Journal of Environmental Management 372 (2024) 123414

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

# Supporting knowledge justice through community science air quality monitoring and a reciprocal reporting process

Valentina Serrano-Salomón [a,*], Marisa Westbrook [b], Noemy Pérez [c], Jay Pecenka [d], Aniya Khalili [f], Sumit Sankhyan [f], Shelly Miller [f], Shivakant Mishra [e], Esther Sullivan [d]

[a] Department of Sociology, University of Colorado Boulder, UCB 327 Ketchum 195, Boulder, CO, 80309, USA
[b] OHSU-PSU School of Public Health, Portland State University, 1810 SW 5th Ave, Portland, OR, 97201, USA
[c] Department of Sociology, University of Northern Colorado, Candelaria 2285, Greeley, CO, 80639, USA
[d] Department of Sociology, University of Colorado Denver, 1385 Lawrence St, Suite 420, Denver, CO, 80217, USA
[e] Department of Computer Science, University of Colorado Boulder, 430 UCB, 1111 Engineering Dr, Boulder, CO, 80309, USA
[f] Department of Mechanical Engineering, University of Colorado Boulder, 427 UCB, 111 Engineering Dr, Boulder, CO, 80309, USA

ARTICLE INFO

Handling editor: Lixiao Zhang

*Keywords:*
Community science
Air monitoring
Knowledge justice
Logics of inquiry
Environmental justice
Air quality

ABSTRACT

In community science on air quality, low-cost air monitors have emerged as an opportunity to democratize data reporting and support knowledge justice by providing participants with instantaneous access to air quality data. In this study, we equipped residents in four environmental justice communities in North Denver with low-cost air monitors to collect real-time air quality data for four separate 30-day field deployments over two years. We conceptualize an improvement to conventional report-back processes by suggesting a 3-part approach – a *reciprocal reporting process* that includes 1) bidirectional open channels of communication with participants, 2) democratized data access via instant monitor data and written data summaries, and 3) responsive intervention opportunities to respond in real-time to participants air quality concerns. Through 120 interviews with 30 air quality monitor users after each of the four field deployments, we identify how this reciprocal reporting process increased Air Quality (AQ) awareness and supported distinct modes of environmental learning, which we term *data-driven, health-conscious, and progressive logics of inquiry*. In addition, this non-prescriptive approach centered participants' alternative ways of knowing, such as sensory experiences to understand pollution exposure, and fostered collective learning that ultimately furthered knowledge justice. Our study highlights the potential for a more robust and holistic approach to report-back processes within community science projects to foster flexibility, reciprocity, and responsiveness.

## 1. Introduction

Community science, also known as citizen science or participatory science (Commodore et al., 2017), is a collaborative approach that enhances environmental justice by encouraging active involvement of residents in Environmental Justice (EJ) communities to address environmental concerns (Ottinger, 2023). Community science has gained prominence in EJ communities, particularly in air monitoring studies, which promote environmental awareness, community empowerment, education, and encourage behavioral changes (Masri et al., 2022; Schio, 2022).

Effective community science relies on methods of sharing data with participants. Most often this is done via report-back procedures which take a variety of forms, but generally entail reports of finalized data from study personnel to study participants (Brody et al., 2021; Claudio et al., 2018; Dobson et al., 2020; Morrens et al., 2021; Payne-Sturges et al., 2004; Polka et al., 2021; Tomsho et al., 2019). Low-cost air monitors democratize data reporting by providing participants with

*Abbreviations:* **U.S. EPA**, Environmental Protection Agency; **VOC**, Volatile Organic Compounds; **PM**, Particulate Matter; **AQ**, Air Quality; **FD**, Field Deployment.

* Corresponding author.
*E-mail addresses:* Valentina.serranosalomon@colorado.edu (V. Serrano-Salomón), marisaw@pdx.edu (M. Westbrook), nrod012@gmail.com (N. Pérez), jay.pecenka@ucdenver.edu (J. Pecenka), maryam.khalili@colorado.edu (A. Khalili), sumit.sankhyan@colorado.edu (S. Sankhyan), shelly.miller@colorado.edu (S. Miller), shivakaht.mishra@colorado.edu (S. Mishra), esther.sullivan@colorado.edu (E. Sullivan).

https://doi.org/10.1016/j.jenvman.2024.123414
Received 17 June 2024; Received in revised form 9 November 2024; Accepted 17 November 2024

instantaneous access to their air quality data (deSouza, 2022; Mahajan et al., 2021). But *how* research design enables participants to engage with, ask questions of, and respond to their data likely impacts their environmental understandings and the ultimate efficacy of community science. How then can increasing flexibility, reciprocity, and responsiveness in the report-back process shape the kinds of data collected and individual changes that may occur?

To answer this question, we equipped residents in four EJ Communities in North Denver with low-cost air monitors to collect real-time data for four separate 30-day periods over two years. Through focus groups within the community, the key community concerns that arose included construction and highway pollution – thus, we equipped residents with monitors using a sensor widely tested for measuring a composite index of particulate matter ($PM_{2.5)}$ volatile organic compounds (VOCs), and overall AQ scores. Over four 30-day monitoring periods (hereafter called “field deployments” or FDs), 102 community scientists viewed their air quality (AQ) instantaneously via an app while using the monitor. Additionally, we provided participants (and the public) access to anonymized AQ data through our study’s website and social media channels. Following each FD (FD1-4), we conducted 30 interviews with participants to discuss their experience (study sample = 60 individuals, 120 interviews total; see Fig. 2). After FDs 3 and 4 respectively, each participant received written and electronic PDF reports that further detailed and summarized their individual data. After the fourth FD, optional follow-up calls were offered with AQ experts on our team to address participants’ inquiries and concerns.

Our study seeks to understand how low-cost AQ monitors facilitate data gathering, contribute to environmental learning, and potentially foster *knowledge justice,* a conceptual framework that respects the authoritative voice and logics of inquiry of residents of EJ communities (Allen, 2018). We conceptualize our data-gathering and data-communications efforts as a multi-part report-back process, incorporating multiple forms of data input and visualization, and extending beyond conventional report back methods, as suggested by Becker et al. (2021). We refer to this multi-step, iterative process as a *reciprocal reporting process* that includes:

1. **Bidirectional open channels of communication with participants** to guide the project and address participants’ specific needs and interests. This included early-stage focus groups as we developed the study, post-FD individual interviews, and detailed data debriefs with AQ experts. We also engaged residents through regular text for troubleshooting, data syncing reminders, and answering questions.
2. **Democratized data access (via instant monitor data and written data summaries)** so study participants had easy access to individual and community-level data, and comparisons to U.S. Environmental Protection Agency (EPA) pollutant thresholds. Data included: instantaneous readings via a smartphone app connected to their AQ monitor [the Atmotube Pro]; written and electronic personalized AQ summaries; AQ data via a website for cross-cohort comparison; and FD summary 1-pagers.
3. **Responsive intervention opportunities** to respond in real-time to participant concerns and needs and encourage participants to further interrogate their assumptions, findings, and behaviors. We provided participants with a Corsi-Rosenthal box fan air cleaner (Sankhyan et al., 2023) to run in their homes and provided suggestions for improving AQ through written summaries and optional phone calls with AQ experts to discuss specific questions and provide advice.

To assess the impact of this reciprocal reporting process we ask the following questions:

- How does personal exposure monitoring facilitate knowledge production among community scientists? How does this change over time with the aid of the reciprocal reporting process?
- In what ways does a reciprocal reporting process address the documented limitations of conventional report-back methods, including: a) the lag between data collection, analysis and return; b) the identification of specific pollution sources; and c) the difficulties people encounter in comprehending technical data?
- How does the implementation of a home air cleaner intervention impact the learning process of community scientists?
- How does a reciprocal reporting process stimulate free-choice learning; inform individual and collective action; and/or contribute to knowledge justice?

## 2. Background

While community science fosters public participation (Brown et al., 2012); epistemic injustice, which involves the disregard of individuals’ knowledge capabilities, persists in Environmental Justice (EJ) communities (Ottinger, 2023). EJ communities are places where low-income and people of color are disproportionally affected by environmental hazards (Bullard and Wright, 1993). Residents of EJ communities are often denied status as knowledge producers by experts from regulatory agencies and industry (Ottinger, 2023). Often, their health concerns are ignored, or they are overwhelmed with science that does not reflect their observations (Allen, 2018). To overcome these challenges, *knowledge justice* offers a conceptual framework that respects the logics of inquiry of residents of EJ communities (Allen, 2018). Centering expert knowledge often marginalizes lay perspectives by reducing their perspectives to issues of “context” or “values” (Gagdil, Berkes, and Folkes, 2021; Healy, 2003). The rise of community science (Davis and Ramírez-Andreotta, 2021a,b) highlights the increasing recognition of resident insights as a valuable form of scientific reasoning (Santos, 2018).

Yet, recognizing alternative knowledge forms does not guarantee access to knowledge production and dissemination tools. Democratizing knowledge production requires reciprocal information flow (Corburn, 2005; Howarth and Monasterolo, 2017; Polk, 2015) for effective communication, community empowerment, and better decision-making (Corburn, 2002; Evans, 2004).

Addressing knowledge gaps and achieving knowledge justice within EJ communities involves reporting back exposure results (Adams et al., 2011; Morello-Froch et al., 2009). Report-backs facilitate co-created knowledge, environmental health education, and exposure risks awareness (Altman et al., 2008; Brody et al., 2014; Dobson et al., 2020; Downs et al., 2010; Tomsho et al., 2022). Environmental exposure report-back processes create a novel, informal educational environment encouraging free-choice learning (Lebow-Skelley et al., 2020). Ramirez-Andreotta et al. (2016:02) conceptualize free-choice learning as a “cumulative process involving connections and reinforcement among the variety of learning experiences people encounter in their lives.”

Reporting data back to participants enhances environmental health literacy (Altman et al., 2008; Claudio et al., 2018; Ramirez-Andreotta et al., 2016) and facilitates behavioral changes to reduce environmental exposures (Adams et al., 2011; Dobson et al., 2020; Semple et al., 2018; Tomsho et al., 2022). Additionally, this practice can lead to collective action by motivating participants to elicit change in their communities (Adams et al., 2011; Altman et al., 2008; Downs et al., 2010; Tomsho et al., 2018).

Despite benefits report-backs face limitations, including: the lag between data collection, analysis and return, the identification and communication of potential pollution sources, and selecting optimal timeframes to assess AQ relevant to home environments (Tomsho et al., 2022). Complex information can cause anxiety due to comprehension issues (Adams et al., 2011) especially in Spanish-speaking communities with limited science communication resources in environmental health sciences (Van Horne et al., 2023).

Environmental studies employ various report-back approaches in air monitoring, biomonitoring, and exposure studies through written, oral, and/or multiple reporting forms. However, many involve one-way communication of data from researchers to study participants (Brody et al., 2021; Claudio et al., 2018; Dobson et al., 2020; Morrens et al., 2021; Payne-Sturges et al., 2004; Polka et al., 2021; Tomsho et al., 2019). Conventional report back processes often serve the purpose of gauging participants' understandability of scientific data and, in some cases, occur after a substantial time gap following data collection (Adams et al., 2011; Becker et al., 2021). Some studies rely on single-time data collection efforts to report back to participants (Adams et al., 2011; Tomsho et al., 2019; Payne-Sturges et al., 2004; Dobson et al., 2020; Schollaert et al., 2018). A limited number of studies employ multiple instances of data collection. Yet, when this approach is adopted, stationary AQ monitors are used, and data is typically collected within participants' homes, thus preventing them from accessing real-time exposure data (Semple et al., 2018; Tomsho et al., 2018).

Our study is novel in different ways 1) we expanded conventional report back processes by considering all forms of data input and visualization as Becker et al. (2021) suggested 2) we conducted a long-term reporting process spanning two years of data collection using the Atmotube, a wearable personal air monitor that tracked participants' indoor and outdoor AQ over a 30-day period in each FD. Instantaneous real-time data through the Atmotube app granted participants immediate insight into their AQ scores from the outset of the study, eliminating the wait for end-of-study data 3) we implemented a reciprocal reporting process, where knowledge sharing was bidirectional through passive and active individual and community AQ reports, individual interviews, AQ interventions through a box fan air cleaner, and one-on-one calls to address questions and concerns. Through these mechanisms, participants shared their own observations and interpretations, and we reciprocated by conveying our findings to them. We consider participants monitoring, experimenting, and reporting as part of the studies' reciprocal reporting process.

This paper analyzes how various forms of learning were fostered by this reciprocal reporting process, and examines how these various forms of monitoring, reporting, and learning can contribute to knowledge justice.

## 3. Data and methods

The parent study, Social Justice & Environmental Quality – Denver (SJEQ-D), received ethics approval from the University of Colorado's Institutional Review Board. The study obtained informed written consent from all participants, as well as oral consent at the beginning of each interview.

### 3.1. Neighborhood context

This study involves residents from four neighborhoods in North Denver, Colorado –Globeville, Elyria-Swansea, Cole, and Clayton (GESCC), an EJ community with a history of environmental contamination. The zip code covering these neighborhoods was identified as the most polluted residential area in the US by at least one environmental index (ATTOM Data Solutions, 2016). The GESCC neighborhoods consist of various housing types and small businesses, industrial facilities, and major interstate highways. In 2018, a $1.2 billion project was approved to expand a ten-mile stretch of I-70 through the communities, leading to lawsuits citing environmental and health impacts (Meltzer, 2017).

### 3.2. Sampling and recruiting

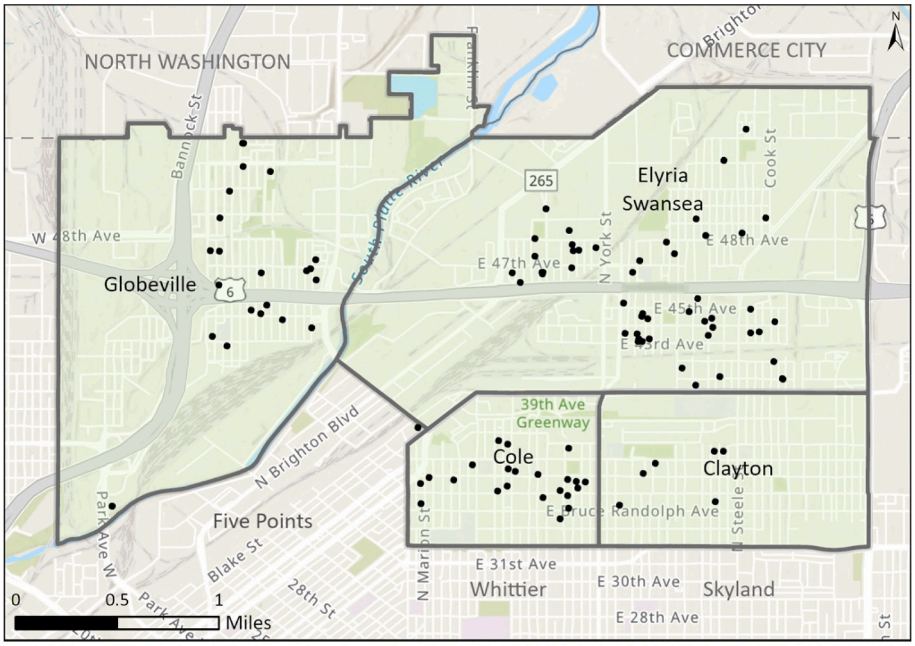
We recruited GESCC residents by conducting outreach with over fifteen community organizations and service providers through social media and newsletters, flyers in food assistance boxes, tabling at 40 local events, and distributing thousands of flyers door-to-door before each FD to ensure that our sample represented the majority Hispanic/Latino population of these neighborhoods (see Table 1). We employed four community connectors (residents from the neighborhoods trained on project design and goals) for recruitment. Using this strategy, we engaged 50 study participants to use AQ monitors for each FD, FD1 through FD4 across GESCC (see Fig. 1). Prior to the AQ monitor study, in the spirit of participatory research design, we engaged 32 community residents in focus groups in English and Spanish to identify their primary local environmental concerns – six of whom then participated in the AQ monitoring described here (for additional detail about the focus groups and participant recruitment, see Westbrook et al., 2024). While the general research topics were designed prior to neighborhood engagement, these focus groups and ongoing feedback from participants during our interviews helped the project team continually amend the research design.

After each field deployment with 50 monitor users (FD1-4), we invited a sub-sample – 30 monitor users each FD – to participate in an interview with the authors on the phone. Participants were selected for interviews if they participated in the full month of monitor use and did not have significant monitor malfunction. Interview participants were contacted in order of those who used it the most (according to days of data synced, identified as between 25 and 30 days). Participants received $30 for using the AQ monitor for a month and a $25 gift card for participating in interviews.

**Table 1**
Descriptive characteristics by study area (5 Census tracts) and air quality monitor sample group.

| | Census Area (*n=19,654*)[a] | AQ Monitor Group (*n=85*) (%) |
|---|---|---|
| **Gender Identity** | | |
| Men | 10,753 ± 991 (54.7) | 23 (26.06) |
| Women | 8,901 ± 673 (45.3) | 59 (69.41) |
| **Race Ethnicity** | | |
| Non-Hispanic White | 5,428 ± 737 (27.6) | 44 (54.32) |
| Non-Hispanic Black | 1,319 ± 354 (6.7) | 3 (3.70) |
| Asian or Pacific Islander | 189 ± 88 (0.96) | 1 (1.23) |
| Hispanic | 12,134 ± 1,223 (61.7) | 27 (33.33) |
| Indigenous American | 104 ± 77 (0.53) | 2 (2.47) |
| Other | 480 ± 191 (2.4) | 4 (4.94) |
| **Primary Language Spoken** | | |
| English | 9,306 ± 973 (50.3) | 72 (81.82) |
| Spanish | 8,891 ± 1,163 (48.0) | 16 (18.18) |
| Other | 310 ± 179 (1.70) | – |
| **Total Household Income** | *n = 6,658* | |
| 0 - $9,999 | 514 ± 161 (7.72) | 3 (3.53) |
| $10,000 – $24,999 | 968 ± 225 (14.5) | 8 (9.41) |
| $25,000 – $49,000 | 1,259 ± 297 (18.9) | 22 (25.88) |
| $50,000 – $74,999 | 1,179 ± 258 (17.7) | 16 (18.82) |
| $75,000 - $99,999 | 705 ± 145 (10.6) | 12 (14.12) |
| $100,000–124,999 | 569 ± 157 (8.55) | 8 (9.41) |
| More than 125,000 | 1,464 ± 259 (21.9) | 16 (18.82) |
| Income below third of the median | 1,482 ± 277 (22.3) | 11 (12.94) |
| Income below median | 3,920 ± 481 (59.0) | 49 (57.64) |
| **Education** | | |
| Less than high school | 3,729 ± 571 (30.4) | 7 (8.24) |
| High school diploma | 2,553 ± 407 (20.8) | 10 (11.76) |
| Some college | 2,357 ± 340 (19.2) | 17 (20.00) |
| Bachelors degree | 2,302 ± 299 (18.8) | 30 (35.30) |
| Graduate or professional degree | 1,331 ± 288 (10.8) | 21 (24.71) |

Note.
[a] All tract level data come from the 2021 American Community Survey 5-year estimates. Cell entries denote ordinal and categorical variables. Census tracts displayed in the table include United States, Denver County, Census Tract 15, Census Tract 35.01, Census Tract 35.02, Census Tract 36.01, Census Tract 36.02. All data on monitor users come from a subset of participants from the SJEQ-D longitudinal survey which was administered to 128 participants between 2022 and 2023.




Projection: WGS 1984
Public Data Source: County and City of Denver, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA, USFWS, Esri, NASA, NGA, USGS,

**Fig. 1.** Spatial distribution of air quality monitor users interviewed during four Field Deployments.
Note: Points jittered by a quarter mile to anonymize participants' homes, which obscures some unique households.

We conducted 120 interviews across four FDs with 60 unique individuals (see Fig. 2 for research design flow chart). Of the 60 unique individuals interviewed across time, 25 participants were interviewed only once, 17 participants were interviewed twice, 9 participants were interviewed three times, and 9 participants were interviewed four times (sample = 60 individuals, interviews = 120). All air monitor participants were surveyed on demographic and housing characteristics via Qualtrics before Deployment 1 (Table 1).

### 3.3. Air monitoring equipment

Participants carried the low-cost wearable AQ monitor Atmotube® PRO (ATMO®' San Francisco, CA, USA). Atmotube PRO is particularly good at measuring PM and VOCs, which is documented in a widely cited field and lab test conducted by the South Coast Air Quality Monitoring Division, in addition to several lab characterization studies done on the Sensirion SPS30 p.m. sensor (the $PM_{2.5}$ sensor contained within the Atmotube PRO) (Demanega et al., 2021; South Coast Air Quality Management District SCAQMD, 2021). Participants used the linked Atmotube smartphone app, which provides real-time AQ data to users. The study team translated the app's English language to Spanish and provided this information on paper.

### 3.4. Report-back approaches

We provided three individual reports. After the second FD (the earliest cleaned and analyzed data was available), we provided a paper summary of individual monthly $PM_{2.5}$ data. After the fourth FD, we also provided a paper summary of individual $PM_{2.5}$ data in each participant's box and emailed an electronic version of the individual report synthesizing data from all FDs in which a person participated. The electronic report detailed monthly, daily, and hourly $PM_{2.5}$ averages, explained $PM_{2.5}$, its measurement, health concerns, and included resources for tracking and/or reducing exposure. Each chart included the U.S. EPA thresholds for $PM_{2.5}$ 24-h average concentrations. Interviewers trained by environmental engineers on the project guided each participant through the charts depicting $PM_{2.5}$ variance levels at different timescales. During oral report-backs, we used visual aids (pictures comparing different PM sizes to familiar objects, scales, and graphs). We presented numerical information (AQ score) and graphs (monthly, daily, and hourly $PM_{2.5}$ averages). These were written in participants' language (English or Spanish) using plain language (while still including relevant AQ terms, such as VOC, $PM_{2.5}$, etc.). These strategies sought to ensure that participants understood their data meaningfully and could actively engage in the research.

### 3.5. Interviews

The authors conducted phone interviews after each FD (March–April 2022 for FD1; June–July 2022 for FD2; October–November 2022 for FD3; March–April 2023 for FD4). 30 participants were interviewed each time, some individuals interviewed after two, three, or all four FDs and our total sample includes 60 unique individuals. 23% of interviews were conducted in Spanish. The interview guide covered motivations for carrying the monitor, experiences from using the monitor and interpreting data in the home and neighborhood, and behavior changes from using the monitor. Before the FD3 and FD4 interviews, participants received a written summary of their data and were asked about their interpretation of their report. During FD4 interviews, participants also had their data summary reviewed and presented to them as an oral report-back by a project team member who walked through daily and hourly changes in their $PM_{2.5}$ exposure and answered questions they had. After FD4, participants could request a follow-up interview with team AQ experts if they had additional questions specific to their data and wanted feedback. All interviews were recorded, transcribed, and coded.

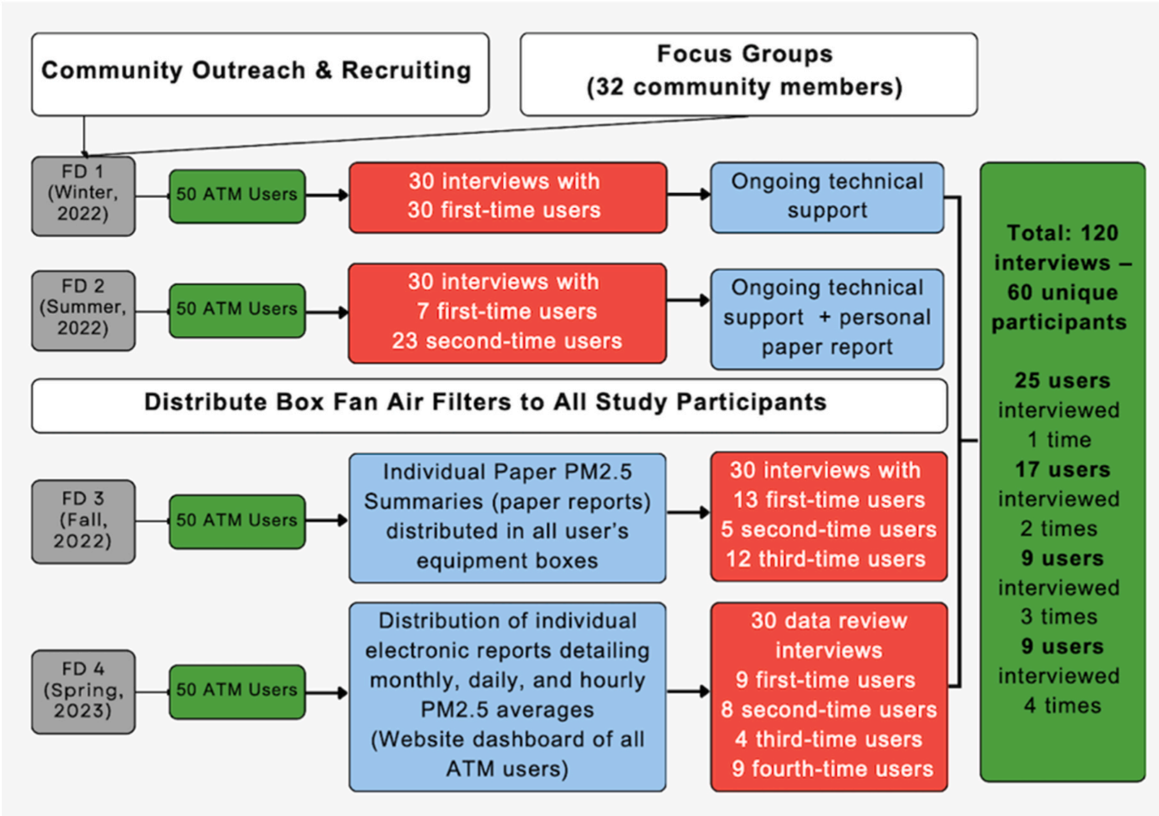



**Fig. 2.** Research design - flow chart.

### 3.6. Analysis

To code interviews, we used a two-coder process to review the transcript, extract representative quotes, and develop a list of initial themes emerging from the data. This abductive analysis approach iteratively linked empirical data with social science theory (Timmermans and Tavory, 2012). After each interview, the transcribed interview document was coded according to broad codes that reflected the primary questions asked in the interview protocol, including motivations for using the monitor, experiences, and methods of AQ monitoring, interpretations of data, and any changes to homes, behaviors or routines as a result of AQ monitoring. A second coder re-coded interviews for reliability. We created analytic notes to identify emerging themes and revaluated and synthesized data document the contexts, parameters, frequencies, and examples of major conceptual findings. This flexible coding strategy is useful for qualitative research across multiple FDs with several collaborators and numerous interviews (Deterding and Waters, 2021). All participants were given pseudonyms. Authors met bi-weekly to discuss emerging themes and draft the findings presented below.

## 4. Findings

### 4.1. Logics of inquiry

The use of low-cost air monitors combined with a reciprocal report back process enhanced AQ awareness and environmental learning, which we characterize as the following related and non-mutually exclusive logics of inquiry: Data-driven learning, health-conscious learning, and progressive learning. These logics are not strictly linear. Participants exhibited multiple logics of inquiry, combining elements of each, and evolving their learning throughout the study (see Fig. 3).

#### 4.1.1. Data-driven logic of inquiry

The reciprocal reporting process allowed participants to engage actively with their personal AQ data, leading to increased awareness and informed decision-making regarding their immediate environment. We refer to this as a *data-driven logic of inquiry* and find that both equitable data access (via instantaneous air monitor data viewable on their smartphone and written and oral AQ summaries), and responsive intervention opportunities (follow-up calls to discuss AQ summaries) fostered this logic of inquiry. Some of these data-driven learners also engaged in experimentation to test the relationship between their AQ and potential influencing factors.

Most (51/60 participants 85%) participants used the instantaneous air monitor data to learn about their AQ in various settings, which influenced daily decisions. For Dellen, live air monitor data and an easily readable interface led her to change her travel plans upon observing “extremely high red days.” She asserted, “I couldn’t really tell the difference if I didn’t have the monitoring system on. I wouldn’t not have known that it was high alert.” Similarly, Alex adapted his activities, describing air monitor readings as "scary and eye opening. "He observed “it [monitoring] made me want to get outside more and get to places that have better air quality.” Similar comparisons between places and setting were mentioned 76 times across 120 interviews.

Twenty-five out of 60 participants (40%) experimented or tested hypotheses. Participants carried their monitors within different places (indoors and outdoors) to observe AQ changes within different neighborhoods, grocery stores, and parks. These comparisons (mentioned 30 times across 120 interviews) allowed participants to identify the AQ differences and make informed decisions based on their experimental results.

Braxton reflects the experiences of many participants who learned about AQ through constant experimenting with the live air monitor data. During a family trip, upon discovering poorer AQ at his mom’s house, he used his air monitor "comparing different rooms and going outside and inside" and identified negative impacts of activities like candle burning. Similarly, Abbi enhanced her understanding by comparing scores while moving "into rooms to check out the different quality levels based on what the monitor was saying." Like other participants, she relied on air monitor data rather than sensory perceptions (i.e., odors) to make decisions, such as choosing to leave a place.

Written AQ reports were distributed to all participants in FDs 3 and 4. 11 out of 41 interviewees that participated in FDs 3 and 4 or 27% -reported that these follow-up discussions further enhanced their awareness of AQ. Amelia explained, "viewing this information (written AQ report) […] just makes you very aware that my particulate matter is extremely high in our home, so I need to continue finding methods to lessen that." Others like Carmela expressed a newfound willingness to open windows and run her air cleaner more frequently only after additional discussions on her AQ report, where she realized "how tiny those particles ($PM_{2.5}$) were" and their potential impact on her lungs. Deeper understanding from the follow-up conversation was mentioned in 17 out of 60 interviews.

#### 4.1.2. Health-conscious logic of inquiry

The reciprocal reporting process offered participants a deeper understanding of how AQ could be linked to their health. Participants consulted AQ scores when experiencing health issues and adopted ventilation techniques, like opening windows, turning on air cleaners, or using vent hoods, to mitigate health symptoms related to AQ. They also incorporated scientific language and knowledge into their understanding of health issues underlining a shift towards linking scientific concepts with personal health. This finding of health consciousness was not a design feature of the program, but rather emerged from participants own interests and motivations in joining the study (Westbrook et al., 2024).

Thirty-five of 60 participants (58%) reported using the monitor to monitor a health-related concern, as noted in 69 out of 120 interviews. Participants used the monitor to better understand health symptoms, such as asthma, headaches, allergies, coughing, stuffiness, sneezing, wheezing, and fatigue and to investigate whether AQ was a contributing factor. Alice noted "I get migraines a lot … sometimes I would get like a slight headache while driving, and I would check the air quality when I was driving." Alice, like 35 other participants, used AQ monitoring as a tool for deciphering and managing symptoms. Matt reported a pattern of headaches aligning with high $PM_{2.5}$ exposure: "I sometimes get headaches pretty bad in my house, or just sometimes at the end of the day, and it makes sense because the AQ monitor shows high levels." Direct engagement with AQ data allowed Matt to identify potential environmental triggers for his health issues, like outdoor odors and smog from traffic and construction. Similarly, Fanny, living near a construction site, observed "a big change in my breathing since the I70 [construction] project started." This allowed her to take preventive measures to manage her asthma more effectively. Jacob also attributed "better AQ management" to "less allergy problems this year." Amy managed air flow and would "shut the windows" in response to "really low" AQ readings. Like Amy, 21/60 other participants used strategic ventilation during cooking or other activities, indicating a dynamic learning experience that had tangible health benefits and reflected a heightened awareness of the indoor environment. In Denise's words: "I try to be strategic … I've been much more deliberately opening a window during the cooking process."

The reciprocal reporting process supported participants not only with data but also with the understanding to interpret it, enabling them to directly apply scientific concepts to health management. Johanna reflected on the importance of understanding $PM_{2.5}$ after noticing her asthmatic husband's response to an air purifier, seeing the improvement in AQ scores, and reviewing the individual summary of $PM_{2.5}$ with the research team. She stated, "having that air purifier makes a huge difference, and then we have the other one from the study in our basement room, where we hang out most of the time." Similarly, Samantha reported a change in perspective after receiving the air cleaner through the study, noticing "that [it] helps with the dust and the allergens specifically in our house." Fanny further highlights the shift towards integrating scientific AQ data with personal health decisions: "Living so close to industrial activity made me realize I need to be informed. Learning about $PM_{2.5}$ and other pollutants from the study made me more proactive about checking daily AQ levels and taking precautions."

#### 4.1.3. Progressive logic of inquiry

Participants shared specific examples of their growing AQ knowledge across multiple FDs. Some began with limited information about AQ and needed support to progress, while others shifted their beliefs around AQ, or overcame technological barriers over time. Progressive learning was fostered by specific elements of the reciprocal reporting process, especially the ability to 1) compare instantaneous monitor data to aggregated individual reports and 2) use open bidirectional communication to ask questions and test interpretations. This learning style overlaps with those above but highlights the element of time and multiple FDs as an important component of learning.

All participants highlighted the importance of time in supporting progressive learning. Over two-thirds of the 35 participants that participated in multiple FDs reported checking their AQ monitors the same amount of time or more regularly in FDs 2–4 than in the first deployment. Many built a routine over time that benefitted their learning progression through exposure to AQ data in different scenarios. Mady, who participated in four FDs, expressed that by the fourth deployment: "It took me awhile to really kind of comprehend what it meant … But I think the longer I used it, the more I really understood the numbers and what it was trying to tell me." Alice expressed that using the AQ monitor across four FDs helped her engage more deeply: "I don't think I realized I had a low score until maybe cohort two in my car. … So, it took a while to notice some of those things." Across multiple FDs, participants stated that comfort in using the AQ monitor facilitated the greatest support for progressive AQ learning, bolstered by individual interactions and oral report-back processes rather than the written report-back process.

For the remaining group of participants, engagement with AQ monitors decreased in later FDs (4 people in FD2, 6 people in both FD3 and FD4). This group reported checking their monitor less often, indicating that the monitor wasn't the driving force of their progressive learning. Rather, talking with the project team through individual interviews and oral report-backs was most beneficial. Carmela, a Spanish-speaking resident, looked at the AQ monitor in terms of colors throughout the four FDs– red as bad and green as good. This was common among a small group of participants (4 or 5 each deployment) who did not progress in their learning on their own due to language and technical barriers. Carmela did not recall looking at her written report-back summary, and it wasn't until the oral report-back (in Spanish) with the research team that she expressed learning about $PM_{2.5}$ and how it could affect her health: "I didn't know that those particles were so tiny and that they affect our lungs. … I didn't learn that before, but now that you explained it to me, now that I see my information about the spikes, I will pay more attention."

For a small group of progressive learners who did independent research (2–4 in each deployment), the oral report-back process facilitated additional learning. For example, when presented a figure illustrating the size of $PM_{2.5}$ in comparison to common objects such as sand and hair, Alice identified that "I always kind of use that air quality [metric], but I feel like the diagram was very helpful." Many participants noted that this explanation and visual of PM advanced their learning. Miriam specified during FD3 that, "I know they told me when they first came, but you forget all that stuff" about how to interpret the AQ score on her monitor. She wanted to "actually hear from someone. They can explain it easier … it'll probably make some more sense than me just trying to do it on my own." While AQ monitors democratize data, several participants valued tailored, top-down information. A flexible reciprocal

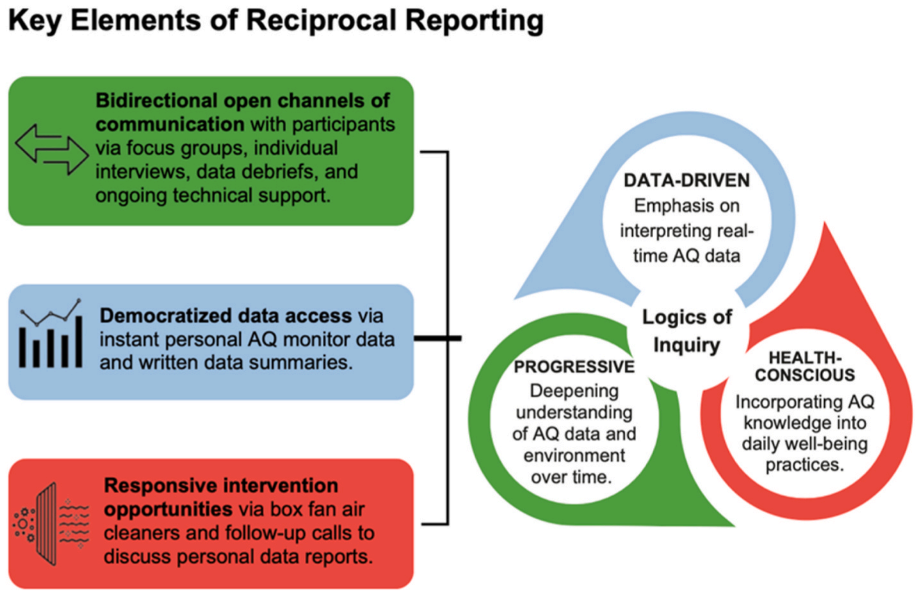



**Fig. 3.** Key elements of reciprocal reporting.
This diagram illustrates the learning style types within the context of air quality reciprocal reporting. Each point represents a distinct learning approach. Participants may simultaneously exhibit characteristics of multiple learner types or experience their learning journey differently. The represented order represents how participants' engagement and learning might evolve throughout the study. Different learners may move through these stages at varying paces or may display a combination of traits from multiple learner types throughout the study.

reporting process and two-way communication acknowledges different learning styles, from self-experimentation to request for scientific guidance.

A small, but notable, group (3–5 participants in FDs 1 & 2) initially felt apathetic, doubtful of AQ change, and/or resigned to neighborhood pollution. Yet, through the reciprocal reporting process, most of these participants shifted towards empowerment as they progressively gained AQ knowledge and intervention opportunities, reporting behavioral changes or adjustments in their routine. No participant reported feelings of apathy or helplessness in FD 4. Early FDs revealed participants' limitations in making changes, such as uncertainty about effective improvements, financial constraints, and/or perceived inevitability of poor AQ in the neighborhood. Colton explained, "There's not much you can do to change it. You can't wear a respirator everywhere you go." Jasmine, a resident facing chronic illness, said "it's frustrating, there's not much I can do. … I don't own my place, I rent. I can't afford to put in an air cleaner. I can't afford to do what needs to be done." Yet, across cohorts, there was a decrease in people reporting "no changes" to their behavior or routines. This corresponded with the air cleaner intervention. After Jasmine received an air cleaner (during the third FD), her language shifted from frustration to interest as she saw improvements in her indoor AQ: "I want to keep using the air filter for sure." This motivated her to open windows more frequently and feel confident in her ability to impact AQ at home: "It really worked. I was startled by how much it worked. … I'm really glad you guys invented an affordable solution. I felt relieved that maybe there is a solution." Miriam noted during the first interview that "there's not much, not really anything I could do about the air in my area," but shared in the last FD that they were using their air cleaner "at all times." In sum, experiences with the air cleaner, or simple tips from the study team such as opening windows or ensuring ventilation while cooking, impacted reticent participants who had been less engaged in earlier FDs.

### 4.2. *Contributing to knowledge justice through community science*

The reciprocal reporting process supported different logics of inquiry: data-driven, health-conscious, and progressive. Participants were positioned as primary knowers supported by a panel of outside scholars. This approach supported knowledge justice by recognizing alternate ways of knowing, including participants' sensory experiences and personal experimentation as valid forms of data collection. The approach further supported knowledge justice because participants' insights cultivated a larger community dialogue that extended participant learning to non-participant residents.

#### 4.2.1. *Recognizing alternate ways of knowing*

In interviews, we did not present the Atmotube as having definitive technical answers to AQ questions. We took seriously participants reports using their sensory experiences of smog, dust, and smoke, allowing them to center their own experience of the environment and use the monitor as an auxiliary tool to investigate the relationship between their sense of pollution and quantifiable PM measures.

Before participating in all four FDs, Alice stated she had no idea what AQ was "really like" and relied solely on sensory measures like odor or visibility. Carrying the air monitor provided her with an additional line of evidence to draw her own conclusions about her experience of pollution and her measured exposure. During FD4**,** Alice noted that the monitor's results reaffirmed her sensory observations, such as the negative impact of air fresheners or aerosol disinfectants on AQ. Later, Alice leveraged real-time data from the monitor alongside an air cleaner to test how aerosols could be eliminated from the air. Other participants (15/60 25%) similarly used the monitor to validate their sensory experiences, focusing on industrial emitters, piecing together their sensory perception of pollution, patterns of emission, and quantitative measures using the Atmotube. Like Alice, Jade used the monitor to validate her suspicions of the noxious odors emitted each week from the local Purina dog food facility, stating that "those things [odor and AQ numbers] are correlated." Notably, in other cases, the monitor contradicted participants' sensory experiences. Braxton, for instance, observed days where "it seems like [Purina is] cooking up a new batch of dog food … and the smell can be pretty strong." However, while checking the air monitor, he didn't see any striking correlation between the odor and his AQ score. In these and similar examples, participants reported using the Atmotube as an auxiliary tool, combining it with their sensory pollution perceptions. Our reciprocal reporting process broadened the questions participants could ask, methods they could use, and knowledge gaps they identified.

This process allowed participants to freely engage with data to investigate their own questions and facilitated a larger learning process that highlighted the validity of embodied sensory experiences in understanding and mitigating pollution.

#### 4.2.2. Fostering peer-to-peer engagement and collective learning

While the reciprocal reporting process mainly centered around individual AQ data, for some participants (15/60, or 25%), it facilitated peer-to-peer engagement leading to collective learning. These interactions (mentioned in 17 interviews out of 120) included political discussions, civic participation, and sharing knowledge with neighbors, friends, and family to educate them or encourage behavioral changes, and in two instances, also included political discussions and civic participation. Two of our respondents, Dalia and Peter, both initially considered moving out of their neighborhood due to air pollution but, because of the intervention, began to engage more in improving things through political action. Dalia emphasized how her AQ awareness led her to pay "more attention to legislation and changes that happen in the community," and make "choices based on what candidates were talking about air quality and the community itself." Likewise, Peter's commitment to supporting "politicians who want to do something about it [the environment]" became a topic of ongoing household discussion.

Other participants described how environmental insights from participating led to conversations with others. Becca carried her air monitor everywhere, using it to confidently discuss AQ data with friends: "I'll show them what PM is looking like, and what VOCs are [ …] and they're just "that's neat to be able to see that sort of data firsthand, right there in front of you." Becca found that sharing her AQ scores and VOC readings resulted in "changes even for our friends, not just here at the house." Similarly, Abbi, involved in community organizations, found opportunities to share her knowledge with neighbors: "anytime someone would see it [air monitor], I would just tell them about it." The reciprocal reporting process supported this knowledge sharing: "I was so comfortable with the material, and I knew that there would be data that would come out [publicly] … people were very interested."

Some of these participants expressed how their collective learning experiences translated into meaningful actions. Fanny, who frequently voiced frustration about being in an overlooked community, used her knowledge to inform her neighbor about the current AQ during the fourth FD: "I would call my neighbor – elderly with COPD – try to let him know so he is not trying to take a walk or do too much." Similarly, Jacob, after discussing his high $PM_{2.5}$ exposure levels with AQ experts, was motivated to talk to his son about the potential "effects of smoking at home" on their indoor AQ. Intervention opportunities allowed participants like Mike to share information about the air cleaner provided by our study, encouraging others to build their own: "I have mentioned it to people I know who are traveling in their RVs [ …]. I have told them, "you can build one of these filters to get everything out of the air."

Beyond family, neighbors, and friends, other participants like Braxton and Jade contributed to collective learning through their engagement with students. Braxton, a high school chemistry teacher in Elyria-Swansea, displayed his monitor and "spread the word" about AQ to his high school students. Similarly, Jade identified polluted settings -such as the nail salon-that prompted her to take an educational initiative by bringing her students to the salon, using her air monitor's readings as evidence of "high pollution in that place."

## 5. Discussion and conclusion

Low-cost community AQ monitoring has potential for reducing environmental pollution in EJ communities (Masri et al., 2022; Schio, 2022). Our study highlights the potential of a flexible, reciprocal, and responsive reporting process to expand the impacts of low-cost AQ monitoring from merely gathering data and documenting pollution, to supporting community scientists engaged in their own logics of inquiry and extending their learning to others in their communities. Individual AQ monitoring can move beyond data collection and foster free-choice learning (Lebow-Skelley et al., 2020) when the reciprocal reporting process includes: bidirectional open channels of communication, equitable data access, and responsive intervention opportunities.

Interviews with participants over four FDs across over two years of community air monitoring allowed us to analyze various elements of the reciprocal reporting process. We find that bidirectional open channels of communication offered participants opportunities to make sense of their AQ experiences. Equitable data access allowed participants to explore their own inquiries and engage with instantaneous AQ data in various settings and at different times. Lastly, responsive intervention opportunities, like air cleaners, allowed participants to enact real changes, measure results, and interpret their monitor data and embodied experiences within their own environments and routines.

Our methods depart from prescriptive community science approaches, embracing participants' capacity to interpret AQ data through their own logics of inquiry. We find that these logics include (but are not limited to): data-driven learning, health-conscious learning, and progressive learning. Low-cost AQ monitors democratize AQ data access: 85% of participants described their immediate access to personalized AQ data as a main benefit of the study. Immediate access to individual data and follow-up reports detailing more fine-grained exposure profiles enabled participants to make informed decisions, experiment, and test hypotheses. The reciprocal reporting process also supported health-conscious learning in which participants focused on the nexus of AQ data and embodied health experiences. Thirty-five of 60 participants (58%) reported using the monitor to monitor a health-related concern. Our findings highlight the value of low-cost monitors and a robust reciprocal reporting method not only as educational tools that empower participants with the knowledge to protect and improve their health.

Regardless of their initial expertise level, participants' engagement across two years and multiple FDs, facilitated progressive learning. This learning manifested as shifts in beliefs about AQ misconceptions or increased technological proficiency. This highlights the potential of iterative engagement to improve both conceptual understandings and practical skill sets to address environmental issues.

Approaching community science in this way offers a model of free-choice learning. For university partners, this approach offers insight into how externally led community monitoring projects can better address the questions that matter most to members of EJ communities. The diversity of investigations participants engaged in and the growth of participants' AQ knowledge was embodied in the questions that arose during interviews – questions regarding the nature of off-gassing paint, furnace efficacy, air cleaner mechanics, and the relationship between indoor and outdoor AQ.

This model of community science air monitoring also has limitations due to technical and language barriers. Knowledge justice emphasizes decentralizing knowledge production and democratizing access. Technical and language barriers, such as a lack of low-cost AQ monitor interfaces in Spanish, impede free-choice learning for some. Those who struggled with technical and language-based barriers did not accumulate knowledge in the same way and often expressed a need for more structured education and intervention. This desire for more prescriptive information raises questions about how to support free-choice learning when participants look to external partners as arbiters of knowledge. Even technology aimed at improving educational and health outcomes, can reproduce environmental injustice if it fosters dependance on expert interpretation. While low-cost AQ monitors have potential for democratizing access to environmental data, we must critically examine their accessibility for a diversity of users. App developers and researchers should continue to develop user-friendly interfaces and educational materials that empower meaningful engagement with scientific data.

Another key limitation stems from the individualized nature of personal monitoring programs. While centered on principles of environmental justice, many of the insights and actions that participants took away from our program relate to individual behavior change, especially in households' home environments. This increased focus on the individual sphere of action might be at odds with other principles of environmental justice, such as distributive justice that advocates for more equitable allocation of resources, opportunities, and risks and procedural justice that advocates for fairness in the processes and decision-making that lead to environmental outcomes. While we acknowledge this limitation of our current study, we hope that this does not need to become an ingrained feature of personal monitoring projects. Our study lays the groundwork for future projects that might weave together individual monitoring and thoughtful approaches to collective data interpretation, peer data sharing, and community action geared toward specific structural barriers or political opportunities.

By centering community scientists' experiences, our reciprocal reporting process aligns with knowledge justice principles: expanding data access, validating participant sensory experiences, and providing iterative feedback from AQ experts on participants' own logics of inquiry. Without prescribing monitor usage, participants' individual experiences guided their AQ investigations. Empowering residents in this way centers a democratic, bottom-up approach to AQ monitoring and sidesteps the potential risks of reducing the complex issue of pollution to a technological one. We find that incorporating personal AQ monitoring into a flexible, reciprocal, and responsive data reporting process not only increases AQ awareness but also structures modes of environmental learning that may better elucidate the context, causes, and consequences of individual pollution exposures and catalyze forms of knowledge sharing that extend beyond the limits of individual monitoring projects.

## CRediT authorship contribution statement

**Valentina Serrano-Salomón:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Marisa Westbrook:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **Noemy Pérez:** Writing – original draft, Investigation, Formal analysis. **Jay Pecenka:** Writing – original draft, Investigation, Formal analysis. **Aniya Khalili:** Investigation. **Sumit Sankhyan:** Investigation. **Shelly Miller:** Project administration, Investigation, Funding acquisition. **Shivakant Mishra:** Project administration, Funding acquisition. **Esther Sullivan:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

## Research on human subjects statement

This study was approved by the University of Colorado Boulder Institutional Review Board [IRB# 20–0318].

## Funding sources

This work was supported by the National Science Foundation [award #1952223] and the University of Colorado Office of Research Services.

## 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 *Social Justice & Environmental Quality - Denver* research team, especially research assistant Emily Evans, and all participants in our study.

## Data availability

The data that has been used is confidential.

## References

Adams, Crystal, Brown, Phil, Morello-Frosch, Rachel, Green Brody, Julia, Rudel, Ruthann, Zota, Ami, Dunagan, Sarah, Tovar, Jessica, Patton, Sharyle, 2011. Disentangling the exposure experience: the roles of community context and report-back of environmental exposure data. Health Soc Behav 52 (2), 180–196. https://doi.org/10.1177/0022146510395593.

Allen, Barbara L., 2018. Strongly participatory science and knowledge justice in an environmentally contested region. Sci. Technol. Hum. Val. 43 (6), 947–971. https://doi.org/10.1177/0162243918758380.

Altman, Rebecca Gasior, Morello-Frosch, Rachel, Brody, Julia Green, Rudel, Ruthann, Brown, Phil, Averick, Mara, 2008. Pollution comes home and gets personal: women's experience of household chemical exposure. Health Soc Behav 49 (4), 417–435.

Becker, Anna Maria, Marquart, Heike, Masson, Torsten, Helbig, Carolin, Schlink, Uwe, 2021. Impacts of personalized sensor feedback regarding exposure to environmental stressors. Curr. Pollut. Rep. 7 (4), 579–593. https://doi.org/10.1007/s40726-021-00209-0.

Brody, Julia Green, Dunagan, Sarah C., Morello-Frosch, Rachel, Brown, Phil, Patton, Sharyle, Rudel, Ruthann A., 2014. Reporting individual results for biomonitoring and environmental exposures: lessons learned from environmental communication case studies. Environ. Health 13 (1), 40. https://doi.org/10.1186/1476-069X-13-40.

Brody, Julia Green, Cirillo, Piera M., Boronow, Katherine E., Havas, Laurie, Plumb, Marj, Susmann, Herbert P., Gajos, Krzysztof Z., Cohn, Barbara A., 2021. Outcomes from returning individual versus only study-wide biomonitoring results in an environmental exposure study using the digital exposure report-back interface (DERBI). Environ. Health Perspect. 129 (11), 117005. https://doi.org/10.1289/EHP9072.

Brown, Phil, Brody, Julia Green, Morello-Frosch, Rachel, Tovar, Jessica, Zota, Ami R., Rudel, Ruthann A., 2012. Measuring the success of community science: the northern California household exposure study. Environ. Health Perspect. 120 (3), 326–331. https://doi.org/10.1289/ehp.1103734.

Bullard, Robert D., Wright, Beverly H., 1993. Environmental justice for all: community perspectives on health and research. Toxicol. Ind. Health 9 (5), 821–841. https://doi.org/10.1177/074823379300900508.

Claudio, Luz, Gilmore, Jalisa, Roy, Mohana, Brenner, Barbara, 2018. Communicating environmental exposure results and health information in a community-based participatory research study. BMC Publ. Health 18 (1), 784. https://doi.org/10.1186/s12889-018-5721-1.

Commodore, Adwoa, Wilson, Sacoby, Muhammad, Omar, Svendsen, Erik, Pearce, John, 2017. Community-based participatory research for the study of air pollution: a review of motivations, approaches, and outcomes. Environ. Monit. Assess. 189 (8), 378. https://doi.org/10.1007/s10661-017-6063-7.

Corburn, Jason, 2002. Combining community-based research and local knowledge to confront asthma and subsistence-fishing hazards in greenpoint/williamsburg, brooklyn, New York. Environ. Health Perspect. 110 (Suppl. 2), 241–248. https://doi.org/10.1289/ehp.02110s2241.

Corburn, Jason, 2005. Street Science: Community Knowledge and Environmental Health Justice. MIT Press, Cambridge, Mass.

Davis, Leona F., írez-Andreotta Mónica, D. Ram, 2021a. Participatory research for environmental justice: a critical interpretive synthesis. Environ. Health Perspect. 129 (2), 026001. https://doi.org/10.1289/EHP6274.

Davis, Leona F., Ramírez-Andreotta, Mónica D., 2021b. Participatory research for environmental justice: a critical interpretive synthesis. Environ. Health Perspect. 129 (2), 026001. https://doi.org/10.1289/EHP6274.

Demanega, Ingrid, Mujan, Igor, Singer, Brett C., Anđelković, Aleksandar S., Babich, Francesco, Licina, Dusan, 2021. Performance assessment of low-cost environmental monitors and single sensors under variable indoor air quality and thermal conditions. Build. Environ. 187, 107415. https://doi.org/10.1016/j.buildenv.2020.107415.

deSouza, Priyanka Nadia, 2022. Key concerns and drivers of low-cost air quality sensor use. Sustainability 14 (1), 1–23.

Deterding, Nicole M., Waters, Mary C., 2021. Flexible coding of in-depth interviews: a twenty-first-century approach. Sociol. Methods Res 50 (2), 708–739. https://doi.org/10.1177/0049124118799377.

Dobson, Ruaraidh, O'Donnell, Rachel, Tigova, Olena, Fu, Marcela, Enríquez, Marta, Fernandez, Esteve, Carreras, Giulia, Gorini, Giuseppe, Verdi, Simona, Borgini, Alessandro, Tittarelli, Andrea, Veronese, Chiara, Ruprecht, Ario, Vyzikidou, Vergina, Tzortzi, Anna, Vardavas, Constantine, Semple, Sean, 2020. Measuring for change: a multi-centre pre-post trial of an air quality feedback intervention to promote smoke-free homes. Environ. Int. 140, 105738. https://doi.org/10.1016/j.envint.2020.105738.

Downs, Timothy J., Ross, Laurie, Mucciarone, Danielle, Calvache, Maria-Camila, Taylor, Octavia, Goble, Robert, 2010. "Participatory testing and reporting in an environmental-justice community of worcester, Massachusetts: a pilot project." J. Environ. Health 9 (1), 34. https://doi.org/10.1186/1476-069X-9-34.

Evans, Jason, 2004. Frank fischer, citizens, experts, and the environment: the politics of local knowledge. J. Agric. Environ. Ethics 17 (2), 204–216. https://doi.org/10.1023/B:JAGE.0000017399.54990.e0.

Gadgil, Madhav, Berkes, Fikret, Folke, Carl, 2021. Indigenous knowledge: from local to global: this article belongs to ambio's 50th anniversary collection. Theme: biodiversity conservation. Ambio 50 (5), 967–969. https://doi.org/10.1007/s13280-020-01478-7.

Healy, S., 2003. Epistemological pluralism and the 'politics of choice.'. Futures 35 (7), 689–701. https://doi.org/10.1016/S0016-3287(03)00022-3.

Horne, Van, Ornelas, Yoshira, Carroll, Stephanie Russo, Chief, Karletta, Lothrop, Nathan Z., Richards, Jennifer R., Begay, Mae-Gilene, Charley, Perry H., Ingram, Jani C., Beamer, Paloma I., 2023. Using environmental health dialogue in a diné-centered approach for individualized results reporting in an environmental exposure study following the gold king mine spill. Enviro Res 231, 116196. https://doi.org/10.1016/j.envres.2023.116196.

Howarth, Candice, Monasterolo, Irene, 2017. Opportunities for knowledge Co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. Environ Sci Policy 75, 103–110. https://doi.org/10.1016/j.envsci.2017.05.019.

Lebow-Skelley, Erin, Yelton, Sarah, Janssen, Brandi, Erdei, Esther, Pearson, Melanie A., 2020. Identifying issues and priorities in reporting back environmental health data. Int J Environ Res Public Health 17 (18), 6742. https://doi.org/10.3390/ijerph17186742.

Mahajan, Sachit, Luo, Cyuan-Heng, Wu, Dong-Yi, Chen, Ling-Jyh, 2021. From do-it-yourself (DIY) to do-it-together (DIT): reflections on designing a citizen-driven air quality monitoring framework in taiwan. Sustain. Cities Soc. 66, 102628. https://doi.org/10.1016/j.scs.2020.102628.

Masri, Shahir, Cox, Kathryn, Flores, Leonel, Rea, Jose, Wu, Jun, 2022. Community-engaged use of low-cost sensors to assess the spatial distribution of PM2.5 concentrations across disadvantaged communities: results from a pilot study in santa ana, CA. Atmosphere 13 (2), 304. https://doi.org/10.3390/atmos13020304.

Meltzer, Erica, 2017. Your guide to the I-70 expansion lawsuits. Denverite. https://denverite.com/2017/08/11/guide-70-lawsuits/. (Accessed 22 March 2024).

Morello-Frosch, Rachel, Brody, Julia Green, Brown, Phil, Altman, Rebecca Gasior, Rudel, Ruthann A., Pérez, Carla, 2009. Toxic ignorance and right-to-know in biomonitoring results communication: a survey of scientists and study participants. Enviro Health 8 (1), 6. https://doi.org/10.1186/1476-069X-8-6.

Morrens, Bert, Jonker, Hans, Den Hond, Elly, Coertjens, Dries, Colles, Ann, Schoeters, Greet, Van Larebeke, Nicolas, Nawrot, Tim, Covaci, Adrian, Vera, Nelen, Frédéric, Vandermoere, Loots, Ilse, 2021. Participant experiences in a human biomonitoring study: follow-up interviews with participants of the flemish environment and health study. Toxics 9 (4), 69. https://doi.org/10.3390/toxics9040069.

Ottinger, Gwen, 2023. Careful knowing as an aspect of environmental justice. Environ Politics 1–20. https://doi.org/10.1080/09644016.2023.2185971.

Payne-Sturges, Devon C., Schwab, Margo, Buckley, Timothy J., 2004. Closing the research loop: a risk-based approach for communicating results of air pollution exposure studies. Environ. Health Perspect. 112 (1), 28–34. https://doi.org/10.1289/ehp.6354.

Polk, Merritt, 2015. Transdisciplinary Co-production: designing and testing a transdisciplinary research framework for societal problem solving. Futures 65, 110–122. https://doi.org/10.1016/j.futures.2014.11.001.

Polka, Erin, Childs, Ellen, Friedman, Alexa, Tomsho, Kathryn S., Henn, Birgit Claus, Scammell, Madeleine K., Milando, Chad W., 2021. MCR: open-source software to automate compilation of health study report-back. Int J Environ Res Public Health 18 (11), 6104. https://doi.org/10.3390/ijerph18116104.

Ramirez-Andreotta, Monica D., Brody, Julia Green, Lothrop, Nathan, Loh, Miranda, Beamer, Paloma I., Brown, Phil, 2016. Reporting back environmental exposure data and free choice learning. Environ. Health 15 (1), 2. https://doi.org/10.1186/s12940-015-0080-1.

Sankhyan, Sumit, Clements, Nicholas, Allison, Heckman, Hollo, Aniya K., Gonzalez-Beltran, Dulce, Aumann, Jonathan, Morency, Cora, Leiden, Luke, Miller, Shelly L., 2023. Optimization of a do-it-yourself air cleaner design to reduce residential air pollution exposure for a community experiencing environmental injustices. Atmosphere 14 (12), 1734. https://doi.org/10.3390/atmos14121734.

Santos, Boaventura de Sousa, 2018. The End of the Cognitive Empire: the Coming of Age of Epistemologies of the South. Duke University Press, Durham NC London.

Schio, Nicola da, 2022. The empowering virtues of citizen science: claiming clean air in brussels. Engag Sci Technol Soc 8 (1), 29–52. https://doi.org/10.17351/ests2022.795.

Schollaert, Claire, Aguilar, Temana, Bongiovanni, Roseann, Chacker, Stacey, Alvarez, Marty, Gillooly, Sara, Vallarino, Jose, Adamkiewicz, Gary, Scammell, Madeleine Kangsen, 2018. Report back of NO2 and PM2.5 concentrations from a community based in-home exposure monitoring study. ISEE Conference Abstracts. https://doi.org/10.1289/isesisee.2018.P01.0750.

Semple, Sean, Turner, Stephen, O'Donnell, Rachel, Adams, Lynn, Henderson, Tracy, Mitchell, Shirley, Lyttle, Susan, Amos, Amanda, 2018. Using air-quality feedback to encourage disadvantaged parents to create a smoke-free home: results from a randomised controlled trial. Environ. Int. 120, 104–110. https://doi.org/10.1016/j.envint.2018.07.039.

South Coast Air Quality Management District (SCAQMD), 2021. *Atmotube Pro field evaluation*. Diamond bar, CA: South Coast air quality management district. https://www.aqmd.gov/aq-spec/sensordetail/atmotube—pro. (Accessed 10 June 2024).

Timmermans, Stefan, Tavory, Iddo, 2012. Theory construction in qualitative research: from grounded theory to abductive analysis. Sociol Theory 30 (3), 167–186. https://doi.org/10.1177/0735275112457914.

Tomsho, Kathryn S., Basra, Komal, Rubin, Staci M., Miller, Claire B., Juang, Richard, Broude, Sylvia, Martinez, Andres, Hornbuckle, Keri C., Heiger-Bernays, Wendy, Scammell, Madeleine K., 2018. Community reporting of ambient air polychlorinated biphenyl concentrations near a superfund site. Environ. Sci. Pollut. Res. 25 (17), 16389–16400. https://doi.org/10.1007/s11356-017-0286-6.

Tomsho, Kathryn S., Schollaert, Claire, Aguilar, Temana, Bongiovanni, Roseann, Alvarez, Marty, Scammell, Madeleine K., Adamkiewicz, Gary, 2019. A mixed methods evaluation of sharing air pollution results with study participants via report-back communication. Int J Environ Res Public Health 16 (21), 4183. https://doi.org/10.3390/ijerph16214183.

Tomsho, Kathryn S., Polka, Erin, Chacker, Stacey, Queeley, David, Alvarez, Marty, Scammell, Madeleine K., Emmons, Karen M., Rudd, Rima E., Adamkiewicz, Gary, 2022. A process for creating data report-back tools to improve equity in environmental health. Environ. Health 21 (1), 67. https://doi.org/10.1186/s12940-022-00880-w.

Westbrook, Marisa, Serrano-Salomón, Valentina, Pecenka, Jay, Sankhyan, Sumit, Hollo, Aniya K., Miller, Shelly L., Sullivan, Esther, 2024. The sphere of exposure: centering user experience in community science air monitoring. Front. Environ. Sci. 12, 1433489. https://doi.org/10.3389/fenvs.2024.1433489.