Science of the Total Environment 874 (2023) 162527

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Monitoring contaminants of emerging concern in aquatic systems through the lens of citizen science

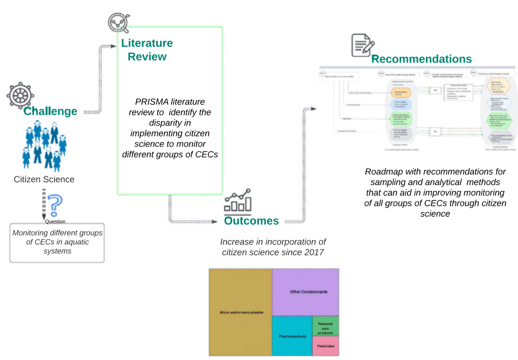
Nandini Vasantha Raman [a,*], Asmita Dubey [a], Edward Millar [b], Veronica Nava [c], Barbara Leoni [c], Irene Gallego [d]

[a] Department of Aquatic Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Droevendaalsesteeg 10, 6708 PB Wageningen, the Netherlands
[b] Environmental Applied Science and Management, Toronto Metropolitan University, 350 Victoria Street, Toronto, ON, Canada
[c] Department of Earth and Environmental Sciences, University of Milano-Bicocca, Piazza della Scienza 1, 20126 Milano, MI, Italy
[d] Department of Aquatic Ecology, Swiss Federal Institute of Aquatic Science and Technology (EAWAG), Überlandstrasse 133, 8600 Dübendorf, Switzerland

HIGHLIGHTS

- Citizen participation to monitor CECs in aquatic systems is increasing since 2017.
- Disparity in implementing citizen science to monitor various groups of CECs exists
- CS is a powerful tool to tackle lack of data on environmental concentration of CECs.
- Roadmap summarizes methods to improve monitoring of CECs through citizen science.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damia Barcelo

Keywords:
Emerging contaminants
Micropollutants
Microplastics
Community science
Community participation
Volunteer participation

ABSTRACT

Global urbanization trends have led to the widespread increasing occurrence of contaminants of emerging concern (CECs) such as pharmaceuticals, personal care products, pesticides, and micro- and nano-plastics in aquatic systems. Even at low concentrations, these contaminants pose a threat to aquatic ecosystems. To better understand the effects of CECs on aquatic ecosystems, it is important to measure concentrations of these contaminants present in these systems. Currently, there is an imbalance in CEC monitoring, with more attention to some categories of CECs, and a lack of data about environmental concentrations of other types of CECs. Citizen science is a potential tool for improving CEC monitoring and to establish their environmental concentrations. However, incorporating citizen participation in the monitoring of CECs poses some challenges and questions. In this literature review, we explore the landscape of citizen science and community science projects which monitor different groups of CECs in freshwater and marine ecosystems. We also identify the benefits and drawbacks of using citizen science to monitor CECs to provide recommendations for sampling and analytical methods. Our results highlight an existing disparity in frequency of monitoring different groups of CECs with implementing citizen science. Specifically, volunteer participation in microplastic monitoring programs is higher than volunteer participation in pharmaceutical, pesticide, and personal care product programs. These differences, however, do not necessarily imply that fewer sampling and analytical methods are available. Finally, our proposed roadmap provides guidance on which methods can be used to improve monitoring of all groups of CECs through citizen science.

* Corresponding author.
E-mail address: N.Raman@nioo.knaw.nl (N. Vasantha Raman).

http://dx.doi.org/10.1016/j.scitotenv.2023.162527
Received 23 December 2022; Received in revised form 8 February 2023; Accepted 24 February 2023
Available online 2 March 2023

Contents

1. Introduction

Among the numerous global change stressors, occurrences of contaminants of emerging concern (CECs), i.e., chemicals or materials "*naturally occurring, manufactured or whose toxicity or persistence are likely to significantly alter the metabolism of a living being*" (Sauvé and Desrosiers, 2014), have increased in aquatic ecosystems in the past two decades (Loos et al., 2013). A heterogeneous diverse group of contaminants falls under the category of CECs, such as pharmaceuticals, personal care products, pesticides, microfibers, and micro- and nano-plastics, which are globally distributed and have toxic effects in aquatic organisms. Accumulation of CECs has been observed in wastewater treatment plants that receive effluent from industries, households, and hospitals (Gogoi et al., 2018; Pulido-Reyes et al., 2022). It is highly likely that CECs are similarly present in almost all water supplies across the world, though perhaps not in the same concentrations as has been found in treatment plants. For instance, human and veterinary pharmaceuticals have been reported in water bodies of 71 countries (aus der Beek et al., 2016). Measurements have shown high pharmaceutical levels in waterways, including the detection of acetaminophen in U.S. streams at 10 μg/L (Kolpin et al., 2002). Non-pharmaceutical CECs have also been quantified at high levels. For example, very high concentrations of the pesticide propiconazole were detected in the Tengi river basin, Malaysia (Elfikrie et al., 2020) and octahydro-tetramethyl-naphthalenyl-ethanone (a fragrance-personal care product) showed concentrations of 21.5 μg/L in sewage treatment plant effluent in Bavaria, Germany (Klaschka et al., 2013).

Field monitoring of CECs in aquatic systems is often challenging because of the unstable and reactive nature of contaminants. Disparity in stability between different categories of CECs is well known, with the more stable CECs (e.g., micro and nano-plastics) usually being better monitored in aquatic systems in comparison with unstable and reactive CECs (i.e. pharmaceuticals and pesticides). Monitoring to determine the concentration of CECs in aquatic systems is often a two-step process. First, participants are tasked with sampling (i.e. collection of samples of interest in which the CEC is being monitored). Second, there is an intensive screening or analysis of samples, either by the participant or by a laboratory. Monitoring often also involves storage and transportation as intermediate steps. Another challenge is that CECs and their transformation products are bioactive at environmental concentrations and can therefore affect non-target aquatic organisms (Maruya et al., 2016). For example, antibacterial triclosan (a component of personal care products) has a half maximal effective concentration (EC_{50}) of 390 μg/L in *Daphnia magna* along with an EC_{50} of 1.4 μg/L and no observed effect concentration (NOEC) of 0.69 μg/L in 96 h- green alga *Scenedesmus* sp. Biomass (Orvos et al., 2002). Similarly, the antidepressant fluoxetine affects the reproduction of the freshwater snail *Potamopyrgus antipodarum* at concentrations below 1 μg/L (Nentwig, 2007). A lack of comprehensive knowledge about the measured environmental concentrations (MECs) of these contaminants has made it difficult to understand their effects on the health status of aquatic systems, a problem which has been identified by the Water Framework Directive (Geissen et al., 2015). National level surveys and monitoring are not standardized across European countries, and there is an urgent requirement for a more coordinated approach for monitoring (Geissen et al., 2015).

Community participation can be of great importance in monitoring the CECs in aquatic systems globally, ultimately aiding in the achievement of good water status for both human and aquatic ecosystem health. While public participation in freshwater monitoring predates the popular use of the term "citizen science" by several decades, community-based water monitoring (CBWM) has also been folded into the broader citizen science concept (Buckland-Nicks et al., 2016; Buytaert et al., 2014; Stepenuck and Genskow, 2019). CBWM groups deploy a range of methodologies and tests for monitoring a suite of biological, chemical, and physical parameters (T. Carlson and Cohen, 2018). Citizen science is often beneficial in cases where there are gaps in the monitoring programs of governmental agencies (Buytaert et al., 2014; Garda et al., 2017; San Llorente Capdevila et al., 2020).

The term citizen science covers a broad spectrum of participation methods, ranging from "citizen sensing" initiatives, in which volunteers are recruited as potential sensors and recorders of ambient environmental conditions (Gabrys, 2019), to "community science" (Carr, 2004; Cooper et al., 2021) or "street science" (Corburn, 2005), in which more active contributions are solicited from communities and where environmental monitoring becomes enmeshed with the goals and principles of environmental justice (L. F. Davis and Ramírez-Andreotta, 2021). Public participation in water monitoring can fit under multiple models of citizen science, from "top-down" models of participation where members of the public can be recruited as volunteers and trained in field methods that have been determined in advance by professional scientists, to "bottom-up" methods where participants take more active roles in all stages of the project from design to completion (Conrad and Hilchey, 2011; Shirk et al., 2012; Wilderman et al., 2004).

While the capability to detect CECs has increased in the past few decades due to advancements in technology, the potential for widespread monitoring of CECs by CBWM groups appears to be untapped. Although largely unregulated in comparison to conventional pollutants, there is a growing social and political interest in the monitoring of CECs, at least in regard to drinking water quality (Valbonesi et al., 2021). For example, the United States Environmental Protection Agency (EPA) has instituted actions to understand and mitigate the presence of perfluoroalkyl and polyfluoroalkyl substances (PFAS) in drinking water (EPA 2022). Similarly, the revised European Directive 2020/2184 identifies emerging pollutants in some supply sources as well as in drinking water (Dettori et al., 2022) while the Directive 2015/495/EU published a Watch List encompassing 17 CECs (Sousa et al., 2019).

In this literature review, we first aimed to explore the extent to which citizen science has been employed over the past two decades (2000 − 2021) to assess water pollution from CECs in marine and freshwater systems. Secondly, we examined the benefits and drawbacks of incorporating citizen science in CEC monitoring of both freshwater and marine systems and identified the main challenges faced while implementing citizen participation in monitoring CECs. Furthermore, by identifying existing gaps in the monitoring of various CEC groups, we can build a roadmap to assist with recommending methods for filling gaps with citizen participation. Additionally, a comprehensive roadmap can also assist with depicting global occurrence of CEC groups in aquatic ecosystems.

2. Methodology

2.1. Literature search

Our literature review followed the PRISMA method (see Fig. 1) and was carried out using multiple search engines (Web of Science, worldcat.org, Springer, Taylor & Francis, ScienceDirect), with searches occurring between 13/02/2021 and 14/04/2021 (Moher et al., 2009). We performed basic searches using two different search terms linked by the "AND" connector. The first term included any of the four terms related to community science that we have defined in the Glossary (Appendix B): *"Citizen Science", "Citizen Sensing", "Community Science"* or *"Community based Monitoring"*. The second term included keywords related to chemicals, particles and/or products with a negative impact on aquatic ecosystems (see Glossary for definitions). A total combination of 4 × 10 categories was used for the basic searches (e.g., *"Community Science"* AND *"Microplastics"*). Each combination of search terms was independently sought by two different members to cover potential underestimations due to limited access to the full references.

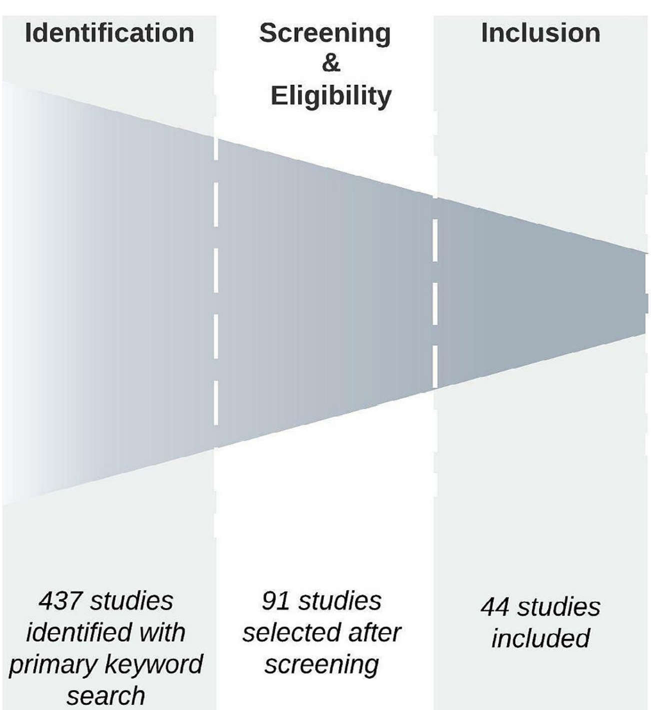


Fig. 1. Diagram illustrating the steps followed in the process of literature selection.

For an article to be eligible for consideration, there were six criteria: 1) the article must be written in English; 2) the article must be published in a journal, regardless of open access status; 3) the article must have been published in last 20 years (between 2000 and 2021); 4) the article must describe a program which monitors CECs in aquatic compartment; 5) the article must discuss the select CECs as outlined in the introduction; and 6) the article must describe the implementation of citizen science methods for CEC monitoring, or must discuss the potential for citizen science methods to be used for monitoring CECs in aquatic compartments. An article was excluded when: (1) it focused on environmental compartment other than water; (2) the parameters monitored were not micropollutants (for example: phosphorus, nitrogen, turbidity, and shoreline assessment); (3) the article focused on the monitoring of CECs outside the scope of the study, such as macroplastics and marine debris.

2.2. Checklist and screening

Articles gathered from the literature search were screened in two stages to select the relevant articles for addressing our research questions. An article was only selected if the answer was 'YES' for all three primary criteria: *"Aquatic Compartment", "Citizen Science"* and *"Emerging Contaminant"*. Checklists that were designed based on our research questions were used for both screening phases. We classified each of the three primary criteria into different categories. For instance, the aquatic compartment criterion was split into categories of 'river', 'lakes', 'ponds', 'groundwater', 'ocean' and 'estuary'. On the other hand, when it comes to screening an article based on the 'citizen science' criterion, we split the articles into two categories. One category included articles which describe existing programs that actively use citizen science methods to monitor one or more groups of CECs. The second category included articles which discuss methods for monitoring CECs that could potentially be expanded to include citizen science, even if no active or existing citizen science project was described. A special designation was made when the article discussed citizen science approaches associated with a larger monitoring program. All of the screened articles were further categorized based on different groups of CECs, such as 'micro- and nano-plastics', 'pesticides', 'pharmaceuticals', 'personal care products', and 'others'. The selected references were later reviewed to discard potential false positives. Lastly, once we selected our set of articles, we evaluated existing gaps in implementation of citizen science to monitor selected CEC groups.

3. Results

The primary literature search with selected keywords was carried out taking into account both inclusion and exclusion criteria (see Section 2.1). A total of 437 studies were compiled from the primary keyword search, with most articles being studies of original research. The inclusion of citizen science for monitoring CECs has increased exponentially since 2016. Out of our 437 studies compiled, we selected 91 studies that fulfilled at least one of our first set of criteria, i.e. *"Aquatic Compartment", "Citizen Science "* and *"Emerging Contaminant"*. We found that 47 articles (out of 91) did not fulfill all our primary criteria. These false positives mostly focused on macro-contaminants (e.g., macroplastics, nutrients, heavy metals) or on environmental litter (e.g., beach litter or shoreline debris). The remaining 44 articles (see Appendix A) focused on the monitoring of one or more of the CEC groups in aquatic systems by implementing or testing potential citizen participation methods over the past two decades (2000 to 2021). Fig. 2 shows the distribution of the selected articles over time (A), by aquatic compartment classification (B), and by type of contaminants of emerging concern (C). In further sections, we review current citizen science approaches for monitoring CECs (see Section 3.1), the proportion of programs which focused on different categories of CECs (see

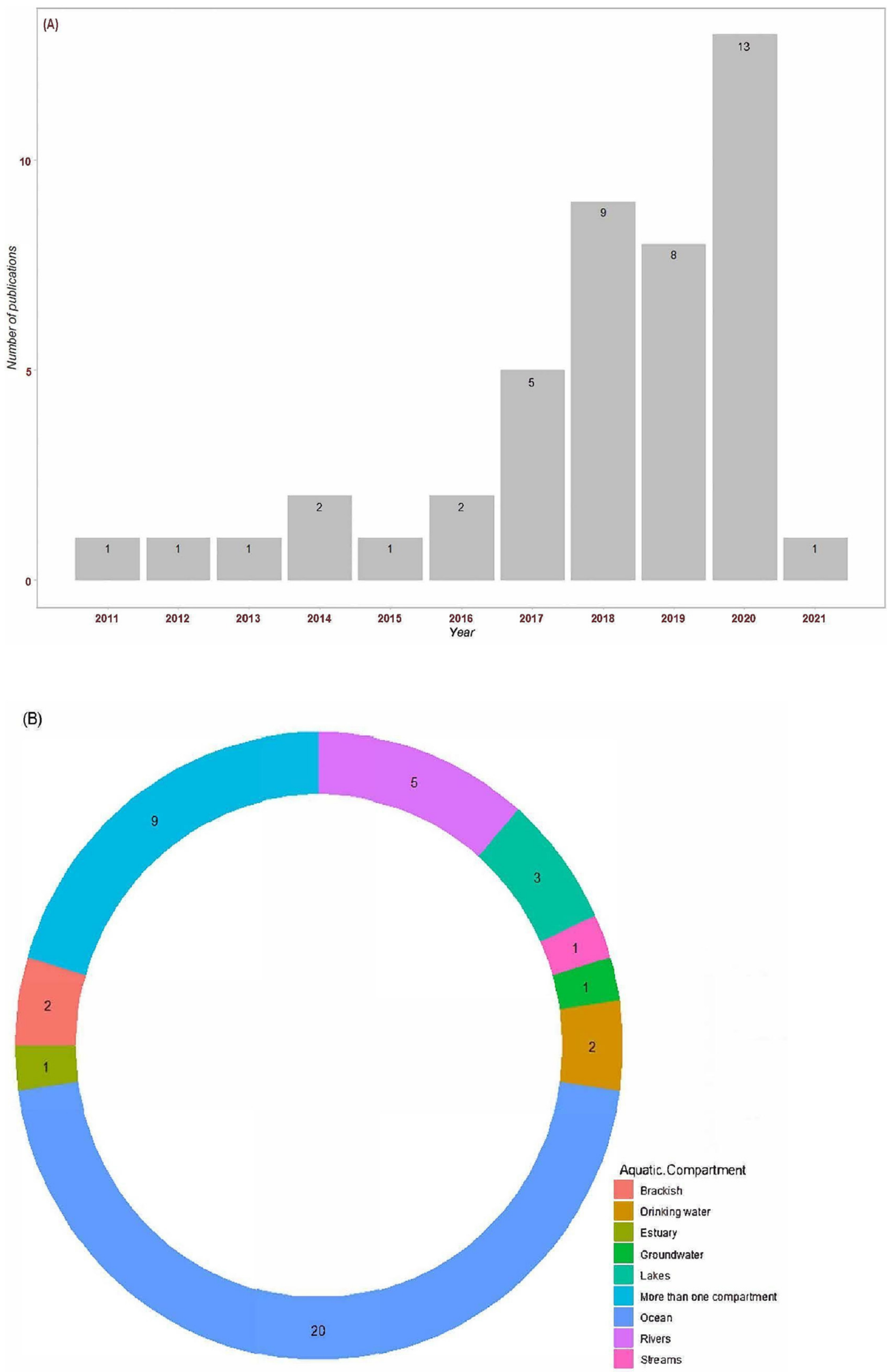


Fig. 2. Distribution of 44 selected articles from literature search based on: (A) total number of articles published per year between 2000 and 2021; (B) total number of articles focusing on different aquatic compartments; and (C) total number of articles focusing on different categories of contaminants of emerging concern.

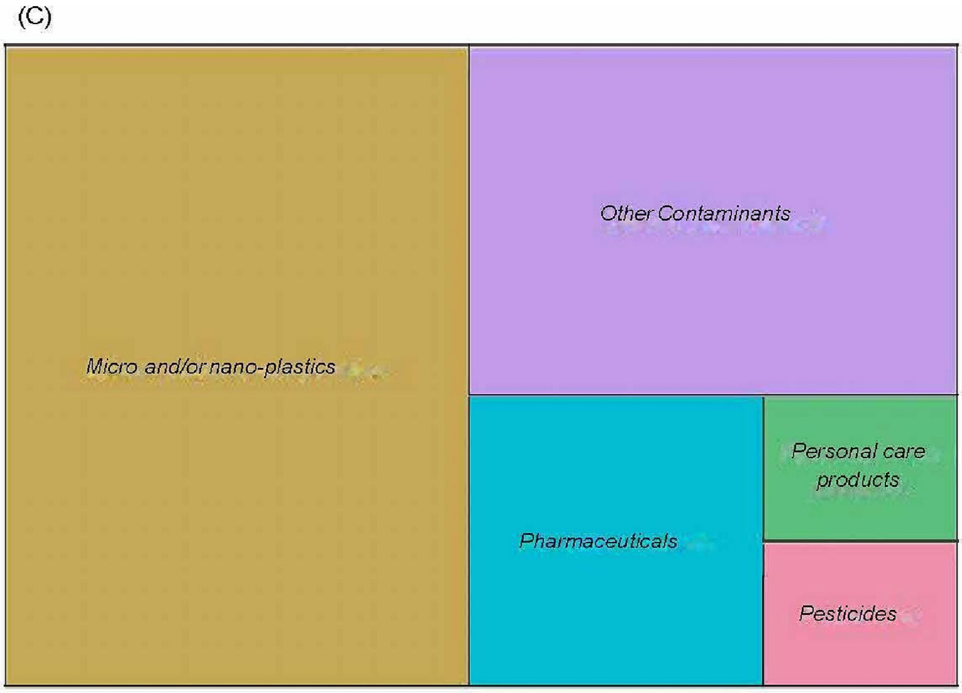


Fig. 2 (*continued*).

Section 3.2), and the challenges that these programs encountered (see Section 3.3). Following this, we also highlight the benefits and drawbacks of monitoring contaminants of emerging concern with active participation of citizen scientists (see Section 3.4).

3.1. Current status of the use of citizen science to monitor CECs

Citizen science methods in aquatic ecosystems frequently require that volunteers perform the less intensive first step in monitoring, i.e., collecting water samples and mailing them to a laboratory for analysis by trained professionals. This less intensive sampling can be used to monitor the presence of CECs and can include methods such as grab sampling, active sampling, and passive sampling. In some cases, citizen scientists conducted in situ counts and classifications of debris by type (Carbery et al., 2020). This method can be tailored so that it can be performed by volunteers with varying levels of training and skill. Another example of a similar monitoring situation was carried out as a part of the International Pellet Watch (IPW) project, which recruited volunteers from middle school science classes (Grade 7) to count beached plastic resin pellets as indicators of pieces of plastic (Dohrenwend, 2012). Such visual identification and classification of CECs is common in coastal monitoring projects, however this is only possible for CECs which are visible to the human eye, such as microplastics.

In the Salish Sea in Washington State, the regional science center coordinated 600 citizen scientists from 16 local community groups to conduct biannual sampling of sandy beaches. These samplings were done in quadrants using sieves and buckets. Concurrently, field site data was gathered including GPS, photographs, sketches, and field notes (W. Davis and Murphy, 2015). After collecting samples, volunteers joined laboratory technicians with sample processing (i.e. drying, sorting, counting and weighing of beach debris) and classifying into eight categories (i.e. fragments, foams, pellets, films, filament, cigarette butts, glass, and other) (W. Davis and Murphy, 2015). Microplastics can also be sorted and classified by volunteers according to qualitative categories based on color or shape before samples are sent to a laboratory to be analyzed by polymer type (ATR-FTIR) or concentrations of metals (ICP-MS) (Carbery et al., 2020).

For nearshore sampling of microplastics, volunteers can collect water samples with a Nitex® nylon mesh and Whirl-Pak® bags, and send these samples to the laboratory (Forrest et al., 2019). If citizen scientists have experience with aquatic vehicles, water trawls can be an effective sampling method in open water. "Surfrider Spain", a sub-group of the organization Surfrider Foundation Europe, designed a paddle trawl, or a low-cost manta trawl which can be used by paddle surfboarders to sample nearshore floating microplastics (Camins et al., 2020). After installing the free mobile app "The Wikiloc Outdoor" (Wikiloc, 2021), the surfer's phone automatically records geolocation data (latitude, longitude, time, distance traveled), while paddling along a transects of 30 min to 1 h. After rinsing with freshwater, the samples are transferred into a glass container and sent to the laboratory, where particles are then classified by size and shape (Camins et al., 2020).

Recruiting outdoor recreationists and experienced adventurers allows scientists to sample locations that would be more challenging for untrained citizen scientists to access. Adventure Scientists recruited and trained 120 outdoor recreationists to collect 1 L grab samples in the Gallatin River watershed in Montana (USA) over the course of two years (Barrows et al., 2018b). Volunteers entered information including time, GPS coordinates, field site data and notes (water temperature, depth, substrate type, presence/absence of exposed rocks) using a field datasheet and a smartphone application. Additionally, citizen scientists completed a questionnaire about their sampling technique and provided photographs of their clothing to assess potential sources of sample contamination. Samples were sent to a laboratory for processing and analysis using vacuum filtration and a stereo microscope (Barrows et al., 2018a).

In addition to microplastics and debris monitoring, citizen scientists have participated in monitoring of herbicides, pesticides, pharmaceuticals, and organic micropollutants. One study in Omaha, Nebraska (USA) recruited 136 citizen scientists across 3 different groups based on experience levels (expert, experienced, and inexperienced) to test for the presence or absence of the herbicide atrazine. Participants used test strips (Abraxis®) with a detection threshold of 3 ppb (Ali et al., 2019).

Some studies explore the potential to leverage advancements in artificial intelligence and Internet-based technologies to assist with citizen science efforts. For instance, mobile applications can allow citizen scientists across the globe to identify and tag plastic litter and debris (Emmerik and Schwarz, 2020). Automated image recognition techniques can be used to detect microplastic concentrations in aquatic environments (Bean et al., 2017). These approaches also make it possible to trace the breakdown of macroplastics to micro- and/or nanoplastics along the riverbanks and shoreline. Another approach towards implementing community participation in monitoring CECs is the one followed by "The Open Litter Map project" (OpenLitterMap, 2022), which has attempted to capitalize on the trend towards "web3" technologies. Specifically, this project offers a blockchain-based "Littercoin" award token to participants who have undergone verifications from experienced volunteers. Gathered data is used as training for machine-learning algorithms that perform automated image recognition (Lynch, 2018).

3.2. Variations in monitoring different groups of CECs

Our literature review showed that 21 out of the 44 screened articles focused on monitoring microplastics (see Fig. 2C). This suggests that not all groups of CECs receive equal attention while monitoring aquatic systems. Factors such as the stability of the compound, the half-life or degradation kinetics may have an influence on the types of the CECs that are monitored. Acknowledging the higher quantity of microplastics monitoring, in this section we review the approaches currently applied to monitor CECs in two groups i.e. microplastics and other CECs.

3.2.1. Microplastics

Microplastics are the most monitored of our chosen CEC groups because of their relatively stable and inert properties, thereby making sampling and storage of microplastics less complicated in comparison to more reactive CECs. Various groups of community scientists are actively involved in sampling microplastics, including "adventure scientists" (Barrows, Christiansen, et al., 2018), paddle surfers (Camins et al., 2020), students (Syakti et al., 2017) and other volunteers (Carbery et al., 2020; W. Davis and Murphy, 2015; Gewert et al., 2017). The size of microplastics that were monitored ranged from microfibres of 100 μm in marine environments (Barrows et al., 2018a) to 5 mm long threads in rivers (Barrows et al., 2018b). Along with the size, physico-chemical properties of microplastics are taken into account, including density, color, shape and polymeric composition (Camins et al., 2020; Carbery et al., 2020; Forrest et al., 2019; Pakhomova et al., 2020). The articles we reviewed in our literature search emphasized that the analysis of microplastics requires technical expertise, and specialist equipment that would often be outside the capacity of smaller community-based water monitoring groups and citizen scientists. Techniques used for analysis frequently include Fourier Transform-Infrared Spectroscopy (FTIR) (Barrows et al., 2018a; Barrows et al., 2018b; Camins et al., 2020; Carbery et al., 2020; Forrest et al., 2019; Syakti et al., 2017) and stereo microscopy with staining (Nel et al., 2020).

3.2.2. Other CECs

While pesticides, pharmaceuticals, and personal care products are biologically active and persistent, they are less monitored in comparison to microplastics. The disproportionate monitoring for these CECs is due to the physico-chemical properties of the compounds, particularly that they are highly unstable in storage. Sampling requires the use of organic solvents which are toxic and volatile, thereby requiring application of safety measures (Levet et al., 2016), which may also create barriers for citizen science groups.

However, in our literature review, we observed an increasing trend in recent years (beginning in 2019) towards the implementation of community participation for monitoring organic, biologically active and persistent CECs (i.e. pesticides, pharmaceuticals, and personal care products). The sampling methods implemented range from using test strips for the qualitative determination of atrazine (an agrochemical CEC) (Ali et al., 2019) to uniform test collection kits to sample 61 targeted pharmaceuticals (Wilkinson et al., 2019). When it comes to personal care product CECs, such as titanium dioxide (TiO_2), simpler monitoring activities have been carried out such as identifying TiO_2 in ingredients listed on packages of toothpaste (Wu and Hicks, 2020).

3.3. Challenges encountered while incorporating citizen science in CEC monitoring

In our literature review, we recognized four challenges when citizen participation was applied for CEC monitoring, varying from 1) the assurance of quality data during sampling, 2) transportation or storage of CECs, 3) the level of experience of citizen scientists, and 4) identifying channels for influencing policy and regulatory contexts.

The first challenge while incorporating citizen participation in monitoring CEC in aquatic systems is the lack of quality data and that must be assured by developing clear protocols (Hidalgo-Ruz and Thiel, 2013). Methodological differences between sampling campaigns are common due to technical or human differences (Gewert et al., 2017). Errors caused by the latter can be minimized by attending an in-person refresher on project protocols before each sampling campaign (Barrows et al., 2018a; Barrows et al., 2018b). Another method that can ensure quality assurance can be providing self-assessment questionnaires about the sampling event, or asking for vouchers to that can assist with the data interpretation stage, for instance, asking volunteers to share a picture of the clothing worn while sampling (especially while sampling to monitor microfibres) (Barrows et al., 2018a; Barrows et al., 2018b). Different CECs might need advanced sampling methods. In the case of microplastics, difficulties with collecting, sorting, and distinguishing plastics from other marine debris and materials have been reported (Zettler et al., 2017). Providing detailed instructions that clearly outline sampling methods in language that is accessible to volunteers can help to minimize these issues (Lots et al., 2017).

Secondly, transportation and storage of samples play a critical role in the stability of certain CECs such as pharmaceuticals, pesticides, and many categories of personal care products. Volunteers reported problems with the technology used to assist in data collection while out sampling in the field, due to either programming errors in the application or user errors, but these obstacles can be overcome by guiding the participants through application use and creating systems to permit the use of paper back-ups in cases where data collection technologies fail (Barrows et al., 2018b). To overcome this challenge, scientists must be concise and clear with the instructions, and consider adopting simpler protocols that are easiest for volunteers to follow, and which minimize opportunities for volunteer error.

Thirdly, participants' prior experience with tools to detect and quantify CECs might correlate with the accuracy of the result. One study observed differences in accuracy based on users' experience when they were provided with colorimetric test strips to quantify inorganic pollutants and to detect herbicides in water (Ali et al., 2019). Participants with no previous laboratory experience were more likely to overestimate nitrate and phosphate concentrations when compared to expert participants. Also, they were more likely to report false positives in qualitative tests to detect atrazine. Training the volunteers to ensure that they will succeed in their tasks is an important step and might overcome the problem arising with the lack of experience (Ali et al., 2019). In another study, a significant deviation was recorded when riverine litter composition (including plastics) along courses of 4 rivers (Elqui, Maipo, Maule, and BioBio) in Chile were determined by expert professional and citizen scientists (Rech et al., 2015).

Finally, identifying proper channels to make data available for policy makers is a major challenge (T. Carlson and Cohen, 2018). Until 2016, citizen science was not fully embedded within public agencies (Cunha et al., 2017). Maintaining institutional support needed for long-term program endurance is important for the successful and ongoing operations of community-based water monitoring and aquatic citizen science.

3.4. Benefits of incorporating citizen science in monitoring CECs

Citizen science is usually implemented to increase the amount of data generated and the geographical reach of the study. Barrows et al. (2018a, 2018b) obtained global patterns of microparticle distribution and concentration by implementing citizen science protocols in marine environments over 5 years. Microplastics hotspots in the southeastern-United Kingdom was identified in collaboration with the volunteers from 'Clean Seas Odyssey' (*Expedition | Clean Seas Odyssey*, Expedition, 2021) Nel et al. (2020).

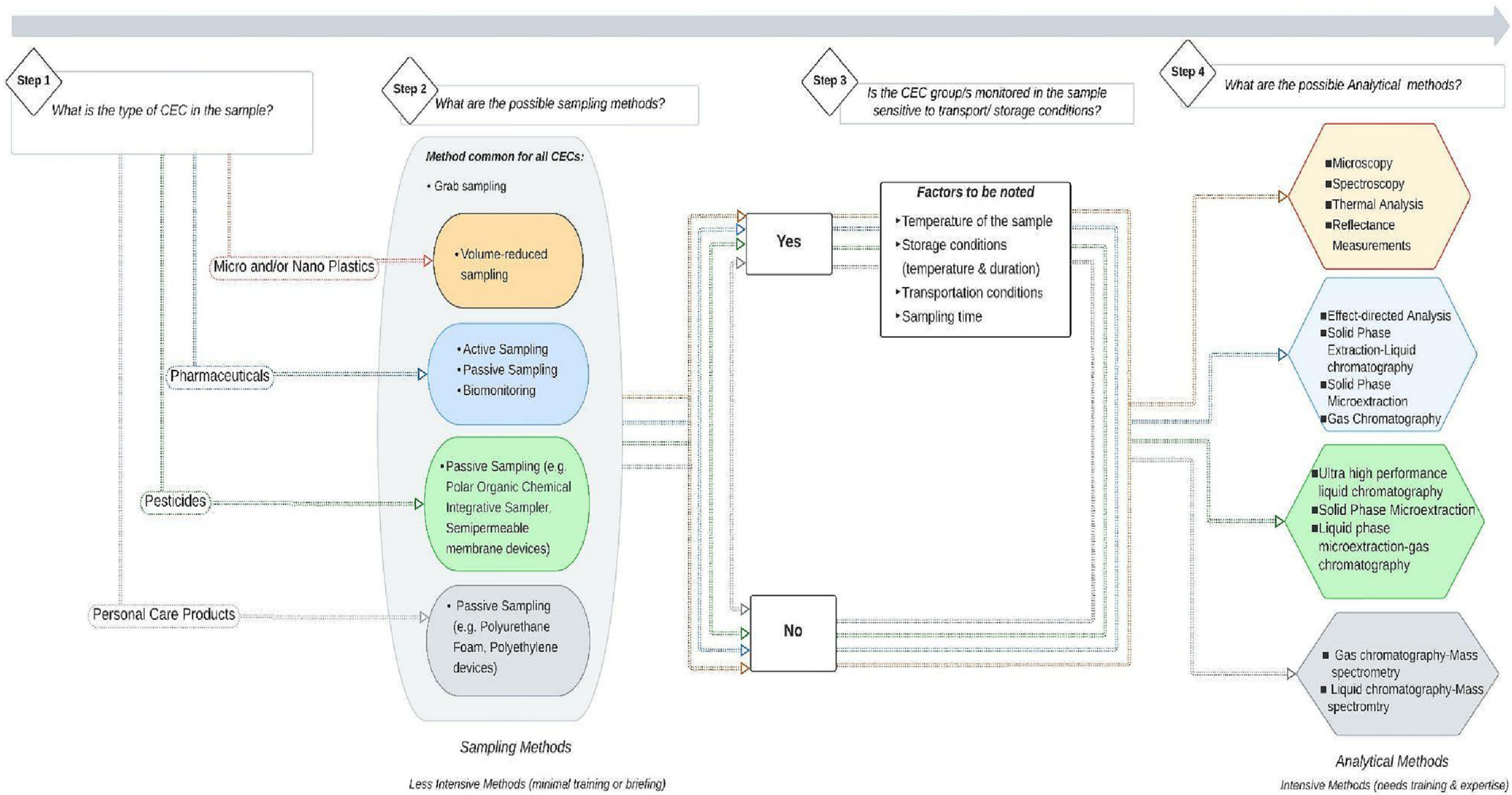


Fig. 3. Roadmap suggesting four steps to monitoring different groups of contaminants of emerging concern (CECs) in aquatic systems. Choice of the dotted pipeline specific to a CEC group can be made based on the response to the questions at the top panel of each step. Dotted pipeline indicates choices of methods for two monitoring steps i.e. sampling, transport/storage conditions and analysis. Sampling methods for different groups of CECs (Micro and/or nano plastics, pharmaceuticals, pesticides, and personal care products) described under bullet points enclosed in the curved rectangles. Analytical method options that can be used to quantify the CEC of interest are enclosed in the hexagonal boxes. The orange, blue, green and grey shapes correspond to micro and/or nano plastics, pharmaceuticals, pesticides, and personal care products respectively.

Lots et al. (2017) for the first time examined the large-scale spatial distribution of microplastic contamination in European beach sediments.

Citizen science is also an educational tool for the general public (Nelms et al., 2017). Participating in citizen science projects has proven to be effective with raising awareness on the negative impacts of synthetic chemicals, such as CECs, on aquatic systems. This awareness is not limited to the participants but can reverberate to people in their circle of influence. For example, student participants have been observed to share their awareness of plastic consumption with their family and peers (Repaci and Duckett Paul, 2015). Involving the community highlights the scope and gravity of CEC pollution, with the goal of inspiring behavioral change. For citizen science to be effective, awareness needs to be translated into behavioral change by carrying out follow-on activities and studies (Repaci and Duckett Paul, 2015). 'The Many Eyes Hypothesis' is a network of citizen scientists with clearly defined protocols and realistic aims, capable of surveying/monitoring vast areas (Caraco et al., 1980; Earp and Liconti, 2020). These networks increase the chances of detecting CEC phenomenon, increase replication rates and distribute monitoring efforts among participants. Along with its usefulness as a public educational strategy, the readily available data citizen scientists generate can be a powerful tool for decision-making processes (Flores-Díaz et al., 2018).

4. Roadmap as a guide to monitor CECs

Monitoring CECs is crucial for achieving a good water quality status, as described by the Water Framework Directive (Joint Research Centre (European Commission) et al., 2020). Considering the widespread occurrence of CECs in aquatic systems and the connectivity of aquatic compartments, it is important to know about contaminant concentrations. Citizen science has been proved to potentially be a useful tool for monitoring

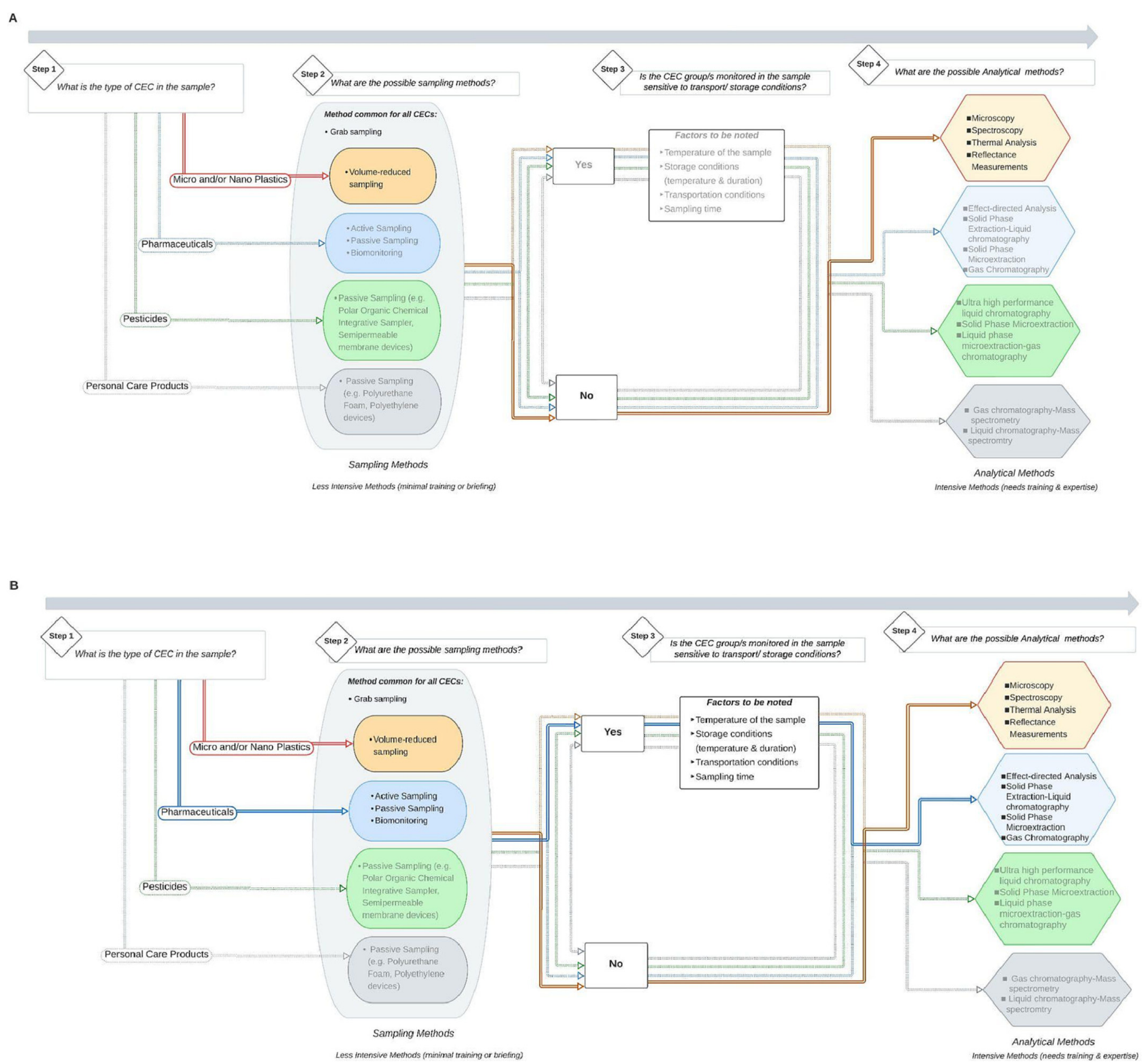


Fig. 4. Two examples in which the roadmap can be followed to monitor CECs in aquatic systems: (A) Path followed and choices made while monitoring micro and/or nano plastics (orange-solid line) in the aquatic compartments. (B) Two paths followed based on the sampling and analyzing of pharmaceuticals (blue solid line) along with micro and nano plastics (orange solid line) in aquatic compartments.

CECs across all aquatic compartments, especially when programs focus on increasing the spatial scale of monitoring by sending volunteers out to collect samples which are then sent into laboratories for analysis. Our proposed roadmap summarizes the steps involved in monitoring CECs in aquatic systems and suggests where community participation can be implemented (Fig. 3).

Our roadmap is structured around four questions. Responses to the question at the start of each step can lead to different paths for monitoring the CEC of interest. The first step to monitor a CEC in any aquatic compartment is to identify the CEC group/s of interest. Individuals can do this by responding to the question '*What is the type of CEC in the sample?*'. The second step is to select a sampling method by responding to the second question i.e. '*What are the possible sampling methods?*'. The sampling methods included in this roadmap are specific for each CEC group apart from grab sampling that can be performed to monitor all 4 CEC groups. Sampling of CECs is a less intensive part of monitoring when compared to analyses and can be performed with training or briefing when the protocols are simple, have in-person training options and that there are back-up instructions. Factors such as funding, volume of sampling kits available, transportation and the expertise of the coordinating personnel and volunteers play an important role while choosing a sampling method. The third step in monitoring CECs in aquatic systems is to categorize where the contaminant has properties that require specific storage and transport conditions. Our third question is therefore '*Is/are the CEC group/s monitored in the sample sensitive to transport/storage conditions?*. When the CEC is sensitive to transport and storage conditions, it is important to keep a record of sample conditions. For example, noting the temperature and date at the time of sample collections. For storage and transportation, a record of temperature, duration and method is crucial. Recording these details will help in accounting for the loss of contaminants during transport and storage. For instance, storage losses are minimal until 20 months when passive samplers (polar organic chemical integrative samplers (POCIS)) were used in monitoring pharmaceuticals and pesticides (J. C. Carlson et al., 2013). The final step in our roadmap is to choose an analytical method to identify and/or quantify the CEC of interest. Analysis is the final step of monitoring protocol, which typically entails intensive processes that require expert handling or prior training.

The roadmap can be applied to monitoring both single and multiple groups of CECs in the water sample, which we describe in Fig. 4. The choices made and the path followed for monitoring a single group of CEC (micro and/or nano plastics) are outlined in Fig. 4A. In step two, a choice can be made from the two sampling methods that are extensively used in the monitoring of micro and nano plastics. Specifically, the choice is between grab sampling, which involves collecting large volumes of water samples, and volume reduced sampling by including on-site filtration of the bulk sample. The samples with micro and nano plastics can then be stored and analyzed to determine their concentrations.

Fig. 4B summarizes additional choices which can be made while monitoring two CEC of two different groups i.e., micro and/or nano plastics and pharmaceuticals. It is important to note that the sampling methods, aside from grab sampling, are different for these two CEC groups. Along with the sampling methods explained in 4A, advanced techniques such as passive sampling can be performed to monitor pharmaceuticals. In contrast to the common perception that reactive CECs are challenging to sample without expertise, the more advanced sampling methods such as passive sampling can still be performed with limited expertise and training. For example, polar organic contaminants integrative samplers (POCIS) are passive samplers for integrated sampling to monitor a wide range of hydrophilic organic contaminants such as pharmaceuticals (Munaron et al., 2012). However, in the scenario illustrated in Fig. 4B, it is important to note the transport and storage conditions (also see Fig. 3) of the sample collected for the pharmaceutical. Two different analytical methods have to be chosen to qualitatively and quantitatively determine the micro and/or nano plastics and pharmaceuticals of interest in the sample.

We also identified drawbacks with respect to the use of citizen science methods for monitoring the various categories of CECs. Firstly, the quality of data collected by citizen science approaches has been questioned frequently, as it is not guaranteed to be of the same quality as data collected with more rigorous methods by professional scientists (Earn et al., 2021). Difference in experience levels of the participants of citizen science projects can also affect the quality of data collected, which can be a potential drawback when considering citizen participation as a potential approach to monitoring CECs (Ali et al., 2019). To some extent, this can be overcome with appropriate supervision or review of the quality assurance (Flores-Díaz et al., 2018), or through the provision of participant training sessions or materials.

Citizen science is often promoted as a cost-effective method for increasing the spatial and temporal scale of monitoring, but this can lead to a tendency to underestimate the costs associated with project materials and administration. Considering that some of CEC groups, such as pharmaceuticals and pesticides, are organic and fast degrading, obtaining funding for the necessary materials, storage and transportation of samples is another challenge with incorporating citizen science, and one which can be more difficult to address. This is why our roadmap suggests that the volatility of samples and the associated modes of sample transportation are among the most important factors to consider when designing citizen science protocols to monitor CECs. This is especially true for CECs where the samples are to be transported and analyzed using chemical analysis methods such as Liquid chromatography-mass spectrometry (LC-MS) (Wilkinson et al., 2019). Our focus on transportation and the volatility of samples is a contribution that our study makes to the citizen science literature, which does not often center issues related to the storage and transportation of water samples in comparison to other stages of the monitoring process. With attention to issues related to volunteer training, sample storage and transportation, and the appropriate selection of data collection protocols, we found that citizen science can help increase the scale of monitoring and help fill important gaps in knowledge about the presence of CEC concentrations in aquatic ecosystems.

Finally, although CECs may introduce some additional challenges for citizen scientists than those that they face when monitoring more conventional water quality parameters (ie. nitrogen, phosphorus, conductivity, calcium, temperature, benthic macroinvertebrates), there is a potential public engagement component that citizen science can add to CECs monitoring. In recent years, there has been greater public attention towards the presence of microplastics and so-called "forever chemicals" in drinking water and aquatic ecosystems in the United States, and the concerns that these might pose to public health, even to the extent where the presence of CECs may impact property values (Bell and Tachovsky, 2022). Although the term "citizen science" has now become associated with the structured participation of volunteers in programs designed by or in collaboration with professional scientists, the term also has roots in the environmental health movement and environmental justice movement, describing community-led efforts to obtain more information on the concentration of environmental contaminants in local areas and to inquire about possible impacts to community health (Cooper and Lewenstein, 2016). The converging goals of scientists seeking more data on concentrations of CECs across the globe, and local communities seeking information about their local waterways might provide an opportunity for the merging of these two meanings of citizen science, which could open up new and fruitful collaborations between aquatic ecologists and community groups.

The financial and logistical requirements associated with monitoring certain categories of CECs may mean that it is not practical to adopt citizen science methods in every instance, but our study demonstrates that a range of methods and approaches are currently being adopted which indicate that citizen science may help to fill knowledge gaps and to increase the spatial scale of CECs monitoring. The fact that since 2019, there has been an increase in published papers describing the use of citizen science for CECs suggests that these monitoring protocols may become even more widespread.

Our roadmap focuses primarily on issues related to methodology, data quality assurance, and technical and logistical challenges. Our recommendations related to the provision of better training materials, simpler methods, and more structured participation can help to improve CEC monitoring from a data quality perspective. At the same time, our focus on programs which are primarily designed and operationalized by professional scientists, and which involve the structured participation of volunteers corresponds with one model of citizen science, "contributory" science focused primarily on scientific investigation (Cooper and Lewenstein, 2016; Shirk et al., 2012; Wiggins and Crowston, 2011).

We recognize that there is also a different interpretation of citizen science, which is rooted in the methods and concerns of the environmental justice movement (Irwin, 2002), and which provides greater scope for community participation at all stages of the research process, including in the identification of research questions, the co-creation of research methods, the identification of sample sites, the analysis and interpretation of results, and the advocacy for political changes based on the data that is collected (Cooper et al., 2021). In the studies that we identified in our literature review, this second interpretation of citizen science was less represented than programs which followed a "contributory" model. Given the public salience of the issue of CECs, and their unknown but potentially harmful impacts on both ecological health and human health, our findings may also open up new areas of investigation related to the potential utility of other forms of citizen science to monitor CEC concentrations or to catalyze CEC monitoring. In particular, there may be a different set of opportunities and challenges related to the adoption of models of citizen science which are rooted in popular epidemiology and the environmental-based health movement (Brown, 1997; Lerner, 2012), which might provide alternative modes of investigating linkages between CEC concentrations and community health (L. F. Davis and Ramírez-Andreotta, 2021).

We also recognize that there are a host of social, cultural, demographic, epistemological, institutional, and political challenges that are associated with the increasing presence of citizen science, and which would each also warrant a deeper discussion with respect to the specific context of CEC monitoring. Nevertheless, our paper contributes to the field of environmental monitoring by providing the first overview of the emerging landscape of the use of citizen science for monitoring presence and concentration of CECs, while also providing an analysis of some technical and logistical factors that could help integrate best practices for CEC citizen science from a data quality perspective.

5. Conclusion

Citizen science is a promising and potentially powerful tool that can be used to generate cost-effective datasets of measured concentrations of various CECs in aquatic compartments, as shown by the growing literature. Citizen science methods assist the landscape of environmental contaminant monitoring by increasing the spatial scale of monitoring and can help to fill gaps.

Our review, for the first time, explores the landscape of citizen science in monitoring four specific CEC groups commonly reported in aquatic compartments over the last two decades. A disparity between the monitoring of different groups of CECs (often accounted for the difficulty in sampling) and lack of data on environmental concentrations of CECs was easily identified, implying a need for a holistic and balanced approach. However, even though the number of citizen science programs focused on monitoring CECs is small in comparison to other forms of aquatic citizen science, there is still monitoring taking place, even with the groups of CECs that are studied less frequently. Our roadmap summarizes the existing monitoring methods (sampling and analyzing) for different groups of CECs and provides guidance to harmonize the integration of citizen science into aquatic studies. We recommend applying the roadmap to standardize the incorporation of citizen science in CECs monitoring methods and to provide a common guideline to assess the status of water quality on a global scale.

CRediT authorship contribution statement

Nandini Vasantha Raman: Conceptualization, Project administration, Investigation, Visualization, Writing – original draft, Writing – review & editing, Supervision. **Asmita Dubey:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Edward Millar:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Veronica Nava:** Conceptualization, Investigation, Writing – review & editing. **Barbara Leoni:** Conceptualization, Investigation, Writing – review & editing. **Irene Gallego:** Conceptualization, Project administration, Investigation, Visualization, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Declaration of competing interest

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

Acknowledgements

We would like to thank the Global Lakes Ecological Observatory Network (GLEON) for providing a forum which made possible the interactions that enabled the development of this study. NVR was funded by the Royal Dutch Academy of Sciences (NIOO-KNAW). AD was funded by Dutch Research Council (NWO). IG was supported by the Eawag Directorate. EEM was supported by the Geoffrey F. Bruce Fellowship in Canadian Freshwater Policy.

Appendix A. Literature reviewed

1. Ali, J. M., Noble, B. C., Nandi, I., Kolok, A. S., & Bartelt-Hunt, S. L. (2019). Assessing the Accuracy of Citizen Scientist Reported Measurements for Agrichemical Contaminants. *Environmental Science & Technology*, *53* (10), 5633–5640. doi:https://doi.org/10.1021/acs.est.8b06707

2. Barrows, A. P. W., Cathey, S. E., & Petersen, C. W. (2018). Marine environment microfiber contamination: Global patterns and the diversity of microparticle origins. *Environmental Pollution*, *237*, 275–284. doi: https://doi.org/10.1016/j.envpol.2018.02.062

3. Barrows, A. P. W., Christiansen, K. S., Bode, E. T., & Hoellein, T. J. (2018). A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. *Water Research*, *147*, 382–392. doi:https://doi.org/10.1016/j.watres.2018.10.013

4. Bean, T. P., Greenwood, N., Beckett, R., Biermann, L., Bignell, J. P., Brant, J. L., Copp, G. H., Devlin, M. J., Dye, S., Feist, S. W., Fernand, L., Foden, D., Hyder, K., Jenkins, C. M., van der Kooij, J., Kröger, S., Kupschus, S., Leech, C., Leonard, K. S., … Righton, D. (2017). A Review of the Tools Used for Marine Monitoring in the UK: Combining Historic and Contemporary Methods with Modeling and Socioeconomics to Fulfill Legislative Needs and Scientific Ambitions. *Frontiers in Marine Science*, *4*, 263. doi: https://doi.org/10.3389/fmars.2017.00263

5. Borja, A., White, M. P., Berdalet, E., Bock, N., Eatock, C., Kristensen, P., Leonard, A., Lloret, J., Pahl, S., Parga, M., Prieto, J. V., Wuijts, S., & Fleming, L. E. (2020). Moving Towards an Agenda on Ocean Health and Human Health in Europe. *Frontiers in Marine Science*, *7*, 37. doi:https://doi.org/10.3389/fmars.2020.00037

6. Camins, E., de Haan, W. P., Salvo, V.-S., Canals, M., Raffard, A., & Sanchez-Vidal, A. (2020). Paddle surfing for science on microplastic pollution. *Science of The Total Environment*, *709*, 136,178. doi:https://doi.org/10.1016/j.scitotenv.2019.136178

7. Carbery, M., MacFarlane, G. R., O'Connor, W., Afrose, S., Taylor, H., & Palanisami, T. (2020). Baseline analysis of metal(loid)s on microplastics collected from the Australian shoreline using citizen science. *Marine Pollution Bulletin*, *152*, 110,914. doi:https://doi.org/10.1016/j.marpolbul.2020.110914

8. Conte, A., Brunetti, P., Allevato, E., Stazi, S. R., Antenozio, M. L., Passatore, L., & Cardarelli, M. (2020). Nature Based Solutions on the river environment: An example of cross-disciplinary sustainable management, with local community active participation and visual art as science transfer tool. *Journal of Environmental Planning and Management*, 1–18. doi:https://doi.org/10.1080/09640568.2020.1822306

9. Davis, W., & Murphy, A. G. (2015). Plastic in surface waters of the Inside Passage and beaches of the Salish Sea in Washington State. *Marine Pollution Bulletin*, *97* (1, 2), 169–177. doi:https://doi.org/10.1016/j.marpolbul.2015.06.019

10. Dohrenwend, P. (n.d.). Citizen science InternatioNal pellet Watch. *SCIENCE SCOPE*, 5.

11. Duffy, L. K., Dunlap, K. L., & Godduhn, A. R. (2014). Bias, complexity, and uncertainty in ecosystem risk assessment: Pharmaceuticals, a new challenge in scale and perspective. *Environmental Research Letters*, *9* (9), 091004. doi:https://doi.org/10.1088/1748-9326/9/9/091004

12. Dykman, M., & Prahalad, V. (2018). Tamar Saltmarsh Monitoring Program: Citizen science monitoring of the tidal treasures of the Tamar River estuary, Tasmania, Australia. *Australian Journal of Maritime & Ocean Affairs*, *10* (4), 222–240. doi:https://doi.org/10.1080/18366503.2018.1502030

13. Earn, A., Bucci, K., & Rochman, C. M. (2021). A systematic review of the literature on plastic pollution in the Laurentian Great Lakes and its effects on freshwater biota. *Journal of Great Lakes Research*, *47* (1), 120–133. doi:https://doi.org/10.1016/j.jglr.2020.11.001

14. Earp, H. S., & Liconti, A. (2020). Science for the Future: The Use of Citizen Science in Marine Research and Conservation. In S. Jungblut, V. Liebich, & M. Bode-Dalby (Eds.), *YOUMARES 9—The Oceans: Our Research, Our Future* (pp. 1–19). Springer International Publishing. doi:https://doi.org/10.1007/978-3-030-20,389-4_1

15. Emmerik, T., & Schwarz, A. (2020). Plastic debris in rivers. *WIREs Water*, *7* (1). doi:https://doi.org/10.1002/wat2.1398

16. Flores-Díaz, A., Quevedo Chacón, A., Páez Bistrain, R., Ramírez, M., & Larrazábal, A. (2018). Community-Based Monitoring in Response to Local Concerns: Creating Usable Knowledge for Water Management in Rural Land. *Water*, *10* (5), 542. doi:https://doi.org/10.3390/w10050542

17. Forrest, S. A., Holman, L., Murphy, M., & Vermaire, J. C. (2019). Citizen science sampling programs as a technique for monitoring microplastic pollution: Results, lessons learned and recommendations for working with volunteers for monitoring plastic pollution in freshwater ecosystems. *Environmental Monitoring and Assessment*, *191* (3), 172. doi:https://doi.org/10.1007/s10661-019-7297-3

18. Gérin-Lajoie, J., Herrmann, T. M., MacMillan, G. A., Hébert-Houle, É., Monfette, M., Rowell, J. A., Anaviapik Soucie, T., Snowball, H., Townley, E., Lévesque, E., Amyot, M., Franssen, J., & Dedieu, J.-P. (2018). IMALIRIJIIT: A community-based environmental monitoring program in the George River watershed, Nunavik, Canada. *Écoscience*, *25* (4), 381–399. doi:https://doi.org/10.1080/11956860.2018.1498226

19. Gewert, B., Ogonowski, M., Barth, A., & MacLeod, M. (2017). Abundance and composition of near surface microplastics and plastic debris in the Stockholm Archipelago, Baltic Sea. *Marine Pollution Bulletin*, *120* (1, 2), 292–302. doi:https://doi.org/10.1016/j.marpolbul.2017.04.062

20. Kolok, A. S., Schoenfuss, H. L., Propper, C. R., & Vail, T. L. (2011). Empowering Citizen Scientists: The Strength of Many in Monitoring Biologically Active Environmental Contaminants. *BioScience*, *61* (8), 626–630. doi:https://doi.org/10.1525/bio.2011.61.8.9

21. Locritani, M., Merlino, S., & Abbate, M. (2019). Assessing the citizen science approach as tool to increase awareness on the marine litter problem. *Marine Pollution Bulletin*, *140*, 320–329. doi:https://doi.org/10.1016/j.marpolbul.2019.01.023

22. Lynch, S. (2018). OpenLitterMap.com – Open Data on Plastic Pollution with Blockchain Rewards (Littercoin). *Open Geospatial Data, Software and Standards*, *3* (1), 6. doi:https://doi.org/10.1186/s40965-018-0050-y

23. Mandigo, A. C., DiScenza, D. J., Keimowitz, A. R., & Fitzgerald, N. (2016). Chemical contamination of soils in the New York City area following Hurricane Sandy. *Environmental Geochemistry and Health*, *38* (5), 1115–1124. doi:https://doi.org/10.1007/s10653-015-9776-y

24. Mayoma, B. S., Mjumira, I. S., Efudala, A., Syberg, K., & Khan, F. R. (2019). Collection of Anthropogenic Litter from the Shores of Lake Malawi: Characterization of Plastic Debris and the Implications of Public Involvement in the African Great Lakes. *Toxics*, *7* (4), 64. doi:https://doi.org/10.3390/toxics7040064

25. McCracken, K. E., Angus, S. V., Reynolds, K. A., & Yoon, J.-Y. (2016). Multimodal Imaging and Lighting Bias Correction for Improved μPAD-based Water Quality Monitoring via Smartphones. *Scientific Reports*, *6* (1), 27,529. doi:https://doi.org/10.1038/srep27529

26. Muurinen, J., Pasupulate, A., Lappalainen, J., & Virta, M. (2019). Field-compatible protocol for detecting tetracyclines with bioluminescent bioreporters without pipetting steps. *Luminescence*, *34* (2), 249–254. doi:https://doi.org/10.1002/bio.3602

27. Nel, H. A., Sambrook Smith, G. H., Harmer, R., Sykes, R., Schneidewind, U., Lynch, I., & Krause, S. (2020). Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. *Marine Pollution Bulletin*, *161*, 111,776. doi:https://doi.org/10.1016/j.marpolbul.2020.111776

28. Pakhomova, S., Zhdanov, I., & van Bavel, B. (2020). Polymer Type Identification of Marine Plastic Litter Using a Miniature Near-Infrared Spectrometer (MicroNIR). *Applied Sciences*, *10* (23), 8707. doi:https://doi.org/10.3390/app10238707

29. Panti, C., Baini, M., Lusher, A., Hernandez-Milan, G., Bravo Rebolledo, E. L., Unger, B., Syberg, K., Simmonds, M. P., & Fossi, M. C. (2019). Marine litter: One of the major threats for marine mammals. Outcomes from the European Cetacean Society workshop. *Environmental Pollution*, *247*, 72–79. doi:https://doi.org/10.1016/j.envpol.2019.01.029

30. Rambonnet, L., Vink, S. C., Land-Zandstra, A. M., & Bosker, T. (2019). Making citizen science count: Best practices and challenges of citizen science projects on plastics in aquatic environments. *Marine Pollution Bulletin*, *145*, 271–277. doi:https://doi.org/10.1016/j.marpolbul.2019.05.056

31. Rosevelt, C., Los Huertos, M., Garza, C., & Nevins, H. M. (2013). Marine debris in central California: Quantifying type and abundance of beach litter in Monterey Bay, CA. *Marine Pollution Bulletin*, *71* (1, 2), 299–306. doi:https://doi.org/10.1016/j.marpolbul.2013.01.015

32. San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., & Kirschke, S. (2020). Success factors for citizen science projects in water quality monitoring. *Science of The Total Environment*, *728*, 137,843. doi:https://doi.org/10.1016/j.scitotenv.2020.137843

33. Sandahl, A., & Tøttrup, A. P. (2020). Marine Citizen Science: Recent Developments and Future Recommendations. *Citizen Science: Theory and Practice*, *5* (1), 24. doi:https://doi.org/10.5334/cstp.270

34. Simoniello, C., Jencks, J., Lauro, F. M., Loftis, J. D., Weslawski, J. M., Deja, K., Forrest, D. R., Gossett, S., Jeffries, T. C., Jensen, R. M., Kobara, S., Nolan, L., Ostrowski, M., Pounds, D., Roseman, G., Basco, O., Gosselin, S., Reed, A., Wills, P., & Wyatt, D. (2019). Citizen-Science for the Future: Advisory Case Studies From Around the Globe. *Frontiers in Marine Science*, *6*, 225. doi:https://doi.org/10.3389/fmars.2019.00225

35. Smith, S. D. A., Banister, K., Fraser, N., & Edgar, R. J. (2018). Tracing the source of marine debris on the beaches of northern New South Wales, Australia: The Bottles on Beaches program. *Marine Pollution Bulletin*, *126*, 304–307. doi:https://doi.org/10.1016/j.marpolbul.2017.11.022

36. Smith, S. D. A., Gillies, C. L., & Shortland-Jones, H. (2014). Patterns of marine debris distribution on the beaches of Rottnest Island, Western Australia. *Marine Pollution Bulletin*, *88* (1, 2), 188–193. doi:https://doi.org/10.1016/j.marpolbul.2014.09.007

37. Sullivan, J., Croisant, S., Howarth, M., Rowe, G. T., Fernando, H., Phillips-Savoy, A., Jackson, D., Prochaska, J., Ansari, G. A. S., Penning, T. M., & Elferink, C. (2018). Building and Maintaining a Citizen Science Network With Fishermen and Fishing Communities Post Deepwater Horizon Oil Disaster Using a CBPR Approach. *New Solutions: A Journal of Environmental and Occupational Health Policy: NS*, *28* (3), 416–447. doi:https://doi.org/10.1177/1048291118795156

38. Syakti, A. D., Bouhroum, R., Hidayati, N. V., Koenawan, C. J., Boulkamh, A., Sulistyo, I., Lebarillier, S., Akhlus, S., Doumenq, P., & Wong-Wah-Chung, P. (2017). Beach macro-litter monitoring and floating microplastic in a coastal area of Indonesia. *Marine Pollution Bulletin*, *122* (1, 2), 217–225. doi:https://doi.org/10.1016/j.marpolbul.2017.06.046

39. Turrell, W. R. (2019). Spatial distribution of foreshore litter on the northwest European continental shelf. *Marine Pollution Bulletin*, *142*, 583–594. doi:https://doi.org/10.1016/j.marpolbul.2019.04.009

40. Uhrin, A. V., Lippiatt, S., Herring, C. E., Dettloff, K., Bimrose, K., & Butler-Minor, C. (2020). Temporal Trends and Potential Drivers of Stranded Marine Debris on Beaches Within Two US National Marine Sanctuaries Using Citizen Science Data. *Frontiers in Environmental Science*, *8*, 604,927. doi:https://doi.org/10.3389/fenvs.2020.604927

41. Wang, S., Matt, M., Murphy, B. L., Perkins, M., Matthews, D. A., Moran, S. D., & Zeng, T. (2020). Organic Micropollutants in New York Lakes: A Statewide Citizen Science Occurrence Study. *Environmental Science & Technology*, *54* (21), 13,759–13,770. doi:https://doi.org/10.1021/acs.est.0c04775

42. Wilkinson, J., Boxall, A., & Kolpin, D. (2019). A Novel Method to Characterise Levels of Pharmaceutical Pollution in Large-Scale Aquatic Monitoring Campaigns. *Applied Sciences*, *9* (7), 1368. doi:https://doi.org/10.3390/app9071368

43. Wu, F., Seib, M., Mauel, S., Klinzing, S., & Hicks, A. L. (2020). A citizen science approach estimating titanium dioxide released from personal care products. *PLOS ONE*, *15* (7), e0235988. doi:https://doi.org/10.1371/journal.pone.0235988

44. Zettler, E. R., Takada, H., Monteleone, B., Mallos, N., Eriksen, M., & Amaral-Zettler, L. A. (2017). Incorporating citizen science to study plastics in the environment. *Analytical Methods*, *9* (9), 1392–1403. doi:https://doi.org/10.1039/C6AY02716D

Appendix B. Glossary

1. Citizen Science (CS): Process whereby non-professionals in scientific investigations are involved or engaged in science as researchers i.e. asking questions, collecting data, or interpreting results (Linda and Kruger, 2000). The level of participation in scientific research can be categorized into three types: contributory, collaborative and co-created. It has also been referred to as *community science* and *participatory action research* (Carr, 2004; Miller-Rushing et al., 2012).

2. Community Science (CS): Volunteer programs aimed at tackling local problems have long existed across a region or country and continue to make important contributions to science and resource management today (Miller-Rushing et al., 2012).

3. Citizen Sensing: Citizen-sensor interaction for tracking environmental risk.

4. Community-based Monitoring (CBM): A process where concerned citizens, government agencies, industry, academia, community groups, and local institutions collaborate to monitor, track and respond to issues of common community (environmental) concern (Whitelaw et al., 2003). Also known as volunteer-*based monitoring.*

5. Contaminants of Emerging Concern (CECs): Contaminants naturally occurring, manufactured or man-made chemicals or materials which have recently been discovered or are suspected present in various environmental compartments and whose toxicity or persistence are likely to significantly alter the metabolism of a living being (Sauvé and Desrosiers, 2014). Examples of CECs are: pesticides with neonicotinoids, synthetic hormones, plasticizers, fluorinated compounds, nanoparticles or water treatment by-products such as trihalomethanes or haloacetic acids. CECs also include contaminants present in the environment for a while but for which concerns have been raised recently, (e.g. cyanotoxins), as well as traditional contaminants for which the latest facts arise concerns, such as lead or arsenic (Sauvé and Desrosiers, 2014). Also known as *emerging contaminants*.

6. Micropollutants: Anthropogenic chemicals that occur in the (aquatic) environment well above a (potential) natural background level due to human activities but with concentrations remaining at trace levels, i.e. up to the microgram per litre range (Geissen et al., 2015).

7. Microplastics: Plastic particles (synthetic organic polymers) less than 5 mm that are distinguished into primary and secondary microplastics based on their origin (Cole et al., 2011; Frias and Nash, 2019).

8. Water Quality: Generic term used to describe physical, chemical and biological properties of water (Ritchie and Schiebe, 2000).

9. Water Pollution: Presence of chemical, physical, or biological components or factors producing a condition of impairment of a given water body with respect to some beneficial use. The level of contamination necessary to render a water body impaired is highly dependent on the type of water body, its location, and the types of beneficial uses it supports. A water deemed unfit for drinking water may be suitable for other uses, such as irrigation or recreation (Schweitzer and Noblet, 2018).

10. Pharmaceuticals and personal care products (PPCPs): Diverse group of chemicals, used internally or externally with the bodies of humans, domestic animals and plants, comprising all drugs available by prescription or over-the-counter, new genre of biologics, diagnostic agents, nutraceuticals and other consumer chemicals (e.g. fragrances, sun-screen agents, excipients, etc) (Daughton, 2001).

11. Pharmaceuticals: Molecules designed to produce a therapeutic effect on the body, usually active at very low concentrations, can pass through biological membranes and persist in the body long enough to avoid being inactivated before having an effect (Bottoni et al., 2010).

12. Antibiotics: Antimicrobial substances active against bacteria. They can occur naturally, but the anthropogenic source of pollution is predominant and therefore, commonly classified as *xenobiotics*.

13. Personal care products (PCPs): Any product used by individuals for personal health, cosmetic and cleaning reasons. Examples of PCPs are disinfectants, fragrances, insect repellents, preservatives and UV filters, among others.

14. Pesticides: Pesticides are substances that are used to protect humans against the insect vectors of disease causing pathogens, to protect crop plants from competition from abundant but unwanted plants, and to protect crop plants and livestock from diseases and depredations by fungi, insects, mites, and rodents (Freedman, 1995).

References

Ali, J.M., Noble, B.C., Nandi, I., Kolok, A.S., Bartelt-Hunt, S.L., 2019. Assessing the accuracy of citizen scientist reported measurements for agrichemical contaminants. Environ. Sci. Technol. 53 (10), 5633–5640. https://doi.org/10.1021/acs.est.8b06707.

aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., Küster, A., 2016. Pharmaceuticals in the environment—Global occurrences and perspectives. Environmental Toxicology and Chemistry 35 (4), 823–835. https://doi.org/10.1002/etc.3339.

Barrows, A.P.W., Cathey, S.E., Petersen, C.W., 2018. Marine environment microfiber contamination: global patterns and the diversity of microparticle origins. Environ. Pollut. 237, 275–284. https://doi.org/10.1016/j.envpol.2018.02.062.

Barrows, A.P.W., Christiansen, K.S., Bode, E.T., Hoellein, T.J., 2018. A watershed-scale, citizen science approach to quantifying microplastic concentration in a mixed land-use river. Water Res. 147, 382–392. https://doi.org/10.1016/j.watres.2018.10.013.

Bean, T.P., Greenwood, N., Beckett, R., Biermann, L., Bignell, J.P., Brant, J.L., Copp, G.H., Devlin, M.J., Dye, S., Feist, S.W., Fernand, L., Foden, D., Hyder, K., Jenkins, C.M., van der Kooij, J., Kröger, S., Kupschus, S., Leech, C., Leonard, K.S., Righton, D., 2017. A review of the tools used for marine monitoring in the UK: combining historic and contemporary methods with modeling and socioeconomics to fulfill legislative needs and scientific ambitions. Front. Mar. Sci. 4, 263. https://doi.org/10.3389/fmars.2017.00263.

Bell, R., Tachovsky, M., 2022. Real estate damage economics: the impact of PFAS "Forever chemicals" on real estate valuation. Environ. Claims J. 34 (2), 136–155. https://doi.org/10.1080/10406026.2021.1923926.

Bottoni, P., Caroli, S., Caracciolo, A.B., 2010. Pharmaceuticals as priority water contaminants. Toxicol. Environ. Chem. 92 (3), 549–565. https://doi.org/10.1080/02772241003614320.

Brown, P., 1997. Popular epidemiology revisited. Curr. Sociol. 45 (3), 137–156. https://doi.org/10.1177/001139297045003008.

Buckland-Nicks, A., Castleden, H., Conrad, C., 2016. Aligning community-based water monitoring program designs with goals for enhanced environmental management. J. Sci. Commun. 15 (3), A01. https://doi.org/10.22323/2.15030201.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T.C., Bastiaensen, J., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D.M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., De BiÃ¨vre, B.,

Zhumanova, M., 2014. Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. Frontiers in Earth Science 2. https://doi.org/10.3389/feart.2014.00026.
Camins, E., de Haan, W.P., Salvo, V.-S., Canals, M., Raffard, A., Sanchez-Vidal, A., 2020. Paddle surfing for science on microplastic pollution. Sci. Total Environ. 709, 136178. https://doi.org/10.1016/j.scitotenv.2019.136178.
Caraco, T., Martindale, S., Pulliam, H.R., 1980. Avian flocking in the presence of a predator. Nature 285 (5764), 5764. https://doi.org/10.1038/285400a0.
Carbery, M., MacFarlane, G.R., O'Connor, W., Afrose, S., Taylor, H., Palanisami, T., 2020. Baseline analysis of metal(loid)s on microplastics collected from the australian shoreline using citizen science. Mar. Pollut. Bull. 152, 110914. https://doi.org/10.1016/j.marpolbul.2020.110914.
Carlson, T., Cohen, A., 2018. Linking community-based monitoring to water policy: perceptions of citizen scientists. J. Environ. Manag. 219, 168–177. https://doi.org/10.1016/j.jenvman.2018.04.077.
Carlson, J.C., Challis, J.K., Hanson, M.L., Wong, C.S., 2013. Stability of pharmaceuticals and other polar organic compounds stored on polar organic chemical integrative samplers and solid-phase extraction cartridges. Environ. Toxicol. Chem. 32 (2), 337–344. https://doi.org/10.1002/etc.2076.
Carr, A.J.L., 2004. Policy reviews and essays. Soc. Nat. Resour. 17 (9), 841–849. https://doi.org/10.1080/08941920490493846.
Cole, M., Lindeque, P., Halsband, C., Galloway, T.S., 2011. Microplastics as contaminants in the marine environment: a review. Mar. Pollut. Bull. 62 (12), 2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.
Conrad, C.C., Hilchey, K.G., 2011. A review of citizen science and community-based environmental monitoring: issues and opportunities. Environ. Monit. Assess. 176 (1–4), 273–291. https://doi.org/10.1007/s10661-010-1582-5.
Cooper, C.B., Lewenstein, B.V., 2016. Two meanings of citizen science.The rightful place of science: citizen science. AZ Consortium for Science Policy and Outcomes.
Cooper, C.B., Hawn, C.L., Larson, L.R., Parrish, J.K., Bowser, G., Cavalier, D., Dunn, R.R., Gupta, K.K., Jelks, N.O., Johnson, V.A., Katti, M., Leggett, Z., Wilson, O.R., Wilson, S., Haklay, M., 2021. Inclusion in citizen science: the conundrum of rebranding. Science 372 (6549), 1386–1388. https://doi.org/10.1126/science.abi6487.
Corburn, J., 2005. Street Science: Community Knowledge and Environmental Health Justice. https://doi.org/10.7551/mitpress/6494.001.0001.
Cunha, D.G.F., Casali, S.P., de Falco, P.B., Thornhill, I., Loiselle, S.A., 2017. The contribution of volunteer-based monitoring data to the assessment of harmful phytoplankton blooms in Brazilian urban streams. Sci. Total Environ. 584–585, 586–594. https://doi.org/10.1016/j.scitotenv.2017.01.080.
Daughton, C.G., 2001. Emerging pollutants, and communicating the science of environmental chemistry and mass spectrometry: pharmaceuticals in the environment. J. Am. Soc. Mass Spectrom. 12 (10), 1067–1076. https://doi.org/10.1016/S1044-0305(01)00287-2.
Davis, W., Murphy, A.G., 2015. Plastic in surface waters of the inside passage and beaches of the Salish Sea in Washington state. Mar. Pollut. Bull. 97 (1–2), 169–177. https://doi.org/10.1016/j.marpolbul.2015.06.019.
Davis, L.F., Ramírez-Andreotta, M.D., 2021. Participatory research for environmental justice: a critical interpretive synthesis. Environ. Health Perspect. 129 (2), 026001. https://doi.org/10.1289/EHP6274.
Dettori, M., Arghittu, A., Deiana, G., Castiglia, P., Azara, A., 2022. The revised European directive 2020/2184 on the quality of water intended for human consumption. A step forward in risk assessment, consumer safety and informative communication. Environ. Res. 209, 112773. https://doi.org/10.1016/j.envres.2022.112773.
Dohrenwend, P., 2012. Citizen science InternatioNal pellet watch. Sci. Scope 5.
Earn, A., Bucci, K., Rochman, C.M., 2021. A systematic review of the literature on plastic pollution in the laurentian Great Lakes and its effects on freshwater biota. J. Great Lakes Res. 47 (1), 120–133. https://doi.org/10.1016/j.jglr.2020.11.001.
Earp, H.S., Liconti, A., 2020. Science for the future: the use of citizen science in marine research and conservation. In: Jungblut, S., Liebich, V., Bode-Dalby, M. (Eds.), YOUMARES 9—The Oceans: Our Research, Our Future. Springer International Publishing, pp. 1–19 https://doi.org/10.1007/978-3-030-20389-4_1.
Elfikrie, N., Ho, Y.B., Zaidon, S.Z., Juahir, H., Tan, E.S.S., 2020. Occurrence of pesticides in surface water, pesticides removal efficiency in drinking water treatment plant and potential health risk to consumers in Tengi River Basin, Malaysia. Science of The Total Environment 712, 136540. https://doi.org/10.1016/j.scitotenv.2020.136540.
Emmerik, T., Schwarz, A., 2020. Plastic debris in rivers. WIREsWater 7 (1). https://doi.org/10.1002/wat2.1398.
Expedition, 2021. Clean Seas Odyssey. Cleanseasodyssey. https://www.cleanseasodyssey.org.
Flores-Díaz, A., Quevedo Chacón, A., Páez Bistrain, R., Ramírez, M., Larrazábal, A., 2018. Community-based monitoring in response to local concerns: creating usable knowledge for water Management in Rural Land. Water 10 (5), 542. https://doi.org/10.3390/w10050542.
Forrest, S.A., Holman, L., Murphy, M., Vermaire, J.C., 2019. Citizen science sampling programs as a technique for monitoring microplastic pollution: results, lessons learned and recommendations for working with volunteers for monitoring plastic pollution in freshwater ecosystems. Environ. Monit. Assess. 191 (3), 172. https://doi.org/10.1007/s10661-019-7297-3.
Freedman, B., 1995. 8—Pesticides. In: Freedman, B. (Ed.), Environmental Ecology, Second edition Academic Press, pp. 213–277 https://doi.org/10.1016/B978-0-08-050577-0.50013-3.
Frias, J.P.G.L., Nash, R., 2019. Microplastics: finding a consensus on the definition. Mar. Pollut. Bull. 138, 145–147. https://doi.org/10.1016/j.marpolbul.2018.11.022.
Gabrys, J., 2019. Sensors and sensing practices: reworking experience across entities, environments, and technologies. Sci. Technol. Hum. Values 44 (5), 723–736. https://doi.org/10.1177/0162243919860211.
Garda, C., Castleden, H., Conrad, C., 2017. Monitoring, restoration, and source water protection: Canadian community-based environmental organizations' efforts towards improving aquatic ecosystem health. Water 9 (3), 212. https://doi.org/10.3390/w9030212.
Geissen, V., Mol, H., Klumpp, E., Umlauf, G., Nadal, M., van der Ploeg, M., van de Zee, S.E.A.T.M., Ritsema, C.J., 2015. Emerging pollutants in the environment: a challenge for water resource management. Int. Soil Water Conserv. Res. 3 (1), 57–65. https://doi.org/10.1016/j.iswcr.2015.03.002.
Gewert, B., Ogonowski, M., Barth, A., MacLeod, M., 2017. Abundance and composition of near surface microplastics and plastic debris in the Stockholm Archipelago, Baltic Sea. Mar. Pollut. Bull. 120 (1–2), 292–302. https://doi.org/10.1016/j.marpolbul.2017.04.062.
Gogoi, A., Mazumder, P., Tyagi, V.K., Tushara Chaminda, G.G., An, A.K., Kumar, M., 2018. Occurrence and fate of emerging contaminants in water environment: a review. Groundw. Sustain. Dev. 6, 169–180. https://doi.org/10.1016/j.gsd.2017.12.009.
Hidalgo-Ruz, V., Thiel, M., 2013. Distribution and abundance of small plastic debris on beaches in the SE Pacific (Chile): a study supported by a citizen science project. Mar. Environ. Res. 87–88, 12–18. https://doi.org/10.1016/j.marenvres.2013.02.015.
Irwin, A., 2002. Citizen Science: A Study of People, Expertise and Sustainable Development. Routledge https://doi.org/10.4324/9780203202395.
Joint Research Centre (European Commission)Gomez Cortes, L., Marinov, D., Sanseverino, I., Navarro Cuenca, A., Niegowska, M., Porcel Rodriguez, E., Lettieri, T., 2020. Selection of Substances for the 3rd Watch List Under the Water Framework Directive. Publications Office of the European Union https://doi.org/10.2760/194067.
Klaschka, U., von der Ohe, P.C., Bschorer, A., Krezmer, S., Sengl, M., Letzel, M., 2013. Occurrences and potential risks of 16 fragrances in five German sewage treatment plants and their receiving waters. Environ. Sci. Pollut. Res. 20 (4), 2456–2471. https://doi.org/10.1007/s11356-012-1120-9.
Kolpin, D.W., Furlong, E.T., Meyer, M.T., Thurman, E.M., Zaugg, S.D., Barber, L.B., Buxton, H.T., 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999 – 2000: a national reconnaissance. Environmental Science & Technology 36 (6), 1202–1211. https://doi.org/10.1021/es011055j.
Lerner, S., 2012. Sacrifice Zones. MIT Press. https://mitpress.mit.edu/9780262518178/sacrifice-zones/.
Levet, A., Bordes, C., Clément, Y., Mignon, P., Morell, C., Chermette, H., Marote, P., Lantéri, P., 2016. Acute aquatic toxicity of organic solvents modeled by QSARs. J. Mol. Model. 22 (12), 288. https://doi.org/10.1007/s00894-016-3156-0.
Linda, E., Kruger, M.A.S., 2000. Getting to know ourselves and our places through participation in civic social assessment. Society & Natural Resources 13 (5), 461–478. https://doi.org/10.1080/089419200403866.
Loos, R., Carvalho, R., António, D.C., Comero, S., Locoro, G., Tavazzi, S., Paracchini, B., Ghiani, M., Lettieri, T., Blaha, L., Jarosova, B., Voorspoels, S., Servaes, K., Haglund, P., Fick, J., Lindberg, R.H., Schwesig, D., Gawlik, B.M., 2013. EU-wide monitoring survey on emerging polar organic contaminants in wastewater treatment plant effluents. Water Res. 47 (17), 6475–6487. https://doi.org/10.1016/j.watres.2013.08.024.
Lots, F.A.E., Behrens, P., Vijver, M.G., Horton, A.A., Bosker, T., 2017. A large-scale investigation of microplastic contamination: abundance and characteristics of microplastics in European beach sediment. Mar. Pollut. Bull. 123 (1–2), 219–226. https://doi.org/10.1016/j.marpolbul.2017.08.057.
Lynch, S., 2018. OpenLitterMap.Com – open data on plastic pollution with blockchain rewards (Littercoin). Open Geospatial Data Softw. Standards 3 (1), 6. https://doi.org/10.1186/s40965-018-0050-y.
Maruya, K.A., Dodder, N.G., Mehinto, A.C., Denslow, N.D., Schlenk, D., Snyder, S.A., Weisberg, S.B., 2016. A tiered, integrated biological and chemical monitoring framework for contaminants of emerging concern in aquatic ecosystems. Integr. Environ. Assess. Manag. 12 (3), 540–547. https://doi.org/10.1002/ieam.1702.
Miller-Rushing, A., Primack, R., Bonney, R., 2012. The history of public participation in ecological research. Front. Ecol. Environ. 10 (6), 285–290. https://doi.org/10.1890/110278.
Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. J. Clin. Epidemiol. 62 (10), 1006–1012. https://doi.org/10.1016/j.jclinepi.2009.06.005.
Munaron, D., Tapie, N., Budzinski, H., Andral, B., Gonzalez, J.-L., 2012. Pharmaceuticals, alkylphenols and pesticides in Mediterranean coastal waters: results from a pilot survey using passive samplers. Estuar. Coast. Shelf Sci. 114, 82–92. https://doi.org/10.1016/j.ecss.2011.09.009.
Nel, H.A., Sambrook Smith, G.H., Harmer, R., Sykes, R., Schneidewind, U., Lynch, I., Krause, S., 2020. Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. Marine Pollution Bulletin 161, 111776. https://doi.org/10.1016/j.marpolbul.2020.111776.
Nelms, S., Coombes, C., Foster, L., Galloway, T., Godley, B., Lindeque, P., Witt, M., 2017. Marine anthropogenic litter on british beaches: a 10-year nationwide assessment using citizen science data. Sci. Total Environ. 579, 1399–1409. https://doi.org/10.1016/j.scitotenv.2016.11.137.
Nentwig, G., 2007. Effects of pharmaceuticals on aquatic invertebrates. Part II: the antidepressant drug fluoxetine. Arch. Environ. Contam. Toxicol. 52 (2), 163–170. https://doi.org/10.1007/s00244-005-7190-7.
OpenLitterMap, 2022. https://openlittermap.com/.
Orvos, D.R., Versteeg, D.J., Inauen, J., Capdevielle, M., Rothenstein, A., Cunningham, V., 2002. Aquatic toxicity of triclosan. Environ. Toxicol. Chem. 21 (7), 1338–1349. https://doi.org/10.1002/etc.5620210703.
Pakhomova, S., Zhdanov, I., van Bavel, B., 2020. Polymer type identification of marine plastic litter using a miniature near-infrared spectrometer (MicroNIR). Appl. Sci. 10 (23), 8707. https://doi.org/10.3390/app10238707.
Pulido-Reyes, G., Magherini, L., Bianco, C., Sethi, R., von Gunten, U., Kaegi, R., Mitrano, D.M., 2022. Nanoplastics removal during drinking water treatment: laboratory- and pilot-scale experiments and modeling. J. Hazard. Mater. 436, 129011. https://doi.org/10.1016/j.jhazmat.2022.129011.
Rech, S., Macaya-Caquilpán, V., Pantoja, J.F., Rivadeneira, M.M., Campodónico, C.K., Thiel, M., 2015. Sampling of riverine litter with citizen scientists—Findings and recommendations. Environ. Monit. Assess. 187 (6), 335. https://doi.org/10.1007/s10661-015-4473-y.

Repaci, V., Duckett Paul, E., 2015. Marine plastic pollution: using community science to address a global problem. Marine and Freshwater Research 66 (8), 665. https://doi.org/10.1071/MF14087.

Ritchie, J.C., Schiebe, F.R., 2000. Water quality. In: Schultz, G.A., Engman, E.T. (Eds.), Remote Sensing in Hydrology and Water Management. Springer, pp. 287–303 https://doi.org/10.1007/978-3-642-59583-7_13.

San Llorente Capdevila, A., Kokimova, A., Sinha Ray, S., Avellán, T., Kim, J., Kirschke, S., 2020. Success factors for citizen science projects in water quality monitoring. Science of The Total Environment 728, 137843. https://doi.org/10.1016/j.scitotenv.2020.137843.

Sauvé, S., Desrosiers, M., 2014. A review of what is an emerging contaminant. Chem. Central J. 8 (1), 15. https://doi.org/10.1186/1752-153X-8-15.

Schweitzer, L., Noblet, J., 2018. Chapter 3.6—water contamination and pollution. In: Török, B., Dransfield, T. (Eds.), Green Chemistry. Elsevier, pp. 261–290 https://doi.org/10.1016/B978-0-12-809270-5.00011-X.

Shirk, J., Ballard, H., Wilderman, C., Phillips, T., Wiggins, A., Jordan, R., McCallie, E., Minarchek, M., Lewenstein, B., Krasny, M., Bonney, R., 2012. Public participation in scientific research: a framework for deliberate design. Ecol. Soc. 17 (2). https://doi.org/10.5751/ES-04705-170229.

Sousa, J.C.G., Ribeiro, A.R., Barbosa, M.O., Ribeiro, C., Tiritan, M.E., Pereira, M.F.R., Silva, A.M.T., 2019. Monitoring of the 17 EU watch list contaminants of emerging concern in the ave and the Sousa Rivers. Sci. Total Environ. 649, 1083–1095. https://doi.org/10.1016/j.scitotenv.2018.08.309.

Stepenuck, K.F., Genskow, K.D., 2019. Traits of volunteer water monitoring programs that influence natural resource management and policy impacts. Soc. Nat. Resour. 32 (3), 275–291. https://doi.org/10.1080/08941920.2018.1511022.

Syakti, A.D., Bouhroum, R., Hidayati, N.V., Koenawan, C.J., Boulkamh, A., Sulistyo, I., Lebarillier, S., Akhlus, S., Doumenq, P., Wong-Wah-Chung, P., 2017. Beach macro-litter monitoring and floating microplastic in a coastal area of Indonesia. Mar. Pollut. Bull. 122 (1–2), 217–225. https://doi.org/10.1016/j.marpolbul.2017.06.046.

Valbonesi, P., Profita, M., Vasumini, I., Fabbri, E., 2021. Contaminants of emerging concern in drinking water: quality assessment by combining chemical and biological analysis. Sci. Total Environ. 758, 143624. https://doi.org/10.1016/j.scitotenv.2020.143624.

Whitelaw, G., Vaughan, H., Craig, B., Atkinson, D., 2003. Establishing the Canadian community monitoring network. Environ. Monit. Assess. 88 (1), 409–418. https://doi.org/10.1023/A:1025545813057.

Wiggins, A., Crowston, K., 2011. From conservation to crowdsourcing: a typology of citizen science. 2011 44th Hawaii International Conference on System Sciences, pp. 1–10 https://doi.org/10.1109/HICSS.2011.207.

Wikiloc, 2021. Wikiloc | The Outdoor Trail App for iPhone and Android. Wikiloc | Trails of the World. https://www.wikiloc.com/navigation-app.

Wilderman, C.C., Alissa, B., Imgrund, L., 2004. Top Down or Bottom up? ALLARM's Experience With Two Operational Models for Community Science.

Wilkinson, J., Boxall, A., Kolpin, D., 2019. A novel method to characterise levels of pharmaceutical pollution in large-scale aquatic monitoring campaigns. Appl. Sci. 9 (7), 1368. https://doi.org/10.3390/app9071368.

Wu, F., Hicks, A.L., 2020. Estimating human exposure to titanium dioxide from personal care products through a social survey approach. Integr. Environ. Assess. Manag. 16 (1), 10–16. https://doi.org/10.1002/ieam.4197.

Zettler, E.R., Takada, H., Monteleone, B., Mallos, N., Eriksen, M., Amaral-Zettler, L.A., 2017. Incorporating citizen science to study plastics in the environment. Anal. Methods 9 (9), 1392–1403. https://doi.org/10.1039/C6AY02716D.