mL) at the JRC Water Laboratory and were pipetted into each water sample before the extraction procedure. Internal standard solutions were used for quality control purposes as well as to calculate recovery during analysis.

The bottles were placed on the magnetic stirrer plate and left to extract over 5 h at 800 rpm. After extraction, the stir bars were removed from the amber glass bottles using the magnetic stick and placed into separate pre-labelled vials. These were then shipped back to the Water Laboratory of the JRC for GC–MS analysis.

2.5 Chemical analysis

Stir bars (1 mm × 0.5 mm, PDMS coating) were provided by Gerstel (Germany). Before use, the stir bars were conditioned at the JRC Water Laboratory (300°C for 6 h) under nitrogen flow using a tube conditioner (Gerstel, Germany). After extraction and once received by the JRC Water Laboratory, stir bars were dried under a constant stream of nitrogen and positioned in desorption tubes for thermal desorption and analysed by GC-QToF-MS. Both qualitative and quantitative analyses were conducted on the samples. However, the quantitative analysis falls outside the scope of this paper and will be addressed separately.

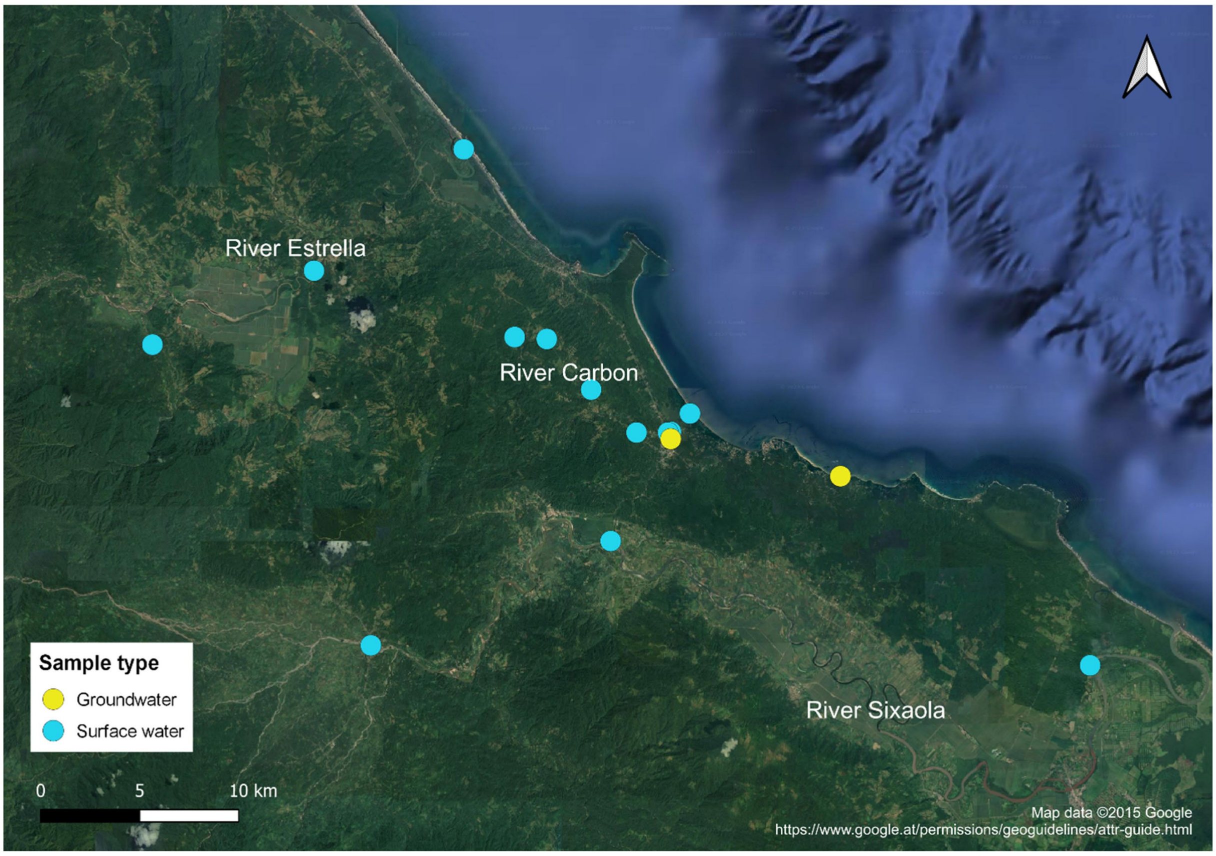

FIGURE 2
Map of the sampling points from Estrella, Carbon and Sixaola rivers and from two underground water wells in the Caribbean area of Puerto Viejo, Costa Rica.

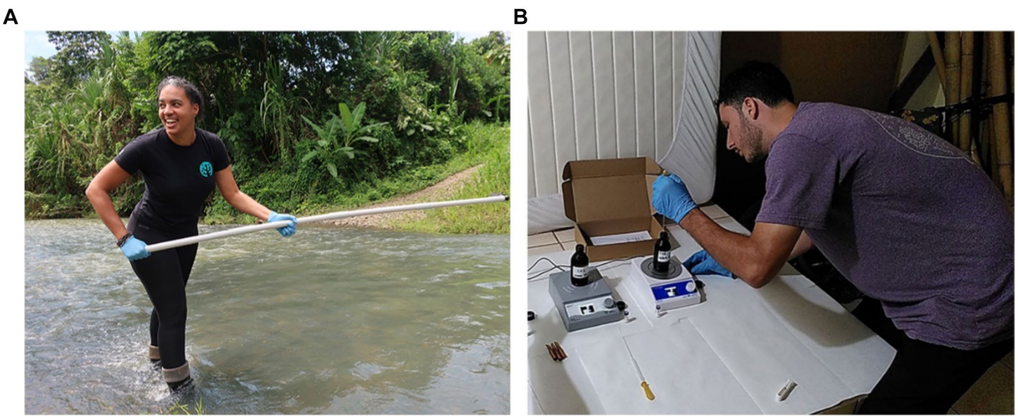

FIGURE 3
Example photos of the March 2023 sampling campaign **(A)** and extraction procedure **(B)** in Puerto Viejo, Costa Rica, as shared by Coral Conservation group.

The method screened 230 pesticides (Supplementary Table S1). The list was updated based on discussions with the Coral Conservation members, who conducted a survey on pesticides commonly used in the local banana plantations ("suggested" in Supplementary Table S1). Fifteen compounds were added including ametryne, azoxystrobin, bitertanol, boscalid, carbaryl, difenoconazole, fenpropidin, fenpropimorph, fluopyram, fluxapyroxad, oxamyl, pyraclostrobin, simazine, thiabendazole and trichlorfon.

3 Results and discussion

3.1 Water analysis

The campaign carried out in March 2023 in the Caribbean area of Costa Rica resulted in the detection of 25 out of 230 pesticides screened, the screening included insecticides (41.7%), fungicides (24.3%) and herbicides (20.0%). Other categories in the

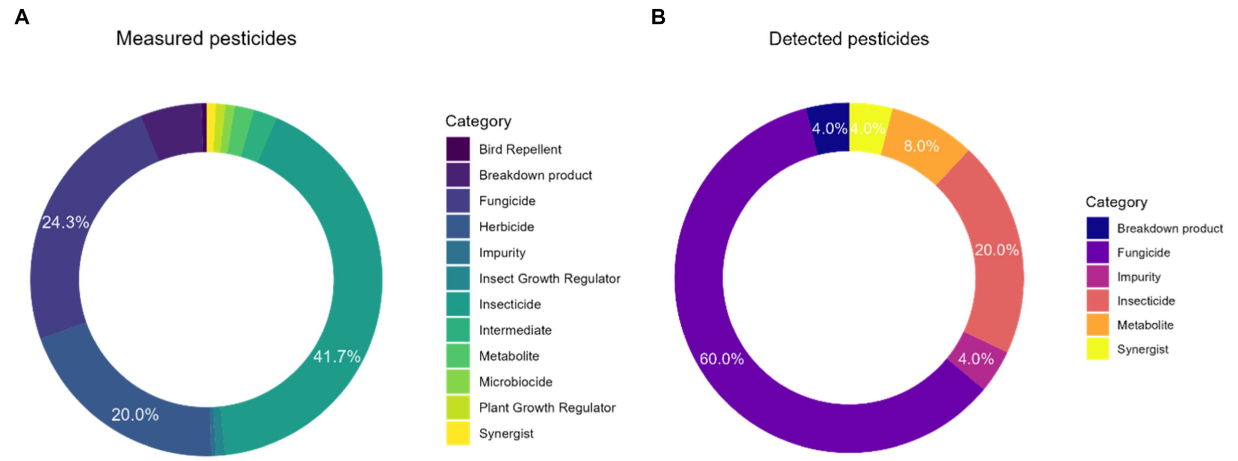

FIGURE 4
Categories of pesticides **(A)** screened in the method (*n* = 230) and **(B)** of pesticides detected (*n* = 25).

method include breakdown products (5.7%) and impurities, synergists and a bird repellant (0.4%) (Figure 4A). The complete list of pesticides screened is available as Supplementary Table S1. In this paper only qualitative results are presented. Pesticides were detected at all sites. Of the 25 detected compounds, 1/4 belonged to the list shared by Coral Conservation (5 fungicides: azoxystrobin, difenoconazole, fenpropimorph, flupyram and thiabendazole). Detected compounds belonged to the classes of fungicides (60%), insecticides (20%), metabolites (8%), synergist, impurities and breakdown products in equal share (4%) (Figure 4B). Previous literature investigating surface waters nearby banana and pineapple plantations in Costa Rica confirms fungicides and insecticides to be the prominent pesticide categories detected (Diepens et al., 2014).

The complete list of detected pesticides and their detection frequency is presented in Figure 5. The most frequently detected fungicides were difenoconazole, flusilazole, fluquiconazole, 2,4,6 tribromoanisole and hexachlorobenzene. Synergist piperonyl butoxide was detected in all samples. Pentachlorobenzene was also detected at all sites (Figure 5). Difenoconazole is a fungicide used on a variety of produce, including fruits, vegetables and cereals; in Europe it is currently in use but listed as candidate for substitution by the end of 2023 as it is considered persistent, bioaccumulative and toxic.[4] Flusilazole is a triazole fungicide, used to control fungal infections and has been used against black sigatoka, a leaf spot disease affecting bananas[5] (CABI, 2022). Flusilazole is not approved for use in European countries, but its use is reported in Australia.[6] 2,4,6-Tribromoanisole is a metabolite of ubiquitous 2,4,6-tribromophenol, which is used as an antifungal agent for wooden pallets, cork and packaging material (Koschier et al., 2011). Penta- and hexachlorbenzene are outdated organochlorine pesticides, listed as Persistent Organic Pollutants in the Stockholm Convention and long banned in European countries and in Costa Rica (Decree 31,997-MAG-S 02/01/2005).[7] These widely banned pesticides are ubiquitous and might be detected in environmental compartments due to legacy issues. Piperonyl butoxide is a synergist used to enhance performance of pyrethroid insecticides.[8] Fungicides difenoconazole, flusilazole, azoxystrobin, epoxiconazole, thiabendazole and fenamiphos have previously been detected in surface waters and sediments both in the Pacific (Rodríguez-Rodríguez et al., 2021) and the Atlantic coasts (Arias-Andrés et al., 2018) of Costa Rica. All mentioned fungicides were detected at the sampling spot located downstream of the Sixaola River, where intensive banana cultivation occurs. Endosulfan, an insecticide, has also been detected previously (Rodríguez-Rodríguez et al., 2021), while in this research it was found in its metabolite form as endosulfan ether.

The site with the highest number of pesticides had 21 out of 25 pesticides detected. At 3 sites a number of detected pesticides in the range of 19–21 was recorded. All 3 of them are located near banana cultivations and 2 of them are located at the downstream reach of the sampled rivers Carbon and Sixaola. Remaining sites resulted in detections ranging from 7 to 17 pesticides. Ten compounds were detected in the upper Estrella River and 17 were detected in the lower reaches. Pesticide traces were also found in sampled groundwaters. A total of 17 compounds were detected in the two wells. In the artisanal well, difenoconazole, fenarimol, fenpropidin, fenpropimorph were detected; these pesticides are commonly used in banana plantations. Additionally traces of bromfenvinphos, hexachlorobenzene and pentachlorobenzene were also detected. In the governmental well, carbophention and flupyram were additionally detected.

4 http://sitem.herts.ac.uk/aeru/ppdb/en/ (Accessed December 13, 2023).
5 https://plantwiseplusknowledgebank.org/doi/full/10.1079/pwkb.species.35304 (Accessed December 13, 2023).
6 http://sitem.herts.ac.uk/aeru/ppdb/en/Reports/350.htm#0 (Accessed December 13, 2023).
7 https://www.sfe.go.cr/SitePages/Registrodesustancias/Estado-de-sustancias-en-registro.aspx (Accessed December 13, 2023).
8 http://sitem.herts.ac.uk/aeru/ppdb/en/Reports/529.htm (Accessed December 13, 2023).

Category	Chemical name	Total frequency (%)
Breakdown product	3,4-Dichloroaniline	60.0
Fungicide	2,4,6-Tribromoanisole	100.0
	Difenoconazole(I)	100.0
	Difenoconazole(II)	100.0
	Flusilazole	100.0
	Hexachlorobenzene	100.0
	Fenarimol	80.0
	Fluquinconazole	80.0
	Pentachloronitrobenzene (quintozene)	66.7
	Fluopyram	60.0
	Fenpropidin	33.3
	Azoxystrobin	20.0
	Fenpropimorph	20.0
	TBZ / Thiabendazole	13.3
	Epoxiconazole (BAS 480F)	6.7
	Pyrimethanil	6.7
Impurity	Pentachlorobenzene	100.0
Insecticide	alpha-BHC	73.3
	Bromfenviphos	53.3
	Carbophenthion	53.3
	Fenpropathrin	53.3
	Fenamiphos	40.0
Metabolite	Pentachloroanisole	60.0
	Endosulfan ether	46.7
Synergist	Piperonyl butoxide	100.0

FIGURE 5
Frequency of overall detection of compounds by pesticide category.

3.2 Scientist-citizen collaborations

3.2.1 Scientists prospective

The first pilot of "The Gems of Water" project provided an opportunity to gain insights and learn important lessons concerning water quality science in collaboration with representatives of local groups or citizens. From the very beginning and design of the activity, quite relevant intention has been put into the creation of content, which resulted in an "instruction manual" for participants. As identified by Rotman et al. (2012), to spark interest and motivate contribution, it is fundamental to produce highly attractive and easily accessible information and training material, especially at the initial phases of citizens engagement. The manual therefore represents a work of translation of scientific knowledge and techniques for water quality monitoring into easy-to-understand language, where additional video links and Spanish translation further expanded accessibility. Creation of material beyond traditional scientific publications is quite a time-consuming activity and one that scientists may not usually do (Metcalfe et al., 2022). Nonetheless, along with communication, proper content creation remains fundamental to fuel and sustainably maintain citizen science projects. Parallel, the development of the method implementing the stir bar for extraction of organic hydrophobic compounds also had to be studied and modified as to become as easy to apply as possible within its scope. Technology and tools were chosen based on their applicability, and the kit was carefully designed to provide a rather complete and accessible laboratory experience to the participants, bringing citizens closer to the scientific environment. Technical and economic feasibility is definitely a criterion to be accounted for when drafting the general plan for a citizen science project. Nonetheless, from "The Gems of Water" project, it remains clear that each sampling program might require *ad-hoc* modification in the method, for instance due to lack of facilities, or difficulties in logistics; therefore, flexibility and adaptability are necessary, and all the while guaranteeing quality assurance. In these cases, it is important to remember the scope of citizen engagement is not merely scientific data collection but enhancing of participation of society in water quality issues and science. The project also highlighted, through lived experiences that failure is to be accounted and can occur at a multiplicity of stages. Logistics pose a tangible challenge to the success of a citizen engagement project. This can be exemplified by the complexitie involved in shipping chemical materials, such as internal standards, which necessitate special packaging and documentation. Additionally, navigating varying customs regulations can be challenging. If packages are not collected within the permitted timeframe, it can result in the chemicals becoming unusable and additional customs charges can be incurred. This underscores the importance of effective communication and precise timing to prevent such failures. Failure can be avoided or amended through transparency in communication, repeated clarification of needs, expectations and timings, simplification of procedures and, ultimately, through trial and error and experience.

Attentive and continuous communication has been repeatedly mentioned throughout the literature as fundamental to retain citizen scientists and to establish an environment of trust (Metcalfe et al., 2022). In this project, this has been achieved by online contact with the group involved through online calls, messaging and emails. In particular, feedback by participants revealed a preference for written communication, as this can reduce language barriers and remove scheduling issues linked to time differences. Updates to the group have been shared with a certain regularity (fortnight to once a month), and transparency was guaranteed in regard to use of materials in conferences or presentations, acknowledging the collaborative work of participants and scientists.

Surveys and an interviews (Data Sheets 1, 2, 3, Supplementary material) have been used to gather views and suggestions on all phases of "The Gems of Water" project and comments have been integrated to improve the communication strategy of the JRC Water Laboratory. Based on feedback survey responses (Data Sheet 2, Supplementary material), the instruction manual was revised to include a section on waste management, which was absent in the initial version. This illustrates the importance of a feedback system between scientists and citizens. From the very definition of the water quality issue, monitoring campaign and timing, the positions of the local groups have been accounted for and respected, thus fostering an equal relationship between scientists and citizens. Such approach must be maintained also when communicating results, clarity should be applied, as those can result in apprehension, to avoid misunderstanding and incorrect conclusions (Buytaert et al., 2014). This strategy has been proven successful in other citizen science projects, allowing community to play a central role in the scientific investigation (Yevenes et al., 2022). Indeed, time management is another key aspect in the design of citizen science projects, especially when involved groups are mainly volunteers, whose motivation to participate can change dynamically (Rotman et al., 2012). Harmonizing the times and expectations of the stakeholders involved can again be done through proper communication and effort on both sides, to avoid incurring complications.

3.2.2 Citizens prospective

Simple, direct and fluent communication between "The Gems of Water" and Coral Conservation was crucial for the success of the project. Given a basis of mutual understanding, the activity contributed to breaking one of the challenges of citizen science, namely that of establishing considerate and transparent communication between scientists and local people. Within the Coral Conservation team, an individual was appointed to design the work plan and distribute tasks. During the research process and project definition four team members were directly involved, while an additional four supported the sampling.

Sampling points were primarily selected based on the proximity of the banana plantations; with locations chosen in the upper, middle and lower catchment of each river. As for water wells, one was a private artisanal well located in a house close by a banana plantation, and the other well was a government drinking water distribution well. The list of pesticides of interest was created based on the official list of the Phytosanitary Service of Costa Rica[9] focusing on pesticides commonly used on bananas. Pesticides permitted in the country were excluded from the list. However, these compounds could be considered for future updates to the list of screened pesticides.

For the volunteers of Coral Conservation involved in "The Gems of Water" project, the engagement activity served as a significant learning experience. Beyond acquiring practical skills needed for sampling and extraction activities, the participants reported gaining an understanding of the complexities involved in establishing a monitoring plan, as well as the level of preparation and organization required. Specifically, the group had to devise creative solutions to address challenges such as building an additional sampling pole and modifying the sampling strategy once a pre-determined location became inaccessible. The experience fostered group cohesion as they navigated new and challenging situations together.

Looking forward, the Coral Conservation team has contacted several organizations that have made similar efforts and participated in similar engagement activities. The idea is to create alliances and to,

9 https://www.sfe.go.cr/SitePages/Inicio.aspx (Accessed December 13, 2023).

respectively, inform and share experiences and outcomes. Through cooperating and sharing of results with others, the hope is to find creative solutions for water quality management and coral conservation. Receiving the results of this research activity was a greatly exciting moment for the Coral Conservation team and represents an important social responsibility to start a dialogue on water quality with the local community and the government institutions involved. A communication strategy and plan for scientific dissemination are being prepared and are expected to be carried out in 2024.

Looking beyond, at a community level, future effort could involve building an alliance with the Carbon River banana company, located nearby where the majority of samples were collected, to support and encourage containment measures for agrochemical-linked pollution and to prevent agricultural-runoff from directly affecting the Estrella River. Furthermore, a second sampling campaign is desirable to sample thoroughly and to acquire accurate information on the high-flow Estrella and Sixaola rivers.

3.3 Outcomes

The tangible outcomes of the joint work strive to be as diverse as possible, to strengthen the outreach of the data collected, the impact and the feedback loop of the project. The data has been shared with the citizen scientists through online meetings, followed by questions and discussions, as well as raw data accompanied with a written interpretation. The first goal is the sharing of qualitative data on pesticide detections, simple statistics, monitoring map, photos and a short description of the project on a dashboard, which will be made accessible on the website of the World Water Quality Alliance and of the Joint Research Centre of the European Commission. This format is chosen not only for its user-friendly and easy-to-share character, but also to transmit the impacts and contribution of citizen science, by capturing experiences in story telling (Wehn et al., 2021). Other conventional outcomes include the drafting, jointly with the participants, of scientific publications on the produced data and on the citizen-engagement activity. On the ground, with the local community, online and in-person workshops are to be organized to share the results and collect ideas on the possible actions to be taken to prevent or amend water quality contamination in the region. Finally, in collaboration with the SciArt team of the JRC, artists are working to transform detected compounds in art forms to trigger interest and educate on water quality degradation and its solutions and to spark new ideas in scientists engaged in water quality monitoring.[10]

4 Conclusion

Looking forward requires identifying limitations and potential improvements of "The Gems of Water" project. The stir bar technique coupled with GC–MS in grab sampling schemes provides information on a variety of compounds present in the limited sample volume at a specific moment in time; therefore, both qualitative and quantitative analysis are not enough for making conclusions on contamination and do not have any legal value. Additionally, because of the physico-chemical characteristics of the stir bar coating only hydrophobic compounds can be detected, while some compounds (i.e., phthalates) are excluded from detection due to the high potential of cross-contamination. On the other hand, the ease of implementation makes the stir bar very apt for citizen engagement projects, simplifying laboratory procedures and logistic organization. Therefore, this technique seems to represent a compromise between data collection and citizen science. Not only does "The Gems of Water" enhance collaboration between scientists and citizens, creating a truly collaborative environment of water quality monitoring; with the wide-screening approach of the stir bar, it also represents an alternative way to identify contamination issues. This aspect combined with previously recognized advantages of citizen science, economic feasibility and wider spatial and temporal distribution (Hadj-Hammou et al., 2017; Hegarty et al., 2021; Metcalfe et al., 2022), make such activity a powerful tool, which could help to identify localized water quality issues and to prioritize monitoring focus in communication with stakeholders such as governmental authorities, through a bottom-up approach. Further research should focus on improving the stir bar application for citizen science around the world by further simplifying logistics and by automating the data analysis process. More research and development could be invested to provide complementary detection technology to the stir bar method, thus expanding wide screening to polar compounds. This could facilitate reproduction of pilot cases in other locations and communities, creating hubs of wide screening water quality monitoring on the ground, independent from high-level monitoring schemes. On citizen science side, the results should trigger proposal for action, such as nature-based solutions, which can help address water quality contamination, while a strategy for measuring impact of such data collection and of responsive actions on the ground is to be implanted. The collaboration described in this paper was the first pilot experiment with citizen scientists of "The Gems of Water" project. It has shown its potential as well as its limitations and it stands as a starting point to improve both the methodology and engagement strategy and training. The project is currently being trialed with other citizen scientist groups around the world and the collection of experiences and results should provide insightful information into its upscaling and feasibility.

10 https://science-art-society.ec.europa.eu/ghosts-anthropocene, https://science-art-society.ec.europa.eu/these-relations-are-forever

Data availability statement

The datasets presented in this article are not readily available because datasets are planned to be shared on publicly accessible repository in the future. Requests to access the datasets should be directed to caterina.cacciatori@ec.europa.eu.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

CC: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft. GM: Formal analysis, Investigation, Methodology, Software, Supervision, Writing – review & editing, Validation, Conceptualization, Project administration. SC: Data curation, Visualization, Writing – review & editing. DM: Investigation, Writing – review & editing. MC: Investigation, Writing – review & editing. JB-T: Investigation, Writing – review & editing. JG: Investigation, Writing – review & editing. ST: Writing – review & editing. RM: Writing – review & editing. JM: Supervision, Validation, Writing – review & editing. VP: Supervision, Validation, Writing – review & editing. BG: Writing – review & editing, Project administration, Resources, Supervision, Validation, Conceptualization.

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Conflict of interest

The 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 TS declared a past co-authorship with the authors CC, GM, ST, and BG.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2024.1358959/full#supplementary-material

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