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TOPICAL REVIEW

Advancing ambient water quality monitoring and management through citizen science in low- and middle-income countries

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Abstract

In contexts where conventional environmental monitoring has historically been limited, citizen science (CS) for monitoring efforts can be an effective approach for decentralized data generation that also raises scientific literacy and environmental awareness. To that end, the United Nations Environmental Program is considering CS as a mechanism for producing ambient water quality data to track progress on sustainable development goal (SDG) indicator 6.3.2: *'proportion of bodies of water with good ambient water quality'*. However, the alignment of SDG 6.3.2 monitoring requirements with CS capacity and results in low- or middle-income countries has not been assessed. Through a systematic literature review of 49 journal publications, complemented by 15 key informant interviews, this article examines the methods and outputs of CS programs in resource-constrained settings. We explore the potential of these programs to contribute to tracking SDG 6.3.2. Using the CS impact assessment framework, we evaluate broader outcomes of CS programs across 5 domains: society, economy, environment, governance, and science and technology. Despite large variability in scope, CS programs were consistently found to generate useful data for national-level reporting on physicochemical and ecological parameters; however, data quality is a concern for CS measurement of microbiological parameters. The focus in literature to-date is predominantly on scientific data production which falls only within the 'science and technology' outcome domain. Societal, governance, economic, and environmental outcomes are infrequently evaluated. Of the studies reviewed in this article, 75% identified some form of pollution but only 22% of them reported follow-up actions such as reporting to authorities. While CS has important potential, work is still needed towards the 'formalization' of CS, particularly if intended for more vulnerable contexts.

1. Introduction

The United Nations' sustainable development goal (SDG) indicator 6.3.2 emphasizes the importance of ambient water quality monitoring as a means to ensure the safety of water resources and protect human health and ecosystems. However, many countries struggle to meet the indicator 6.3.2 reporting requirements due to limitations in financial resources, technical expertise, and inadequate monitoring infrastructure (Kirschke *et al* 2020). The latest UN Water report 'Progress on Ambient Water Quality Mid-term status of SDG Indicator 6.3.2 and acceleration needs, with a special focus on Health' (UN Water 2024) summarized data for indicator 6.3.2 from unique 120 country records (up from 98 in 2020), but significant data gaps remain (figure 1). In 2023, over 2 million water quality measurements were used to report on this indicator, but the countries that represent the lowest-income half of the world contributed less than 3 per cent of this total (60,000). The widespread gaps in ambient water quality data hinder formulation of evidence-based policies and impede effective decision-making for water resource

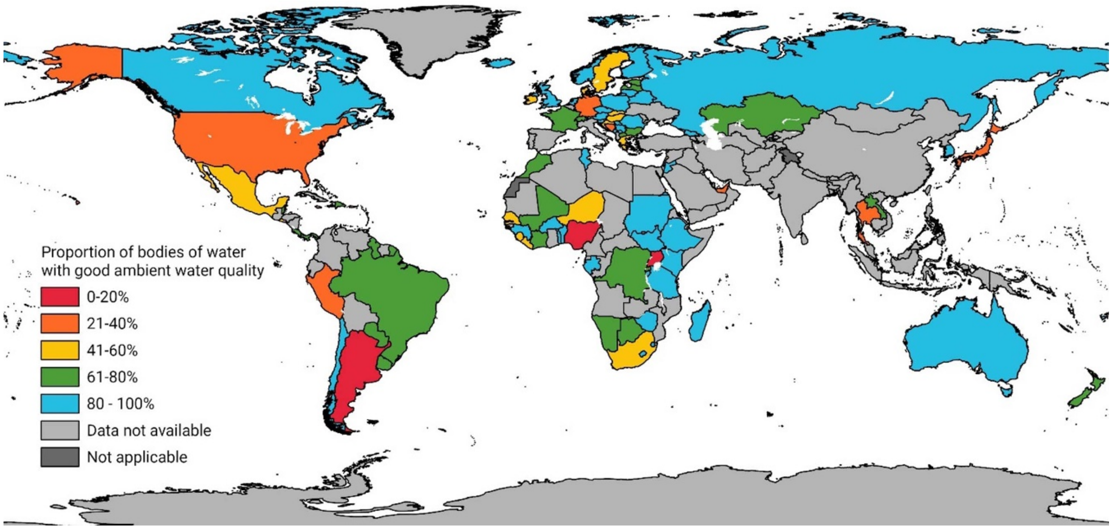

Figure 1. Proportion of bodies of water with good ambient water quality by country, 2017–2020. Countries without sufficient SDG 6.3.2 data are shown in grey. Reproduced with permission from 'Summary Progress Update 2021: SDG 6—Water and Sanitation for All', United Nations, 2021. Reproduced with permission from United Nations Environment Programme (2021).

management. An estimated 4.8 billion people, whose health and livelihoods depend on unmonitored ecosystems, are at risk if ecosystem degradation compromises their drinking water, fisheries, and other ecosystem service (UN Water 2024).

SDG indicator 6.3.2 reporting is designed to enable a comprehensive assessment of ambient water quality: reporting requirements are structured in two levels. Level 1 focuses on global priority indicators including nitrogen, phosphorus, oxygen, pH, and salinity. Level 2 focuses on more context-specific monitoring and data collection (UNEP 2023). Both Levels are challenging for resource-constrained countries because traditional water quality monitoring approaches, reliant on expensive equipment and trained personnel, often prove impractical and financially burdensome (Kirschke *et al* 2020).

Data collection costs are further exacerbated by the complexity of monitoring ambient waters across vast geographical areas with diverse ecosystems, geologies, climates, and anthropogenic drivers of water quality. To add to the challenge, United Nations Environmental Program (UNEP) guidelines recommend that data be collected for at least three years to determine baselines and account for seasonality (UNEP 2023). To overcome these challenges and enhance water quality monitoring, alternative methods are used. These include remote sensing and modeling, which aim to improve the cost-effectiveness and scale of data collection and analysis (Yang *et al* 2022). However, primary data are still required to calibrate and validate models and remote sensing of water quality remains a complex challenge (Chen *et al* 2022) with accurate measurement limited to optically active parameters (Gholizadeh *et al* 2016, Cao *et al* 2022).

In recent years, citizen science (CS) has emerged as another potential approach for reducing the costs of ambient water quality monitoring by engaging local communities in water monitoring initiatives. As noted by Haklay *et al* (2021): '*defining citizen science and its boundaries remained a challenge, and this is reflected in the literature—for example in the proliferation of typologies and definitions. There is a need for identifying areas of agreement and disagreement within the citizen science practitioner's community on what should be considered as citizen science activity.*'

Acknowledging this ambiguity, this article reserves the CS label for water quality monitoring programs in which citizens directly produce water quality data, meaning that measurements of water quality parameters are done by non-expert citizens. Thus, cases where citizens were only consulted or informed about monitoring are not included in our definition of CS for the purposes of this article. By involving non-experts in data collection, CS programs have the potential to fill data gaps and increase the spatial coverage of water quality monitoring (Kelly-Quinn *et al* 2023).

To actualize the potential of CS to fill data gaps, projects must grapple with data use and reporting challenges, which have been highlighted in studies of CS environmental monitoring projects. For instance, Theobald (2015) notes that the majority of CS-collected data do not reach peer-reviewed literature. Nerbonne and Nelson (2004) found that CS projects are commonly designed to increase public awareness but not to drive structural or legislative change. Several studies have specifically evaluated aspects of CS for SDG reporting in low- and middle-income countries (LMICs) (Pateman *et al* 2021), for ambient water quality monitoring (Capdevila *et al*

2020, Wu *et al* 2022) and more specifically for SDG 6.3.2 reporting (Quinlivan *et al* 2020, Hegarty *et al* 2021). However, the potential of CS for SDG 6.3.2 reporting in the specific context of LMICs had not been systematically reviewed. This is partly due to the absence of nationally coordinated efforts to utilize CS for ambient water quality monitoring in LMICs prior to October 2021. This has changed in recent years; for example, Earthwatch and UNEP have collaborated through the World Water Quality Alliance (WWQA) to support CS programs in collecting nationally relevant ambient water quality data sets in Sierra Leone and Tanzania (Warner *et al* 2021).

A specific review of CS outcomes in LMICs as opposed to in high-income countries (HICs) is warranted, for example, because of differences in the opportunity costs of volunteering and the availability of resources to respond to identified pollution problems. Thus, this review examines whether the methods and outputs from CS ambient water quality monitoring programs in LMICs are useful, in terms of the quality, focus and format of produced data, for tracking progress on SDG indicator 6.3.2.

Further, to review outcomes beyond data production, we build on previous investigation of the participant experience of public engagement in water science following from Walker *et al* (2021). Their 2021 review demonstrated the importance of evaluating participant experiences to understand the full scope of CS impact. Their results pointed to a need for more research to understand the participant experience of water-related CS particularly in the 'Global South'. Earlier reviews of the participant experience of environmental CS included limited water-focused cases, mostly from HICs (e.g. Stepenuck and Green 2015). Thus, attention to the participant experience is an important inclusion in our work, which aims to be relevant for the ongoing dialogue on leveraging CS to achieve SDG 6.3.2 targets and ultimately improve water quality management in LMICs.

2. Methodology

2.1. Impact assessment conceptual framework

Given the surge in popularity of CS in the past decade, research has increasingly assessed impacts from CS projects. Chandler *et al* (2017) assessed 51 Earthwatch projects, which spanned 7 yr and aimed to understand outcomes across various domains. Similarly, the European Union funded study 'Citizen Science for Environmental Policy' (Turbé *et al* 2018) looked at 45 EU CS projects across 94 dimensions. As Chandler *et al* (2017) demonstrated, use of evaluation tools can improve reporting and increase project outcomes. However, to date, there is no universally accepted approach for evaluation of CS projects. In our work, we chose to apply the CS impact assessment framework (CSIAF). The CSIAF was developed based on empirical qualitative analysis by the EU Horizon 2020 funded "Measuring Impact of Citizen Science" project). As demonstrated by Wehn *et al* (2021), it has proven value for structuring qualitative review of CS projects that reflects the importance of participant experiences and captures a breadth of outcomes beyond data production. It has been taken-up as an evaluation framework by high-profile water CS projects such as the EU Horizon funded MONOCLE and FreshWaterWatch projects.

The CSIAF guides evaluations of CS programs to consider outcome indicators across 5 domains: society, economy, environment, science and technology, and governance. The inclusion of each indicator is supported by peer-reviewed empirical evidence (supplementary table 3). The society domain includes 43 outcome indicators and is concerned with CS impacts on individual and collective values, understandings, behaviors and well-being. The economy domain considers impacts on production and exchange of goods and services (8 indicators). The environment domain focuses on bio-chemical-physical impacts, including changes in the quantity and quality of natural resources (6 indicators). The science and technology domain guides evaluations to capture impacts on scientific methods and research activities more broadly (16 indicators). Finally, the governance domain focuses on formal and informal decision-making institutions, including impacts on processes and relationships within and between institutions (9 indicators). Supplementary table 3 provides the full list of CSIAF outcome indicators with links to supporting information.

2.2. Data collection and qualitative analysis

We conducted a systematic literature review to identify publications reporting on CS ambient water quality monitoring programs in LMICs (section 2.2.1). Acknowledging the limitations of journal publications as a sole source of evidence, particularly due to inconsistent reporting and journal scopes, interviews were conducted to collect primary data to complement, compare, contrast, and nuance insights from the literature considered (section 2.2.2). We compare the methods and outputs of the assessed CS programs against the monitoring requirements of SDG indicator 6.3.2 (supplementary figure 1; section 3.1). To develop contextual understanding and characterize variability in the scope of the CS programs, we summarized program aspects including the types of water body being monitored, the uses of the monitored water, the number and types of citizens participating, and the program duration (section 3.2). Finally, we evaluated the findings of the assessed CS programs against the multi-dimensional outcome indictors set-out by the CSIAF. We used a lenient tabulation approach, which means we recorded outcomes that were reportedly pursued in each case study even if they were not fully defined or measured (section 3.3).

2.2.1. Systematic literature review

A literature review was conducted following the Reporting Standards for Systematic Evidence Synthesis (ROSES) methodology (Haddaway *et al* 2018). The search terms for the review were chosen based on key studies including Capdevila *et al* (2020), Kirschke *et al* (2022), Wu *et al* (2022) and Cunha *et al* (2017): 'Water OR Water Quality OR Surface Water OR Groundwater' AND 'Citizen Science OR Citizen Engagement OR Community Science OR Community Monitoring OR Crowdsourcing' AND additional filter for names of low-income countries (LICs), LMICs, and upper-middle-income countries (UMICs) as per the World Bank 2023 list ('World Bank Country and Lending Groups – World Bank Data Help Desk'). Searches were run on the Web of Science and Scopus databases for English and Spanish language articles published before April 2023. The database searches yielded >8000 results so a semi-automated selection tool (Rayyan.ai) was exploited for the pre-identification of relevant publications. A set of 67 'seed' papers that were manually identified by the first author were utilized to iterate ('train') the ranking system of the tool, speeding up the process of identifying publications that meet the inclusion criteria. The reference lists of the articles identified through the database searches were also manually scanned by all authors for additional peer-reviewed articles to include in the review. An additional 3 articles were included through this manual scanning process.

Criteria for inclusion were: (1) publication must be peer-reviewed to mitigate against issues of bias in evaluations of and reporting from CS programs; (2) non-expert citizens directly contributed to water quality data production (for the purpose of this review, 'citizen' is defined in line with Sakai *et al* 2018 as any individual without prior formal skills training relevant to the task performed); (3) water quality monitoring was done according to standard techniques with technology that had been validated; and (4) ambient water quality was monitored, excluding cases where only drinking water quality was monitored. This final criterion was used because, while there is a large overlap between the chemistry and tools for drinking and ambient water monitoring, the legal as well as societal implications (as well as the specific SDG indicators) are substantially different. Semi-structured key informant interviews.

2.2.2. Semi-structured key informant interviews

Interviews were conducted to deepen and nuance insights from the literature. Key informants were selected based on direct participation in one or more of the following activities in the last 10 yr: (1) developing and or managing a CS ambient water quality monitoring program; (2) developing a technology or tool specifically for CS ambient water quality monitoring; or (3) engaging ('on the ground') with citizens in training and implementation of technologies for ambient water quality monitoring. Initial contacts were identified as authors of key publications reviewed in early literature scoping (three of which are authors of studies included in the review) or as active members of the 'Citizen Science for SDG 6.3.2' workstream of the WWQA. Further connections with key informants were made via snowball sampling. A total of 15 key informants were selected to represent the global CS ambient water quality monitoring community broadly. Their experiences were not exclusively from LMICs (table 1). This provided insight into the experiences, attitudes, and assumptions within the CS community regarding the particular potential and challenges of CS implementation in resource constrained settings.

Interviews were conducted on zoom between May and August 2022. They lasted between 30 and 60 min. To develop a more wholistic systems-based perspective on CS program implementation (Meadows 2008, Arnold and Wade 2015) the semi-structured interview guide focused on: management structures and processes; legal considerations; financing models; limitations associated with specific technologies and contaminants; processes of data collection, management and use; and perceptions of the value of different program outcomes. Upon receiving informed consent, the interviews were audio recorded, transcribed verbatim using Trint automatic transcription software with manual correction, and coded in NVivo v12 through two cycles of inductive coding (Saldana 2021). The coding results informed the wider list of variables against which the systematic literature review results were compared (supplementary table 2) and enabled rich description of key determinants that influence CS program outcomes. Ethical approval for this research was received from the University of Oxford Central Research Ethics Committee (CUREC reference number: SOGE1A2021-076).

3. Results & discussion

The systematic review identified 49 publications for analysis (figure 2). Most of the publications (29) reported on CS ambient water quality monitoring in UMICs, another 17 publications reported on programs implemented in LMICs and only 3

Table 1. Summary of key informants.

Identifier	Role corresponding to selection criteria	Affiliated organization type	Years of experience	Zone(s) of experience
INT1	Management (1), Implementation (3)	Environmental Research Institute	> 10	Global
INT2	Implementation (3)	Academia	< 2	LIC
INT3	Management (1)	Environmental Research Institute	< 2	HIC
INT4	Management (1), Implementation (3)	Environmental Research Institute	> 7	HIC
INT5	Management (1), Implementation (3)	Academia	> 5	LIC
INT6	Management (1)	Academia, International Organization	> 10	HIC, LIC
INT7	Technology development (2)	Environmental Research Institute	> 5	HIC, LIC
INT8	Management (1)	Academia	> 7	MIC
INT9	Technology development (2), Implementation (3)	Environmental Research Institute	> 10	HIC
INT10	Management (1)	International Organization	> 7	Global
INT11	Management (1)	Environmental Research Institute	> 10	HIC
INT12	Management (1)	International Organization	< 2	Global
INT13	Management (1)	Academia	> 7	Global
INT14	Management (1), Implementation (3)	Government	> 10	MIC
INT15	Management (1)	Government	> 5	LIC

publications reported on programs implemented in LICs. The title, authors, journal, year, program country name, and World Bank country income category for each publication are listed in supplementary table 1.

3.1. Comparison with SDG indicator 6.3.2 Level 1 and 2 parameters

The range of parameters considered in the reviewed studies is highly variable and the SDG indicator 6.3.2 Level 1 parameters (nitrogen, phosphorus, oxygen, pH, and salinity) were measured in only 33% to 60% of cases (table 2). The most consistent set of parameters considered across the reviewed studies were temperature, turbidity (using a Secchi disk), pH (via strips), and some measurement of *N* and *P* (likewise with strips). The prevalence of these measurements in CS programs is largely associated with the popularity of the FreshWater Watch kit from Earthwatch. This might be an artificial skew given the recent 8 yr long HSBC-backed campaign, but the kit was reportedly used in projects outside the campaign too. Beyond water quality measurements, 31 studies also generated hydrological data, demonstrating value in integrating quantity and quality monitoring, although quantity parameters are not included in the SDG indicator 6.3.2 reporting requirements.

Across the reviewed studies, CS program measured parameters in all three Level 2 categories including physico-chemical, biological/ecosystem, and pathogens (table 2). In the physico-chemical category, few studies considered organic or inorganic pollutants, with only three studies measuring heavy metals and no study measuring organic pollutants or pollutants of emerging concern such as microplastics. For the biological/ecosystem category, the miniSASS method for macroinvertebrate sampling was common. Studies also reported citizen monitoring of algal blooms and cyanobacteria, though these remain rare. For the third Level 2 category, direct measurement of pathogen parameters (mainly *E. coli* and fecal coliforms) solely by citizens was reported in 12 studies.

Beyond assessing which parameters are being measured in CS programs, the key informant interviews highlighted that data quality control and assurance (QAQC) has implications for data uptake and utility for different purposes. Key informant INT4 suggested, based on more than 7 yr of experience managing CS programs in a HIC setting, that 25%–30% of samples should be cross validated with laboratory duplicate measurements for sufficient QAQC. This represents an additional cost for CS programs, although QAQC requirements vary across parameter types. For example, in the studies identified through

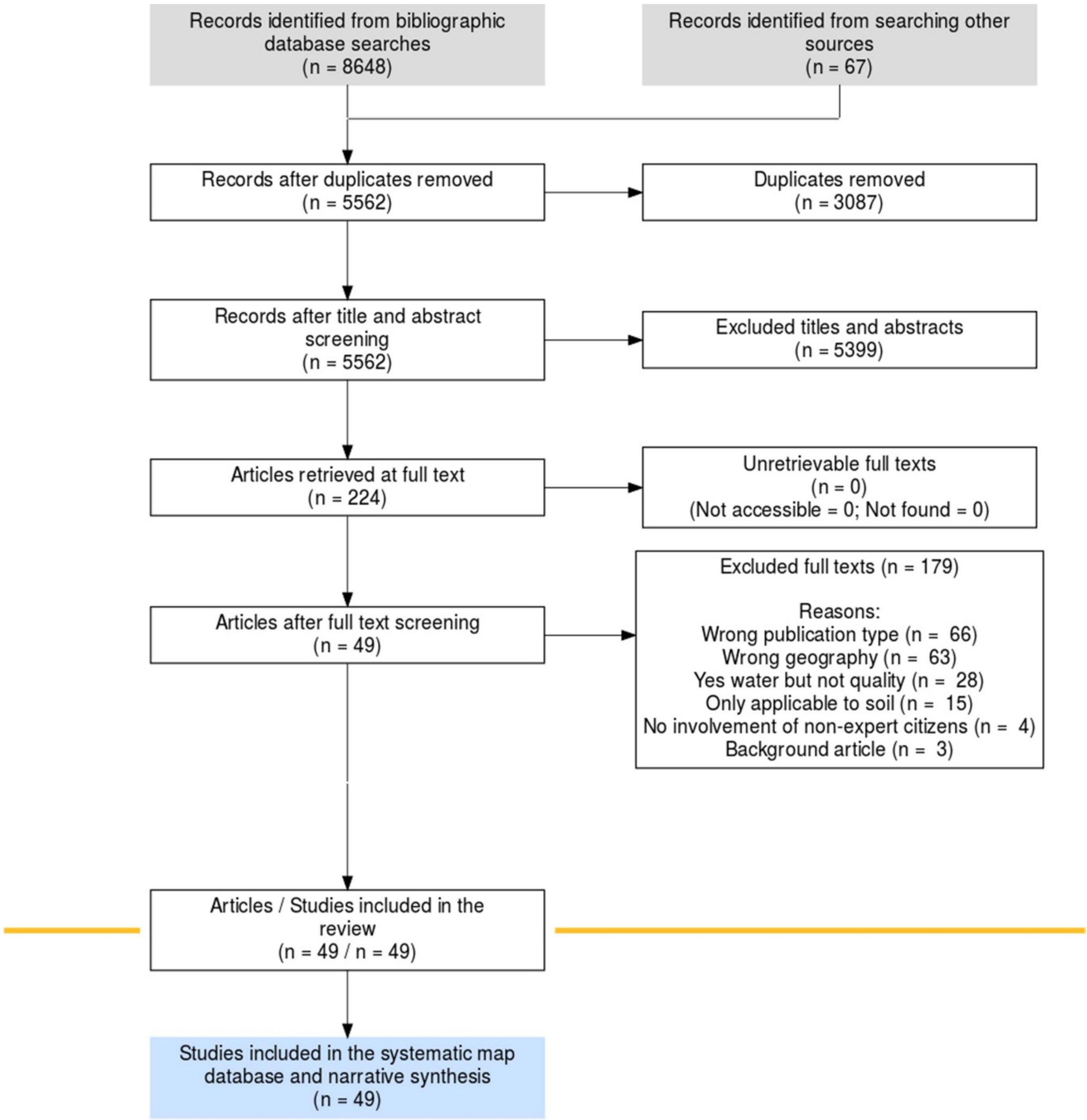

Figure 2. Systematic review flow chart based on the ROSES method.

Table 2. Parameters monitored through CS programs, from the reviewed studies.

SDG 6.3.2 reporting level	Category	Parameter	Number of cases
Level 1	Water Quality Index	Nitrogen	27
		Phosphorous	15
		Oxygen	18
		pH	21
		EC	17
Level 2	Physico-Chemical	Temperature	15
		TDS/Turbidity	31
		Heavy metals	2
		Other	0
	Pathogens	Bacteria	12
		Virus, protozoa	0
	Biological/ecosystem	Macroinvertebrates	3
		Algae, cyanobacteria, phytoplankton	5
		Birds	1

our systematic review, direct measurement by citizens of temperature and turbidity was consistently reported as being highly accurate. In-situ measurement is a key determinant of accuracy for these types of parameters, so cross-validation with laboratory duplicates may not be required or even feasible. Instead, best practices calibration records and storage temperature logs may be the best form of quality assurance. Some studies reported use of tools which are easy to use, such as apps to report pollution (Zheng *et al* 2017, Cochero 2018) and even some hydrometric data (Fehri *et al* 2020) but for which no QAQC may be feasible. This, however, is not to say that there is no value in these tools; one study even reported associated medium-term ecological improvements (Hsu *et al* 2020).

About half of the reviewed studies (22) mention specific data validation strategies (most commonly cross-testing with laboratory duplicates). The remainder do not mention strategies or limitations related to data QAQC, though (Fehri *et al* 2020) largely focuses on the topic of data fusion for near-automated ambient water quality data control. Moshi *et al* (2022) argue that there is a tendency for larger deviation between citizen measurements and expert laboratory measurements for pathogen parameters as compared to other parameters. This may be due to the increased complexity of microbiological sampling methods, the possibility of contamination of samples, and the low accuracy of current *in-situ* or onsite testing methods (Ramírez-Castillo *et al* 2015). While this is not an issue for mandatory Level 1 reporting, it indicates a limitation regarding which Level 2 reporting parameters can reliably be measured through CS.

3.2. The scope of CS ambient water quality monitoring programs

Here we characterize the reviewed CS programs based on general descriptors: the types and uses of waterbodies being monitored, the number and roles of citizen participants, and program duration.

3.2.1. Waterbody types and uses

Of the studies identified in our systematic review, 23 focused on rivers and 11 on lakes. Two studies focused on wetlands and one specifically on coastal waters. Coastal communities, particularly in small island nations, are among the most impacted by climate change (Lalit *et al* 2020), so particular attention to developing capacity for CS monitoring may be warranted in these settings. Beyond surface water, only 4 studies measured groundwater quality. This reflects that the infrastructure and techniques needed for groundwater monitoring, particularly for accessing groundwater to collect samples, are largely beyond the scope of a standard CS program. However, as the state of groundwater quality remains uncertain, and with clear signs of deterioration worldwide (UN WWDR 2022), the need for data is highlighted. The UNEP has recently developed guidance on groundwater monitoring (and reporting) for SDG indicator 6.3.2 (UNEP 2023). Although this guidance is not targeted for CS, it could be valuable to inform the design of future CS programs.

The reviewed studies represent a balanced split of rural (20) and urban (15) or peri-urban (12) focus, but interestingly only 2 including a mix of rural, peri-urban, and urban localities. The waterbody usage characteristics were also varied: 25 were considered mixed-use, 10 predominantly agricultural use, 6 predominantly commercial use, 5 predominantly environmental services use, with no study focusing on waterbodies primarily used for recreation. Given interest groups that have been associated with successful long-standing CS programs, such as anglers and surfers (Brooks *et al* 2019, Bresnahan *et al* 2022) this is an avenue to be further explored.

None of the reviewed studies directly mentions citizen scientists' main economic activities being directly impacted by water quality (or their main economic activities impacting water quality). Notably, only one study focused on assessing pollution risks from a specific industry (mining) (Ruppen *et al* 2021). As the transition to low carbon economies drives the demand for key minerals, often found in LICs and LMICs (Church and Crawford 2020), CS programs may have an important role to equip populations with skills necessary for sustainable development.

3.2.2. Citizen participation

Only 30 (62%) of the reviewed studies reported the number of participants involved. Across these studies the total participation ranged from 5 to nearly 2000 citizens, with a median of 40 and an average of 219. For the larger programs, a reportedly successful program structure can be categorized as 'nested clustering', were a more experienced citizen or professional is 'in charge' of a small group of citizens, they in turn report to a project coordinator who then aggregates data, flags issues (such as cross-site inconsistency) and ultimately reports (INT1, 7, 11, 14, 15). These project coordinators are either formally trained scientists or citizen scientists who have been involved in the program for a longer time and are comfortable with the tools used. This tactic helps with retention and participants can be 'promoted' within the program to become trainers or supervisors. The interviews highlighted a need for feedback across scales, which is facilitated by this type of structure. Cluster leaders can sufficiently provide personalized feedback to participants and at the same time, they can send 'up' feedback to coordinators, to raise questions about pollutants, identify priority sites, and inform other bottom-up tailored improvements.

The role of renumeration in encouraging citizen participation is subject to active debate with contrary views expressed in both the literature and by key informants. Of the reviewed studies, 4 report that participants received renumeration, and they encourage it not as a form of income or reward but rather as a means to overcome participation barriers.

For instance, a study reported that: '*real payment or reward was not necessary, since the intrinsic motivation of the participants seemed to be sufficient when lack of money was overcome*' (Weeser *et al* 2018, p 1597). Beyond direct payments, providing participants with the airtime necessary for data transmission was particularly encouraged by key informant INT5.

Besides renumeration, another key driver of recruitment is citizen interest in learning from the monitoring results. This driver can be amplified if citizens have input into the monitoring program design and objectives. This type of 'place-based' CS that prioritizes local needs has also been argued to improve likelihood of projects to contribute to management decisions (Chandler *et al* 2017, van Noordwijk *et al* 2021). Our interviews highlighted that citizen involvement in monitoring program design has real potential for bottom-up knowledge co-creation and for making CS programs more relevant to citizen priorities. For example, key informant INT5 highlighted that outbreaks of pathogenic disease can motivate citizen interest in monitoring microbial water quality and changing personal and community behavior in response to monitoring results. Nevertheless, the studies in our systematic review demonstrate that citizen input for monitoring program design is largely not being sought in resource-constrained settings: only 3 studies mention some involvement of citizens in the selection of sampling sites and/or parameters (Flores-Diaz *et al* 2018, Baalbaki *et al* 2019, Rivas *et al* 2020). The predominant role of citizen participants across all the reviewed programs was taking direct measurements (*in-situ*) and/or collecting samples to send for laboratory analysis, with fewer studies reporting data analysis, interpretation or communication done *by* citizens. Thus, citizen engagement in these programs depends on the alignment of their interests with the objectives set by program management.

Finally, while recruitment is important, the total number of participants is only a partial indicator of citizen engagement. The issue of 'superusers' was highlighted by key informant INT8, who explained that in their experience managing CS programs in a middle-income country setting, it is not uncommon that about 20% of participants contribute about 80% of the data. This has important implications for data quality because biases might be introduced and distort the data sets. We cannot assess how widespread this issue may be because the reviewed literature from LMICs did not report on imbalances in participant contributions.

3.2.3. Program duration

Since water quality management relies on understanding baseline conditions (particularly relevant for setting targets), long-term monitoring is important. However, this is often not reflected in the timelines of CS campaigns, particularly those more academic in nature, which are driven by a variety of other factors such as funding cycles. This is not to say that one-off, short-term programs are not valuable. They can serve a purpose of '*getting the ball rolling (…) in terms of water quality outcomes it can be a drop in the ocean, but it can also be a crucial piece of evidence*' (INT13). For example, one area where short-term CS programs can contribute important evidence is with respect to trialing new technology. Key informant INT12 spoke about a Global Environmental Monitoring System for freshwater (GEMS/Water) project based in 5 different countries (including 4 LMICs) that will be exploring a new technology for monitoring polar organic pollutants with samples collected by citizens. Nevertheless, for CS to offer a reliable pathway for tracking progress on SDG indicator 6.3.2, sustained monitoring initiatives will be needed.

Key informants spoke of examples of long-standing CS programs in HICs, such as the Angler's Riverfly Monitoring Initiative, which has continued and grown in the UK since 2002. But no such examples were available from low- or medium-income countries. Of the studies identified in our systematic review with reported durations, 18% were conducted for less than a year, 59% were conducted over 1–2 yr, 22% were conducted for 3–5 yr, and 6% were conducted for more than 5 yr. No studies lasted or are planned to last for more than 10 yr.

3.2.4. Program funding type

Of the cases reviewed, 18 were privately funded through corporate social responsibility and similar programs, with one additional project funded privately by a community. Ten were funded by local government and a further two had higher-level government funding. Nine were funded through academic research programs and 2 through direct foreign aid. Four had a blend of funding sources and 3 did not provide sufficient information to identify the funding source. Out of the programs with duration of 3 yr or more (in line with the needs of SDG 6.3.2), there was no dominant type of funding. There is no observed relationship between the funding type and the types of outcomes achieved or reported by the CS program cases. For example, only 25% of the publicly funded cases evaluated any outcome that could be classified in the governance domain, or as Chandler *et al* (2017) might refer to as a 'contribution to management plans'. Instead, the focus remains largely on data production. The duration of CS projects has significant implications for the type of outcomes that can be achieved, so it is important that funding duration aligns with the goals that projects seek to accomplish.

3.3. Multi-domain outcomes and the perceived value of CS

A theme that arose across the key informant interviews is that the ability to secure funding and participant engagement, particularly for long-term CS programs, depends on the perceived value of CS outcomes. Yet the literature and key informants supply limited evidence of CS outcomes, particularly because programs are often short (<2 yr) and lack evaluation. The CSIAF proposes that CS programs should be evaluated with reference to outcomes in societal, economic, environmental, scientific/technical, and governance domains. Given that we reviewed journal publications, we recognize that the CS programs may have had outcomes across several domains that were not evaluated or reported. For example, when asked about the main achievements of their CS program, key informant INT8 said:

'*I think top one is scientific literacy. Do you know, is this the correct term, scientific literacy? But, again, I think we still fail to measure the impact on scientific literacy, I do not think we have, you know, good methods to assess how we impacted the volunteer so i am talking about, you know, my perceptions… I really wanted to avoid a monitoring for the sake of monitoring, you know… or collecting data for publishing papers on Science of the Total Environment or any top journal. I think this is also important, but the priority is to develop scientific literacy.*'

Increased scientific literacy is widely highlighted as a desired outcome in the literature and was also discussed by other key informants. Yet only 7 of the reviewed studies explicitly reported that participants were taking measurements for which training was required. For example, Moshi *et al* (2022) reported that participants received a week of training on both practical and theoretical aspects of sampling. Other studies reported training that ranged from 15 min (Zheng *et al* 2022) to 25 d (Perez-Belmont *et al* 2019). However, we presume that in all cases there was some degree of instruction for participants. None of the studies reported outcomes of the impact of training on the scientific literacy of participants.

Although the lack of outcome evaluation evidence is a clear limitation, we seek to understand the extent to which different outcomes are pursued in CS programs. To that end, we evaluated the reviewed studies against the 5 domains of the CSIAF using a lenient tabulation approach, identifying where indicators from the framework had been explicitly or implicitly mentioned. We recorded an outcome as having been pursued if it was described in the study at all, even if not fully defined or measured (table 3).

Of the 49 studies we reviewed, 96% focused on outcomes in the scientific/technical domain. Governance and society domain outcomes were explicitly defined in 11 and 4 studies, respectively. However, these domains also had the most vaguely defined outcomes with a further 13 and 17 studies reporting governance and society outcomes that were only somewhat defined. In these cases, the studies commented on the demonstrated potential of approaches employed for integrating CS monitoring in specific contexts, often looking at specific pollutants or sources of pollution. Given that the arguments for *why* citizens should want to engage in CS programs could largely be classified under the society domain, it is problematic that only 8% of the reviewed studies had a clear definition of such outcomes.

Economy and environment outcomes, which would also presumably motivate citizen engagement and support the case for funding CS, had the least attention in the reviewed studies. Only 1 study explicitly indicated a desired outcome that could be characterized in the economic domain: '*The ultimate aim in the MARVI project was to improve farmer livelihood and sustainable use of water through the formation of village groundwater cooperatives with their own governance mechanisms, sanctions and rules for groundwater use. Further, there was significant focus on both demand and supply side managements to improve livelihood*' (Jadeja *et al* 2018, p 66).

Data on cost associated with these programs was not always sufficiently reported, even the cost of consumables, which is important information to make a case to potential CS funders, was only explicitly mentioned in a single study (George *et al* 2021).

The environment domain was not much better, only 2 papers reported achievement of any specific environmental outcomes. Nearly all of the reviewed studies in which generating good quality data was the main aim of the study (as opposed to studies reporting trials of a new tool) reported some level of elevated pollution (37 studies). Of the studies that reported pollution, only 30% (11 studies) reported any follow-up activity such as informing environmental agencies or community leaders. Long-term implications for the communities were also not commonly discussed, with a notable exception of Ruppen *et al* (2021) noting:

'*The data generated in the community-based monitoring was presented by researchers and community monitors in a multistakeholder meeting in April 2019 and in the following, new insights from the monitoring have regularly been exchanged with various stakeholders from local government and mining industry. Most outspoken community monitors formed a pressure group and used the chemical data to advocate for their grievances, which reactivated the mediation process. (…) Even though the monitoring project was able to fulfill its key objectives of identifying the sources of pollution and evaluate health risks, the long-term improvement of the pollution situation in Hwange would need a commitment that exceeds the*

Table 3. Performance of the reviewed studies against the CSIAF outcome domains.

	Science & Technology	Governance	Society	Environment	Economy
Explicitly defined	47	10	4	2	1
Somewhat defined	2	13	16	6	3
Not mentioned	0	26	29	41	45

time-frame of a research funding scheme. In Hwange, some highly motivated community monitors wanted to continue sampling after the official closure of the project but we could not provide the analytical infrastructure any longer.'

3.4. Conclusion and recommendations

Our study findings consistently indicate that CS programs have potential to provide suitable data for national-level reporting on physicochemical and ecological parameters, with some limitations particularly for microbiological parameters related to quality control challenges. However, CS programs to-date are usually not consistent with the timescale required to contribute to monitoring for SDG indicator 6.3.2, particularly where they seek to fill in data gaps in places where monitoring had not previously been done. Shorter-term projects are certainly still valuable, particularly if they expand on previous monitoring efforts or support monitoring technology innovation.

Societal, governance, economic, and environmental outcomes have been evaluated infrequently in the literature, although they often form the basis of arguments for funding CS. We highlight that programmes calling for citizens to engage with data production should be done with sensitivity and realism around citizen expectations for change. This is particularly true where the demand for CS monitoring is due in part to the failure of governments to sufficiently monitor and manage environmental hazards. Further, in agreement with Chandler *et al* (2017), we emphasize the value of evaluation tools that include participant perspectives. These tools can help hold projects accountable and highlight to managers and scientists the characteristics of projects that lead to improved outcomes. With some key intentional management choices, more value can be derived and captured from projects.

CS, despite great potential and some encouraging precedent, is still relatively underutilized in LMICs. Several geographies, including regions facing particularly severe climate change risks such as Small Island Nations, Central America and the Caribbean, and Central Africa, have not seen substantial precedent of utilization of CS. Additionally, a wide range of hydrological contexts such as groundwater, wetlands, and coastal and near-coastal waters have also not been monitored through CS initiatives in LMICS. Key findings and associated recommendations arising from each finding are summarized in figure 3. We suggest the following to improve the uptake of CS for national datasets and SDG 6.3.2 reporting:

- Inclusion of laboratory validation for at least 20% of samples (lab testing and field tools go hand-in-hand for cost-effective high-quality data collection).
- Opportunistic inclusion of hydrological data collection, which adds value at a relatively low incremental cost.
- Inclusion of local water quality needs (Level 2 parameters) as priority for local engagement.
- Attention in data interpretation to 'superusers', who are the largest contributors to datasets but can also skew them. Consideration of 'superusers' is important both for data quality and for project management because highly engaged participants are critical for project longevity.
- Supplementing citizen efforts with professional monitoring of more challenging parameters such as microbiological contaminants.
- For sites where monitoring has historically not been done, program duration should be aimed to be no less than 3 yr to establish baselines and account for seasonality. Projects that are very limited in temporal scope should focus on sites where baselines are already established or should focus on trialing new monitoring technologies.
- Use of data fusion techniques (combination with modeling and remote sensing) to maximize the value of the data collected.
- Defining outputs and outcomes beyond the scientific and technical domain and, to that end, use the CSIAF, or similar, to guide program design, implementation and evaluation.
- Planning for appropriate response to pollution detection as integral part of program design and implementation.

SDG 6.3.2 Level 2 chemical pollutants have only rarely been monitored through CS. These are often the most locally relevant parameters of SDG 6.3.2 monitoring, which should be pursued as per the needs of local actors through co-creation of the projects. As van Noordwijk *et al* (2021) and Chandler *et al* (2017) argue, projects that are place-based and rooted in local context can have better outcomes. Campaigns which solely focus on parameters relevant to SDG 6.3.2 (and not for instance additionally drinking water) may miss opportunities to better

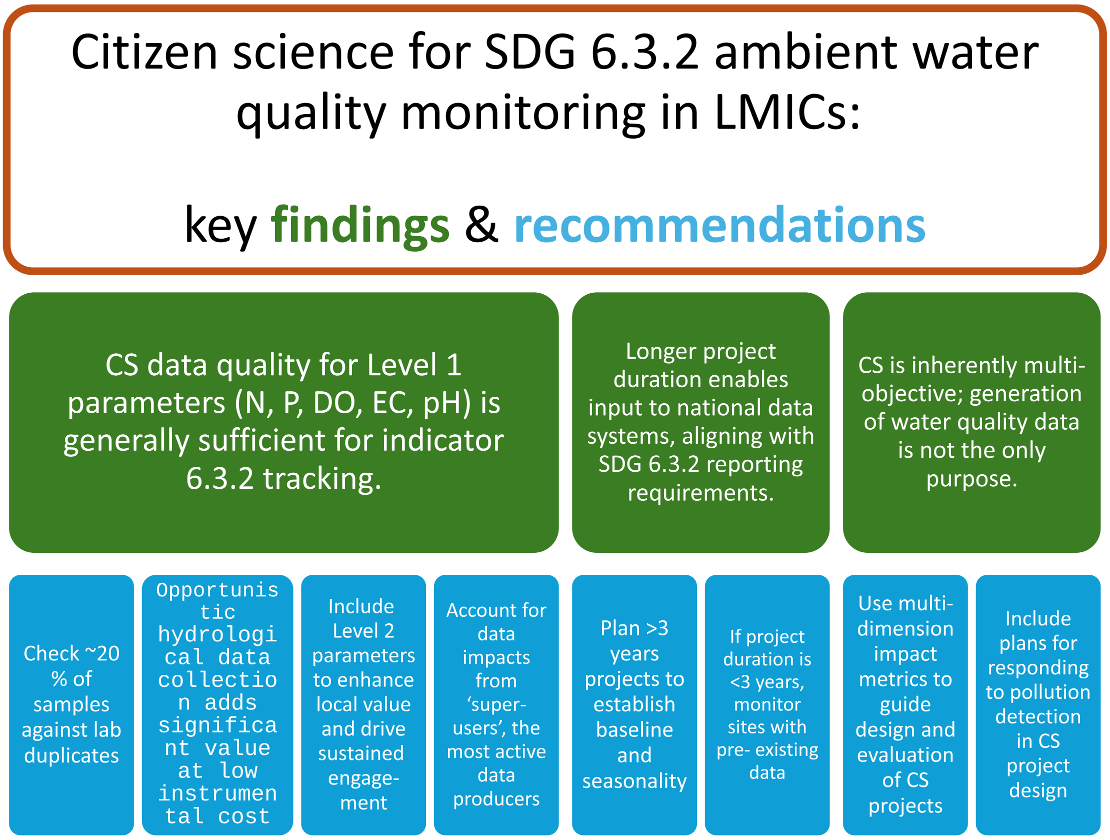

Figure 3. Selected findings and recommendations.

serve and equip communities. Pathways for CS programs to influence environmental, economic, societal, and governance outcomes should be considered with a realistic view of the willingness and resources to respond when environmental hazards are identified. While reporting data to support tracking of SDG indicator 6.3.2 at global level is a worthwhile endeavor, it does little to change the near-term outcomes for the citizens who are contributing their labor for the data collection.

CS must be understood as inherently multi-objective, where the generation of water quality data is not the only purpose. Management of water quality goes beyond understanding water chemistry or riverine ecology, so a siloed approach of focusing only on data collection is inherently incomplete. Efforts to coordinate CS development and approaches, catalyzed by the UNEP through the WWQA, are commendable since it is clear from our results that many key challenges, positional and practical, are being considered by various groups around the world. This review has highlighted the value of longer-term funding for CS projects to establish baselines and capture seasonality. Further to this, we recognize that longer project durations are important for building effective partnerships and establishing pathways for data use. Recent evidence has demonstrated the benefits of longer-term, outcome-based funding structures to enhance the effectiveness of science funding for advancing progress on the SDGs (Hope *et al* 2024). Furthermore, given the disparity in methodologies, protocols, and reporting items, a set of 'guidelines and recommendations for CS for SDG reporting' would be beneficial for practitioners and citizens who want to contribute effectively to SDG tracking. This guidance should account for the importance of flexible CS programming that is responsive to local context and participant interests. Beyond cost-effectiveness considerations, the inclusion of citizens, often directly impacted by the water quality issues studied, represents both an opportunity as well as a responsibility for champions of CS projects. Clarity of expectations and communication of limitations is important. Individual and societal outputs and outcomes should be clearly defined, measured, and reported so that CS programs systematically serve multiple objectives, including generating benefits for citizen participants.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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CRediT author statement

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Conflict of interest

The authors of this manuscript have no conflicts of interests to declare.

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