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REVIEW

The Role of Community Science in Addressing Policy Change: A Critical Review of Air Pollution Literature

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Abstract

Background Community air pollution science serves as a vital tool in public health and urban planning, enabling communities to advocate for policy changes that improve public health outcomes. Despite its potential, there is a noticeable gap in translating research findings into policy actions.

Objectives This review aims to assess the focus of studies on community air pollution science published between 1990-2023 and identify the extent to which these studies address the research-to-policy gap.

Methods We conducted a comprehensive review of 131 studies that utilize low-cost sensors for monitoring air pollution. The review specifically looked for how these studies contribute to bridging the research-to-policy gap.

Results Our findings indicate a significant emphasis on evaluating the performance of low-cost sensors, with 90% of the studies centered on this aspect. Only 10% of the studies explicitly aimed at addressing the research-to-policy gap. Among these, 10 studies employed distinct theories of change to tackle this issue effectively.

Conclusion There is a critical need for a paradigm shift in community science research to enhance the impact of scientific findings on policy-making. This shift should include strategies such as equitable sensor distribution, a broader focus on regions in the Global South, and proactive engagement with policymakers from the early stages of research.

Recommendations Future research should prioritize closing the research-to-policy gap by incorporating these strategies to ensure that community air pollution science fully realizes its potential in shaping public health policies.

Keywords Community air pollution science · Low-cost sensor performance · Research-to-policy gap · Theories of change · Urban planning policy

Introduction

Community science, also termed as citizen science[1], broadly refers to the active engagement of the general public in scientific research tasks [1]. Community science is a growing practice in which scientists and community members collaborate to produce new knowledge for science and society [2, 3]. Community science is expanding in urban planning practice as a way to improve public participation, collect data needed to make planning decisions, and empower and engage the community to participate fully in key planning decisions [4, 5].

Achieving planning interventions or policy changes through community science research is challenging. It requires not only the ability to engage in meaningful and high-quality participatory research but also the capacity to effectively translate and mobilize this scientific knowledge into policy. The intensity and quality of community participation varies across studies, partly because partnering with communities can be time-consuming and costly for researchers depending on project context and training preparedness amongst researchers and community partners [6, 7]. Many researchers would like to collaborate with

[1] We choose to refer to the studies in this paper as "community science" over "citizen science" as "citizen" implies legal citizen status, which is not a requirement to engage productively in knowledge-generating activities. For the purpose of this paper, we refer to the term"community science" to encompass all research that includes scientific investigations undertaken by all publics.

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community members but are limited by a lack of training and burdened by institutional duties [8]. Moreover, there are institutional barriers to community science research, including limited funding mechanisms for community-based research and Institutional Review Boards (IRBs) unfamiliarity with the processes and flexibility needed for such work that jeopardize potential policy outcomes [9, 10]. Mistrust among community members towards academic researchers, rooted in previous negative experiences, further complicates engagement efforts [11]. These challenges are compounded by academic norms that question the legitimacy of community science, making it difficult for researchers to justify such approaches and their potential policy contributions [12–15].

Air pollution is one of the world's biggest environmental health risks and is responsible for nearly seven million premature deaths worldwide annually [16]. Global urbanization processes, including development of intensive transportation infrastructures, paved surfaces, urban fabric density, vehicle travel, and intense energy use, are contributing to air pollution morbidities and associated chronic diseases [17]. Public health and urban planning practitioners are increasingly collaborating with communities to monitor air pollution [18, 19]. A major challenge to widespread air pollution monitoring has been the cost of regulatory air quality monitoring networks and the technical expertise required to operate them [20]. The rise of plug-and-play low-cost sensors (LCSs) for US $100 to $5,000, as defined by the US EPA Air Sensor Toolbox, is considered a key trend in democratizing air pollution data, allowing for increased public participation in monitoring air pollution. [21, 22].

In this paper, we ask: *How does community science serve communities? What are best practices?* To answer these questions, we review the community science literature focused on air pollution and air quality monitoring policy. To our knowledge, only Commodore et al. [23] have provided guidance on how to design community science projects that ultimately lead to air pollution and quality monitoring policy change that reflect the community's needs, values, and goals. As such, we contribute to this discussion within the community-based participatory research (CBPR) framework and propose a new theory of change that guides the co-development and co-implementation of community science in air pollution science. A theory of change is a strategy, action plan, and assessment framework that aims to produce social shifts through a reverse methodology where impact is determined, and the steps to achieve that impact are mapped out [24]. Based on the Results of this review, and our own CBPR experience, we provide recommendations for practitioners engaging in community science to drive regulatory and policy change.

We, the researchers designing and conducting this review, are guided by calls for academic researchers to be transparent in our positionalities in order to contribute to effective change [25–27]. Two of the authors of this paper are community members of a north Denver neighborhood in Denver, Colorado, and leaders within a community organization that has engaged in community air quality monitoring of Suncor, a major oil and gas refinery located adjacent to residential areas. Seven of the authors are academic researchers collaborating with the community organization in support of a continued study of the Suncor oil and gas refinery with the aim to take action and ensure policy change to protect nearby residents. The remainder of the authors are academic researchers dedicated to environmental justice, community collaboration, and community agency. We recognize that community science and academic collaborations are not and cannot be the only way to change policy, but we argue that it should be an important tool and an operating theory of change within scientific research on air quality.

This paper reviews community science case studies in the field of air pollution to illustrate how and when community science can lead to regulatory change, as well as when and how it fails to do so. It also highlights the geographic distribution of existing community science initiatives, the major funders of this research, and the different modes researchers use to engage with community members.

Data and Methods

We review existing published journal articles in the air pollution community science literature to identify and learn from case studies where community science has resulted in changes to policy and when it has failed to do so.

Review Design and Article Gathering

We followed systematic review guidelines set out by Pullin and Stewart, Dixon-Woods et al., Pickering and Byrne, and Haddaway et al. [28–31]. We employed the widely accepted Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)[2] [32, 33] and Search, Appraisal, Synthesis, and Analysis (SALSA)[3] [34] procedures to conduct our systematic review.

[2] The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) is a 27-item checklist used to improve transparency in systematic reviews and was utilized in this review. These items cover all aspects of the manuscript, including title, abstract, introduction, methods, results, discussion, and funding.

[3] SALSA procedures provide generalizable directions in the literature review process. The goal of the 'Search' phase is to determine a preliminary list of publications that will be analyzed. During the 'Analysis' phase, documents collected in the previous phase are reviewed in order to remove irrelevant articles. The 'Synthesis' and 'Analysis' phases consider the grouping of papers in relevance to questions of research interest for the reviewer(s), providing opportunity for reviewer(s) to draw conclusions, identify gaps, and call for further research.

Table 1 Article search strategy, study screening and eligibility criteria

Stage	*Procedure & parameters*	*Details*
Article search	Procedure: Search for peer-reviewed studies in academic databases and individual journals by title and abstract using keywords, from 1990 to 2023 Database: *Clarivate—Web of Science* Parameters: *Type of publication:* Article *Language:* English *Period:* 1990 to 2023 (inclusive) *Date:* May 9, 2023 (inclusive) Search applied to title and abstract	Type of search: Strict Search code[1]: ("citizen science" OR "community science") AND (pollution OR "air quality" OR VOC* OR refinery OR smell*)
Study screening and eligibility	Selected studies from searches based on inclusion criteria	Build a database of all studies, consolidate content, remove duplicates, and read and select studies based on the following inclusion/exclusion criteria: Thematic relation to air pollution, air quality, and ambient odor Focus on citizen science and community science Empirical, review, or conceptual studies

Bolean operators such as AND OR were used in between groups to include or exclude words in the search

Our review focused on English language studies[4] published in peer-reviewed journals utilizing the following strict search code of publication title, keywords, abstracts, and publication dates (1990–2023) in Web of Science: ("citizen science" OR "community science") AND (pollution OR "air quality" OR VOC* OR refinery OR smell*) (Table 1). The interrogation period included 1990 to 2023 to include the most recent thirty years of academic research.

Figure 1 describes the analysis process undertaken for the literature review. The initial database with full-text available studies ($n=644$) was imported into a Google Sheet as well as the reference manager, Zotero, where only English articles were saved ($n=642$) and duplicates were removed ($n=640$). These remaining articles were further filtered based on two inclusion criteria: 1) thematic relation to air quality, and ambient odor, and 2) explicit mention of citizen science or community science. The relevant manuscripts were then carried forward for a full-text review and thematic analysis described below ($n=131$) (Fig. 1, see *Supplementary Information Sect. 2* for technical and procedural details and the full list of studies). Of the 640 entries in the Web of Science database that matched our criteria, 131 papers (22%) met our final inclusion requirements (see Supplementary Information Sect. 3 for full bibliography).

Thematic Classification Analysis

We applied an inductive thematic analysis approach to assign major themes to each article through a standardized format. Analysis parameters first included identification of the major theory of change utilized by researchers, then the sub-theme or specialization, categorization of the type of paper (empirical, review, or conceptual), followed by a subjective analysis of the study's impact on policy. Further parameters used to characterize the identified research included the geographical location of the study to evaluate where the community science projects are taking place. Finally, we considered the type of community engagement, engagement methods and processes, number and categories of participants, and the acknowledged funding sources (see Supplementary Information Sect. 1, Table 2 for table of data item analyzed and data recorded during analysis. See Supplementary Information Sect. 3 for all literature). These analytical parameters reflect the study's ability to incorporate participatory dimensions and were used as proxies to illustrate the degree of participation and how individuals may have contributed to policy change.

[4] English is commonly used in academic studies worldwide, including in the Global South, as it is the predominant language of scientific literature. We recognize that restricting our analysis to English-language articles may introduce a bias by potentially excluding relevant studies published in other languages, which might offer different perspectives or findings. Despite this limitation, the predominance of English in scientific communication ensures that our study encompasses a substantial portion of the available research. Additionally, the literature analysis was conducted by a researcher analyst proficient only in English, which further necessitated the focus on English-language publications to ensure accuracy and reliability in data interpretation.

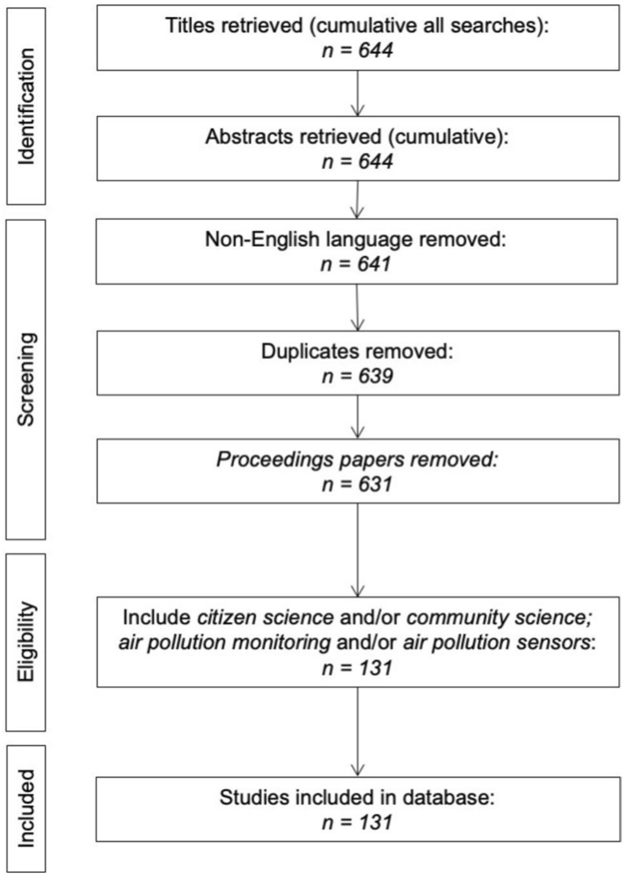

Fig. 1 Flowchart showing the results of the search, based on PRISMA flowchart format (Moher et al., 2015)

Results

Of the final 131 papers that met our search criteria, articles contributed knowledge through empirical (85%, *n* = 111), review (11%, *n* = 15), and conceptual (4%, *n* = 5) formats. Geographical research contexts and locations included a wide range of countries and continents. Most articles were centered in Global North (Europe, United States, Canada, Australia, East Asia) contexts (78%, n = 102). Six articles were located in the Global South (China, India, Kenya) contexts (5%, *n* = 6) and six articles were global in scope (5%, *n* = 6). Only one article provided a comparative context between the Global North and the Global South [35] (1%, *n* = 1). Finally, articles with non-specific geographic locations (12%, *n* = 15) focused on air pollution monitor sensor testing, design, and technicalities of the research (8%, *n* = 10), scoping literature reviews (3%, *n* = 4), and commentary on community science-based air pollution methodology (1%, *n* = 1).

Funding sources of the research projects and researchers included government sources (65%, *n* = 91), the affiliated university (6%, *n* = 9), industry and private interest groups (4%, *n* = 6), non-profit organizations (2%, *n* = 3), and crowdfunding (1%, *n* = 1) (see See Supplementary Information Sect. 1, Figure S3b for count of funding schemes sponsoring the analyzed research articles and their researchers).

Thematic coding of the 131 articles based on their abstracts revealed that they spanned a range of disciplines, including atmospheric sciences, urban planning, engineering, landscape architecture, education, and more. Included papers focused on a range of issues related to air pollution, including the feasibility, cost, and validity of using low-cost air quality sensors; developing exposure assessments from low-cost sensors; conducting personal exposure assessments for epidemiologic research; developing alternative methods to measuring air quality that include community input; and more. The journals identified themselves as interdisciplinary scientific journals, including *Energy and Building*, *Sustainability,* and *Frontiers*, as well as more technical science journals, including *Sensors* and *Atmosphere*. The authors were primarily teams of researchers (95%, *n* = 125), and few articles were formally authored with a community member (5%, *n* = 6).

Table 2 Coding and analytical parameters by data item and type of data recorded

Data item	Data recorded (if available)
Parent theme	Coded themes drawn from sub-theme of each article
Sub-theme	Descriptor of article research objectives and context
Type of paper	Empirical, review, or conceptual
Critique	Rigor and/or influence of the study to change policy
Geography	City, Country
Type of engagement	Descriptor of the type of community engagement
Is the type of engagement provided explanation for how it was achieved?	Yes, No
Number of participants	Descriptor of the number of participants that were engaged as part of the study
Who are the citizen scientists?	Descriptor of the participants
Who are the authors?	Descriptor of the authors

Engagement Methodologies

We identified six engagement methodologies in the selected articles: 1) deployment of low-cost, mobile and stationary air quality sensors and smartphone applications to engage with community scientists (43%, $n=77$); 2) conducting workshops and trainings for community scientists to engage in air pollution monitoring projects (12%, $n=22$); 3) deployment and analysis of surveys of community scientists and their perception toward air pollution and air pollution monitoring (8%, $n=14$); 4) development of participatory research design guidelines amongst researchers and community scientists (7%, $n=13$); 5) conducting structured and semi-structured interviews with community scientists to analyze perceptions of and symptoms to air pollution (6%, $n=11$); and 6) engagement with community [scientists or members?] on data analysis through non-traditional air sensor methods (5%, $n=9$) (see Supplementary Information for detailed analysis and visualization of analysis; see Supplementary Information Sect. 1, Figure S3c for cont of applied research methodoogies from included articles). These methodologies were identified in the coding process through consideration of the means researchers used to communicate, include, and collaborate with community scientists in their research.

Deployment of Low-Cost, Mobile And Stationary Air Quality Sensors and Smartphone Applications to Engage with Community Scientists

This was the most common methodology in the articles reviewed (43%, $n=77$). These studies focused on validating the use of low-cost sensors for accurate air pollution measurements for future deployment by the lay public and did not directly engage with community members. In some studies, community engagement occurred only by involving members in sensor deployment campaigns. For example, in Bo et al. (2020), NO_2 diffusion tubes were purchased and installed by participants of a community science campaign in specific, outdoor locations. The data collected from the campaign were then validated by co-locating the low-cost monitors with regulatory monitors. Researchers also engaged with community members by developing tools, often in the form of smart phone applications, to disseminate the data collected by community scientists. An example is the AQTreks educational program led by Ellenburg et al. (2019) where ozone levels were measured by student participants who wore a mobile sensor suite and were asked to annotate individual data points with personal reflections allowing for enhanced, real-time connection between students and the collected measurements.

Workshops and Trainings

Workshops were used to recruit, engage, and train community members on the purpose and processes of conducting the research (12%, $n=22$). For example, L'her et al. [38] studied the perceptions and motivations of community scientists recruited by their local municipality, via a series of workshops. The workshops were conducted over the course of eight months, with each entailing two hours of training on utilizing low-cost air sensors as well as "mapping, viewing of films with debate, and data analysis" (p. 1). The analyses of these workshops was coupled with the analyses of data collected by each volunteer during a three-month period.

Surveys of Community Scientists

Some studies used stakeholder surveys to measure perceptions of air pollution and its impacts among community members, academics, policymakers, and government officials (8%, $n=14$). For example, Gignac et al. [39] co-designed, an epidemiologic study with residents of a neighborhood in Barcelona to evaluate the impacts of air pollution on health. Specifically, they used a survey to evaluate the kinds of health impacts that community members were most interested in learning about. They then held a community meeting to identify key concerns from the initial survey. A final online survey allowed residents to vote on the health outcomes they were most interested in.

Co-Development of Participatory Research Design Guidelines

Co-development of participatory research design guidelines within the various methodologies amongst researchers and community scientists was an important method of engagement among a small sample of the studies surveyed (7%, $n=13$). Gabrys and Pritchard [40] provide an example of this where the team of researchers in partnership with community scientists collaboratively developed a monitoring kit to measure emissions from fracking and worked together to determine where and how it would be deployed in the field. Unlike other work that focused on improving the data quality of low-cost sensors, Gabrys and Pritchard [40] argued that although the data collected was not the same quality as that of regulatory measurements, it was "good enough" to meet the community needs. Specifically, they detailed the experiments that community members conducted based on their lived experience of living near fracking wells and noted that the data collected served as a powerful negotiation tool for the community to engage with different regulatory bodies to discuss the various community science findings.

Interviews of Community Members

Structured and semi-structured interviews were also used to engage with community members (6%, $n=11$). For example, Errigo et al. [41] used snowball sampling to conduct interviews with academic and industry air pollution experts of the Utah context to estimate the human health and economic costs of pollution. They disseminated these estimates to policymakers and the public. The researchers then interviewed policymakers to assess their reaction to said estimates and analyzed social media comments provided by the public on reporting on the experts' assessments in local newspapers. Their analysis revealed several gaps in knowledge of policymakers and the public's understanding of local air pollution impacts. The article made several recommendations based on these results to hasten effective air quality communication and legislation in Utah.

Non-Traditional Air Quality Analysis

Co-analyzing data with community members as a modality for research engagement was accomplished through several pathways (5%, $n=9$). These pathways included analysis of photos and videos by community members as a proxy for perceived air pollution performed in the context of home, community, and work environments. Often, this modality would ask community members to provide their perceptions of different environments and landscapes and how they felt or experienced air pollution within these contexts. As an example, Johnston et al. organized a participatory air monitoring program with eighteen Los Angeles-based youth wearing portable, low-cost sensors while participating in a digital storytelling regime. During the digital storytelling, youth were asked to take photos and videos of their everyday life experiences and routines. Through these photos, youth could construct the story of their everyday lives while adding details on their exposure to air pollution. For the researchers, the use of digital storytelling was "key to the sustainability of not only the project but also, more broadly, skills in leadership, critical thinking, and environmental health literacy [for the youth]".

No Engagement

Finally, 22 articles did not engage with community directly (17%, $n=22$). These included literature review papers where the authors only referenced and consulted existing academic literature [43–45]. For example, Hubbell offered a commentary on pathways for air quality researchers to partner and collaborate with social scientists in order to advance development, testing, and deployment of low-cost sensors in communities. This commentary considered the ways in which this science could be conducted, the ethical, socio-political, and behavioral considerations of conducting transdisciplinary research, as well as methods for utilizing crowdsourcing capabilities to enhance community science.

Theories of Change

A theory of change is a comprehensive description and illustration of how and why a desired change is expected to happen in a particular context, outlining the causal pathway from actions to outcomes [47]. We identified and coded five major theories of change authors made regarding community science and air pollution monitoring (see Supplementary Information Sect. 1, S4a for a figure of the distribution of the theories of change Figure S4b). Each of the theories of change explored by the authors outlines the activities, strategies, modalities, and assumptions by which the authors posit that the research, evidence, and community participation provide a pathway to positive air quality and air policy outcomes for residents and communities. The five major theories of change are: 1) Low-cost air sensors will democratize air quality research (77%, $n=101$); 2) Documenting qualitative community concerns about air pollution will make specific air quality issues visible and thereby opening the door to advocate for specific policies (11%, $n=15$); 3) Examination of air pollution monitoring case studies that involve community scientists will inform best practice and inform future studies (6%, $n=8$); 4) Alternative, non-traditional air quality sensors will support the realization of improved air quality outcomes for communities (2%, $n=3$); 5) Review of existing community science monitoring projects will identify key issues required to engage with communities effectively (3%, $n=4$) (see Supplementary Information Sect. 1, Figure S4b). These theories of change were identified in the coding process to understand why researchers communicate, include, and collaborate with community scientists in their research.

Low-Cost Air Sensors will Democratize Air Quality Research

Three-fourths of all articles (77%, $n=101$) focused on using low-cost sensors as important tools for democratizing air quality information. In this category of articles, we identified four sub-theories of change: validation and calibration of low-cost sensors; case studies and their outcomes utilizing air pollution monitoring sensors; youth engagement utilizing air pollution monitoring sensors; and, finally, sharing best practices of community science utilizing air pollution monitoring sensors (see Supplementary Information Sect. 1, Figure S4b.)

Device and Data Evaluation, Calibration, and Validation The predominant sub-theory of change related to low-cost air quality sensors was validating the use of low-cost sensor measurements and developing methods to improve data quality to more closely match that of regulatory monitors

(47% of all studies, $n=61$). Through reliable measurements produced by low-cost sensors, this implicit theory of change assumes that data from these devices can effectively fill air pollution data gaps, pinpoint crucial hotspots, and compel policymakers to act. For example, Languille et al. (2020) tested three types of sensors to determine which would be most reliable for measuring personal exposure to air pollutants. Gillooly et al. [49] developed a low-cost, portable, in-home, and real-time air monitor as part of an in-home air pollution monitoring study, and shared lessons learned with communities and researchers interested in replicating the sensor framework.

Other research aimed to use data collected by low-cost sensors deployed by communities for locally relevant applications, which in some cases were defined by the community. The implicit theory of change in this category is bringing attention to specific issues will lead to regulatory action (7% of all studies, $n=9$). For example, Ezeugoh et al. conducted a study of air pollution levels using low-cost air quality sensors at five sites in the town of Bladensburg, Maryland where a concrete plant had announced an expansion. The five sites were chosen in collaboration with community members. The results revealed high levels of pollutants at a site closest to the plant, providing preliminary evidence that supported the community's experiences. Similarly, Hoyos et al. [51] reported significant increases in levels of particulate matter from fireworks by utilizing data from the official municipal monitoring network as well as from a community-based, low-cost sensor network in Medellin.

Community Science with Youth In these studies, researchers posited a theory of change that if youth were empowered to monitor air pollution in their communities, they would be a driving force of change (11% of all studies, $n=15$). Kumar, Omidvarborna, and Yao [52], for example, partnered with teachers and parents of primary-aged children to co-design a protocol to gather levels of carbon dioxide and fine particulate matter from five collection points within and on school grounds to evaluate the effect of car pick-up and drop-off on air pollution levels. They reported significant increases in fine particulate matter levels during car drop-off hours in the playground and classroom. They indicated that the school could use these findings to improve ventilation in classrooms and institute policies to discourage the idling of cars during school pick-up and drop-off. In another example, Brickle and Evans-Agnew partnered with youth to collect and analyze 24-h indoor air samples using a portable air-sampling pump while also performing a photovoice analysis of wildfire smoke event photographs that the youth would take. The photovoice analysis allowed youth to view and reflect on the photos and images selected by the researchers. Through this experience, researchers reported youth experienced enhanced agency and empowerment related to wildfire smoke events.

Case Study Analysis Researchers evaluated the best community engagement practices to measure air pollution using low-cost sensors (12% of all studies, $n=16$). These studies summarized details of the research design and methodology to support future community science research. The implicit theory of change in this research is that improving the organization of community engagement practices, from initial engagement to knowledge translation of outcomes, will improve the efficacy of future science partnerships. For example, Booker et al. [54] considered the implications of low-cost, community science research design through a methodology termed 'critical air quality science' (CAQS). The authors develop CAQS as a methodological theory that aims to reconfigure air quality science by combining natural science and social science concerns to design interventions that address air inequalities. Through interviews with community scientists on a community-initiated air quality monitoring project, the authors use CAQS to reflect on such endeavors. They argue CAQS can be applied to community air pollution monitoring science to achieve ethical and just outcomes.

Documenting Qualitative Community Concerns about Air Pollution will Make Specific Air Quality Issues Visible and Thereby Lead to Positive Change

Beyond utilizing low-cost air pollution monitoring sensors, researchers engaged with a theory of change where documenting qualitative studies of perceptions, perspectives, and opinions of air pollution by community scientists would make specific air quality issues visible and thereby lead to positive change (11%, $n=15$). Hsu et al. (2019) asked Pittsburgh community members to report the characterization and location of unpleasant smells in their neighborhoods through an online, self-reporting portal that would automatically publish the data to a visualized map available to the public and report the smell event to public health officials. These data were then used to predict future smells, sending push notifications to residents if a smell event was imminent. The authors posit that documentation of residents' experiences with odors would "empower communities to advocate for better air quality." In another example, Golumbic, Baram-Tsabari, and Fishbain [56] aimed to understand how non-expert adults perceived and engaged with air pollution data while considering how these understandings would impact the everyday application of the data. Through questionnaires that evaluated residents' interpretation of data, the researchers observed that residents with previous experience in gathering air pollution monitoring data were more likely to interpret and engage with the data correctly. They conclude that the qualitative assessment of residents' understanding of the scientific data demonstrates non-expert ability to be effective scientists and advocate for necessary actions.

Utilizing Case Studies that Involve Air Pollution Monitoring, Community Science will Inform Best Practices and Lead to Positive Change for the Community

Several articles utilized case study methodology to examine the dynamics of air pollution monitoring with community scientist involvement (6%, $n=8$). In these articles, the authors examined unique, longitudinal, exemplary, and outstanding case studies that exemplified air quality policy change because of actions by community scientists and the air pollution monitoring research they were involved in. These case studies are articulated as the implicit theory of change to positive air quality outcomes for communities. deSouza [57] for example, evaluated community science projects in Kenya. deSouza observed that regulators responded to community science measurements on air pollution levels in Kenya by taking short-term measures such as arresting individuals who burned tires and temporarily halting factory operations. Based on these insights, the article argued that for lasting change to occur, the narrative around the community science data collected needed to relate to the larger political economy of air pollution in Kenya. Zilliox and Smith [58] evaluated the role community science projects played in unfolding debates about fracking in Colorado. They noted that such projects could unintentionally restrict public dialogue to scientific issues alone and prevent any normative discussions; as well as lead to reinforcing the scientific authority of local officials, allowing them to dismiss community scientists as unruly. However, the authors argue that community monitoring projects led to increased civic engagement in the community and spurred discussions on ethics, transparency, and fiscal responsibility, which played a role in turnover of local government officials.

Alternative, Non-Traditional Air Quality Sensors will Support the Realization of Improved Air Quality Outcomes for Communities

A handful of articles used non-traditional methodologies to measure air pollution as a means to support improved air quality outcomes for communities (2%, $n=3$). The implicit theory of change in these papers was that increased engagement with environmental sciences would empower young scientists and lead to positive changes for their communities. Specifically, Derrien et al. [59] utilized moss as a bio-indicator for air and heavy metal pollution in a study conducted with youth. Through a literature review, Filippelli et al. [43] investigated case studies where alternative, non-traditional air quality sensors, such as bees and their honey or deployment of drone-based remote sensors to detect heavy metal pollution. The authors argued that the collection of air pollution data through these alternative tools provides vulnerable residents the opportunity to detect health risks and thus take action. Kosmidis et al. (2018) discussed developing an open-source platform that would combine data from low-cost sensors, official air pollution data, and non-traditional sky depicting photographs to produce more robust estimates of pollution in Europe.

Review of Existing Community Science Monitoring Projects Will Identify Key Issues Required to Support Positive Outcomes in Community Science and Air Quality Research

Many researchers operated within a theory of change that the rewiew and assemblage of existing community science monitoring projects, and other relevant academic and policy literature, could be used to make recommendations for future projects and to support policy change (3%, $n=4$). For example, Commodore et al. (2017) reviewed 36 articles that discussed community-based participatory research (CBPR) in the realm of air pollution to investigate the motivations, approaches, and outcomes reported. The authors reported that most CBPR studies were driven by concerns at various community levels regarding the health risks of pollution. Key research questions asked in these studies were (a) Who can help, and (b) What can be done about it? The authors observed that not all research projects had outcomes that matched initial expectations and recommended that strategies such as (a) ensuring the community identified the air quality issues of concern, (b) community members participated fully in all aspects of the project, and (c) appropriate dissemination of results, with a focus on enacting policy change, was needed to minimize such mismatches.

Recommendations to Improve Community Science Impact

The majority (77%, $n=101$) of the research we surveyed focused on evaluating or improving low-cost sensors as a key tool for community engagement. Although some studies focused on leveraging these data for applications supporting best practices in co-development and design with community scientists (13%, $n=16$ of 101), the majority focused on sensor performance (48%, $n=61$ of 101). Fewer studies (3%, $n=4$) investigated the potential of other non-traditional monitoring techniques to accurately capture pollution levels. Only 11% ($n=15$) investigated documenting qualitative community concerns through mapping tools and surveys. There were few explicit examples of research that led to outcomes that offered explicit recommendations for changing policy, as only 10% ($n = 10$) of articles had policy change as a scope within the research project).

Recommendation 1. Further Investigation of Sensor Democratization

The preoccupation with validating the use of low-cost sensors for future community research projects, although important, distracts from the need to pay greater attention to emerging concerns about access and equity. Specifically, deSouza and Kinney [61] evaluated the distribution of one of the most common low-cost sensors on the market, the PurpleAir, and observed that these sensors tended to be deployed in more privileged communities (more white, more educated) compared to the national average and in cleaner air neighborhoods than those with U.S. EPA monitors. This may be due in part to greater access to financial resources, higher technological literacy, and more available non-working hours to deploy low-cost air sensors. This study suggests that the growing use of low-cost sensors will not automatically lead to the democratization of air pollution data without effective regulatory intervention. The authors further highlight tbat more research is needed to improve access to, or public distribution of these technologies, especially among environmental justice communities that bear the brunt of air pollution [62].

Recommendation 2. Further Investigation of the Motivations for Low-Cost Sensor Uses

Research is needed to investigate motivations for the use of low-cost sensors in the first place. Hubbell et al. [46] and deSouza [63] provide the first large-scale analyses that investigated motivations and use cases of the deployment of low-cost sensors by communities, drawing attention to the ethical considerations of how relationships to science and environment change because of sensor usage. Studies on motivation for low-cost sensors are important because a) they can inform how to improve access to these technologies for specific use cases, and b) they can guide existing efforts by regulators to establish performance standards for low-cost air quality sensors [64, 65]. Case studies (6%, $n = 8$) discussing the use of low-cost sensors for community science research in specific settings are also important to inform these objectives. By exploring these motivations more deeply through evidence-based case studies, we can enhance regulatory efforts to establish meaningful low-cost sensor performance standards, thereby improving the policy impact of community science.

Recommendation 3. Situating Air Pollution Community Science in the Global South

It is worth noting that most studies involving the performance validation of low-cost sensors occur in the Global North ($N = 102$, 78%) (see Supplementary Information Sect. 1, Figure S3a for distribution of geographical scopes of included articles). Another important concern is the transferability of these findings to the cities in the Global South, where air pollution sources are very different from those in the Global North. This gap needs to be bridged to benefit populations in the Global South exposed to the highest levels of pollution, globally. We note that the funding sources (see Supplementary Information Sect. 1, Figure S3b for count of funding schemes sponsoring the analyzed research articles and their researchers) for this kind of work are predominantly based in the Global North, which makes it difficult to conduct this work in countries in the Global South. Addressing this gap by funding and conducting research in the Global South could lead to more globally applicable environmental monitoring solutions and better public health outcomes in these high-risk areas.

Recommendation 4. Explanation of the on-the-Ground Impacts of Research Outcomes

Of the research that described specific applications of the use of low-cost sensors in response to community or policy concerns (77%, $n = 101$), *few details were provided about how the results were used to inspire action*. Other research (12%, $n = 15$) more critically engaged with mobilizing the results of community science projects by engaging with youth to empower them to advocate for their communities. Some studies (13%, $n = 16$) went further in this direction by detailing best community engagement practices based on reviews and case studies,not just to mobilize communities to collect air pollution data but to develop effective visualizations for communities to reflect and act upon based on the data. Less research (11%, $n = 15$) explicitly documented community members qualitative concerns that about air pollution and air pollution data. Only a few studies (2%, $n = 3$) conducted thoughtful reviews of existing CBPR research in the air pollution realm and took on the critical task of discussing challenges in this work.

Research that expands beyond the sole performance of low-cost sensors is critical for closing the loop between data collection and action; yet this approach represents only a small number of the studies in our review. We recommend acknowledging this misalignment and developing strategies to bridge it. Without community science leading to effective policy change communities can burn out and not experience the promise and benefits of research. For research that engaged with community in some capacity (i.e., they were not focused solely on evaluating low-cost sensors), the levels of engagement with community varied and took the form of (a) engagement with sensors by including community members in sensor deployments (43%, $n=77$), (b) engaging with communities to develop research designs for air pollution monitoring (7%, $n=13$) and (c) engaging with community members to analyze and disseminate data and findings (5%, $n=9$). Thus, our review suggests that most community air pollution science projects still tend to *fall short of true co-production* of knowledge. Tellingly, there are few instances of formal co-authorship with community members (5%, $n=6$), although co-authorship is a sign of respect and imperative to co-design [66]. Expanding research to include both detailed case studies as well as examples of how data mobilizes community actions or influences policy can provide a model for effective community science pathways. This approach ensures that the benefits of research are tangible and that community involvement in scientific processes will lead to substantial environmental and health improvements.

Reflective Practice: Cultivando Engagement with Community Science

As part of our commitment to conduct co-produced and co-designed air quality research with the intention to impact policy, we present an exercise in reflective practice with the two community co-authors from Cultivando on the environmental injustice occurring within their community. Cultivando is a community organization that represents an under-resourced neighborhood in north Denver and Commerce City adjacent to Suncor, a major oil and gas refinery, that ran a successful community air monitoring project to measure a range of air pollutants (PM, benzene, volatile organic compounds, hydrogen sulfide, and radioactivity) to understand community exposure[4]. Cultivando and scientists from Boulder Air held a press conference to present their findings from a year's worth of air monitoring data [67]. They found hydrogen sulfide levels were as much as 8,000 times higher than health guidelines. Suncor has been fined in the past for exceeding its permitted hydrogen sulfide emissions threshold [67, 68]. They also found major short-term spikes in benzene and $PM_{2.5}$ levels that were not experienced in communities living further afield from Suncor.

Despite the success of the monitoring project in validating community concerns, as articulated by the executive director of Cultivando, Olga Gonzalez, the organization later turned down a $500,000 US EPA grant to continue air quality monitoring for many reasons. For one, Cultivando said that the amount of paperwork and administrative effort required would hinder rather than help them. Moreover, Cultivando explained that most of the money would go into air pollution monitoring science, with little money left to support staff efforts and other air pollution advocacy projects. Finally, Olga Gonzalez asked,"How much data is enough?". How much monitoring was required for regulators to act against Suncor? This is a critical question that must be asked at the start of any community air pollution monitoring project.

Cultivando leaders expressed that true collaboration and cooperation are required to conduct actionable and equitable research between researchers and the community that also leads to policy outcomes for the community. In discussions on best practices with Cultivando's leaders they detailed a set of six questions which they identify as important for researchers to consider before beginning any community science project (Fig. 2). Their questions spanned the length of the research process, from research ideas to methods and outcomes. Specifically, who is defining the question, is policy change a desired outcome, what is expected of the community during and after the study, how will community members be compensated, trained, and acknowledged for their work and other impacts, how are policymakers engaged, and whether community voices will be valued and utilized alongside quantitative data?

Strengths and Limitations of This Review

To our knowledge, community science in air pollution monitoring has not been systematically mapped and analyzed. We are confident in the methodological utilization of established guidelines by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and SALSA methods. We offer additional empirical contributions from community member co-authors, to further clarify best practices in collaborative research with the potential for policy change and positive outcomes for the community.

However, our review has some limitations, offering opportunities for refinement in future systematic evaluations of community science in air pollution monitoring. Despite our efforts to achieve comprehensiveness through a multi-step, multi-method search strategy, potential language barriers and variations in terminology related to community-led air pollution research might have resulted in missed studies. Moreover, this review methodology was unable to include local newsletters or papers that report findings written in accessible language published by community groups and associations, which remains an important outlet for much of this work. The systematic review of these articles was qualitatively conducted by two researchers which can produce researcher-bias. Additionally, we did not evaluate study quality but focused analysis on measurable indicators and study characteristics. However, we relied upon blind peer-reviewed journal articles to assure a baseline level of study quality.

1. Is the researcher guiding the question? Or is the community guiding the question, and the researcher supporting the community?
    a. Ask the community if their goal is policy change?
2. Have you been transparent on what will be asked of the community? Have you made clear what you are asking of community?
    a. Have you asked yourself and the research team, what can I give back to the community?
3. Have you considered if the community will be able to continue this work after you? Are you developing their skills, or are you utilizing them to fulfill a purpose?
4. Have you and the community met with policymakers early on in the research process? Have you found a champion for policy change that is a policymaker?
5. Beyond monetary compensation which should be standardized, have you prioritized skill development and cultural practices, including sharing food, as a form of compensation?
6. Are you prioritizing mixed-methodology research, where qualitative research of community members is prioritized and often combined with quantitative research? It is important that the community sees their evidence, testimonies and information are valid.

Fig. 2 We share a selection of questions presented by community leaders in Cultivando. Through these questions posed to researchers conducting community science, researchers can adequately self-reflect and promote a conducive environment for supportive, positive, and effective change within the community through the co-benefits of community science

Future Directions

A significant focus of our review is on the influence of community science air pollution monitoring research to influence and impact policy change and its realization in communities. We call for future research to prioritize this focus and urge researchers to follow research designs that follow the guidelines set out by our Cultivando co-authors. Further, most of the literature reviewed in the air pollution monitoring community science literature was concentrated in the Global North. Future research would benefit from focusing on the Global South to provide a comprehensive understanding of community science in air pollution monitoring at a global scale. This would require more funding to increase air pollution monitoring research in these countries.

Conclusion

While our review acknowledges the importance of applications of low-cost air quality sensors in response to community concerns, we highlight the need for more action-oriented research to inspire concrete change within-communities. We determined that community science that had a well-defined mechanism to effect policy change was a small subset of the current research landscape. We have brought light to the critical disconnect between. The predominant technocratic emphasis on sensor performance, validation, and calibration, which while important to the advancement of science, lacks a critical step forward in consideration of the potential for policy and real-life change. Without the intention for policy change set out in the initial stages of research co-design and communication, communities may not fully experience the benefits of the research they participate in.

Through our collaboration with community members in this review, we raise questions about the key considerations for planners and researchers engaging with communities and make a call for future research design to include a focus on policy change, clear communication, and intention to engage with policymakers early in the research process. Efforts should further focus on achieving true co-production of knowledge, with formal co-authorship and increased community involvement in various stages of the research, analysis, and dissemination processes. Additionally, exploring implicit theories of change is important to urban planning and public health practitioners and researchers as they can contribute to improving air pollution monitoring, quality, and policy in and for communities. Our hope is that the identification of this overall deficit in true collaboration with community scientists will help to inform future air pollution research across a variety of disciplines. While we focus on air pollution in our review, we maintain that similar inferences and lessons can be made for other ecological risks addressed through community science methods. These directions will contribute to more effective, equitable, and impactful community-led research on air pollution and other environmental health risks.

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Declarations

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