WORLD RESOURCES INSTITUTE

Clean Air Catalyst

WORKING PAPER

CLEAN AIR ACTION: APPLICATIONS OF CITIZEN SCIENCE TO IDENTIFY AND ADDRESS AIR POLLUTION EMISSION SOURCES

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EXECUTIVE SUMMARY

Highlights

- Despite the growing number of citizen science projects designed to investigate air pollution and related health concerns, the public still lacks a clear shared understanding of where air pollution comes from—the relevant sources of emissions. This lack of "source awareness" can impede clear air action in various ways.
- To help strengthen outcomes focused on source awareness, this paper catalogs how citizen science initiatives investigate sources of air pollution.
- The paper summarizes insights drawn from a literature review and outlines a new typology for citizen science initiatives focused on pollution sources. It articulates six pathways for achieving outcomes.
- The review revealed that these initiatives not only help increase public knowledge, but identify new hyperlocal sources, strengthen source-specific enforcement action, tie exposure and health impacts to specific emissions sources, and spur stronger compliance by polluting companies.
- Common features in achieving clear outcomes included taking time to build trust, a commitment to joint scientist-civil society leadership, and defining clear ways to use data.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues.

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- Challenges addressing source awareness arose from the complexity and diversity of air pollution sources and community frustration over the difficulties of definitively connecting pollution emissions data to specific sources.

The Rise of Citizen Science

Growing concern over the health and environmental burden of air pollution combined with access to new low cost air pollution monitors has helped drive the explosion of citizen science initiatives. Despite this momentum and expanded citizen engagement, public attention is still insufficiently focused on the sources or drivers of air pollution.

Part of the challenge lies with the fact that people do not have a clear understanding of transboundary sources or the complex factors causing air pollution. For example, few people understand local chemical and physical dynamics, such as why reducing NOx emissions could increase ozone levels. Broad discussions focused on the health impacts of air pollution and the quantification of pollutant levels do not offer a concrete vision of source reduction or specify the actions people can take to reduce the perceived impacts. And while citizen initiatives have been shown to raise public knowledge and provide an important source of hyperlocal data, air quality regulatory processes require more detailed studies and modeling to delineate the specific local, background, or transboundary sources contributing to air pollution in any given airshed.

Researchers have begun creating analytical frameworks and typologies to evaluate the different outcomes achieved by citizen science. These typologies are needed to reflect both the range of applications, participation levels, and type of data-collection approaches found in citizen science initiatives as well as the specific goals or actors involved. These insights have helped identify the multiple factors driving citizen science in general and what motivates different participants and unpack how citizen science initiatives lead to impact on the ground.

The role of citizen science in improving source awareness is less clear. Without greater emphasis on sources of pollution, scientists or community members using citizen science techniques cannot effectively identify or target interventions that cut emissions. Citizen science initiatives also cannot be used to build pressure for policies that hold specific polluters accountable to legal pollutant limits or best practices.

About This Paper

This paper aims to improve understanding of how citizen science initiatives reflect or focus on sources of air pollution. It presents reflections emerging from a purposive literature review of 33 case studies. Specifically it provides insights into how citizen science methodologies address air pollution sources, summarized into a typology that characterizes the pathways used to achieve impacts. The paper also outlines source-specific outcomes achieved in terms of policy, practice, and behavioral change, and recommends future approaches that could strengthen participatory science focused on pollution sources. The paper is based on an analytical framework that catalogs the stakeholders, project goal and implementation plan, source of pollution investigated, participatory citizen science approaches used, and outcome achieved. A complete summary of the case studies is provided in Appendix A.

Insights and Discussion

The study formulates seven key insights into how sources of air pollution are addressed in citizen science cases studies:

The limited number of case studies found outside of Europe and the United States follows a broader citizen science geographic trend. Twenty-four of the case studies were conducted in the United States, including nine in California alone, and six were located in European countries. Three case studies, in Kenya, Myanmar, and Canada, were also identified. Multiple citizen science objectives were observed across the cases, although strengthening public awareness and knowledge around air quality was a key goal in all of the studies reviewed. The scope of citizen participation also varied.

Citizen science initiatives targeted sources of air pollution in two main ways. The first approach characterized known emission sources to improve accountability to citizen's concerns. The second concentrated on specific geographical areas and leveraged local knowledge and access to identify or characterize potential sources that needed more regulatory focus. The goals for investigating known sources can be divided into three general themes:

- Addressing social equity and personal exposure
- Characterizing temporal and spatial patterns of pollution
- Attempting to influence the policy framework

Investigations into potential sources of emissions were driven by the identification of sources suspected by community members to be a source of pollution exposure or by refining the conclusions of other studies based on hyperlocal monitoring. These community-based insights were often not easily captured by ambient regulatory monitors (located outside of the community or intentionally away from known sources) or by larger-scale modeling efforts.

Few studies incorporated source apportionment or exposure modeling. However study data helped connect regulatory action to sources of community concern and highlighted the need for further investigation. Only two of the case studies incorporated source apportionment analysis, although two additional studies mentioned the need for or planned future analysis.

An environmental justice framing was commonly used to discuss disproportionate exposure and associated potential health risks due to proximity to air pollution sources. Citizen engagement in monitoring efforts was motivated by community concerns about health and disease burdens. The majority of reviewed studies (31) involved low-income or communities of color. An environmental justice lens was explicitly referenced in eleven of the studies reviewed and reflects a growing trend in citizen science.

The collection and public sharing of monitoring data alone was insufficient to spur outcomes. The citizen science initiatives reviewed utilized multiple pathways to transform the data into action. The following six different pathways to achieve impact were identified:

- Raising community awareness of sources of air pollution by educating people about the environmental health impacts of personal exposure; sustaining attention through tools or platforms, print and social media; or raising public awareness through activities by both scientific and citizen project leaders.
- Creating opportunities or forums for engagement with policymakers about community concerns, in the hope of fostering policy effectiveness or informing policy implementation.
- Activating communities interested in collecting more data about the sources of air pollution by, for example, creating networks and lasting partnerships with scientific researchers.
- Spurring pollution reduction or health protection regulatory enforcement action around specific sources.
- Improving modeling inputs and discovering important potential hyperlocal emission sources.
- Changing behavior of the citizens and community members actively engaged in the projects.

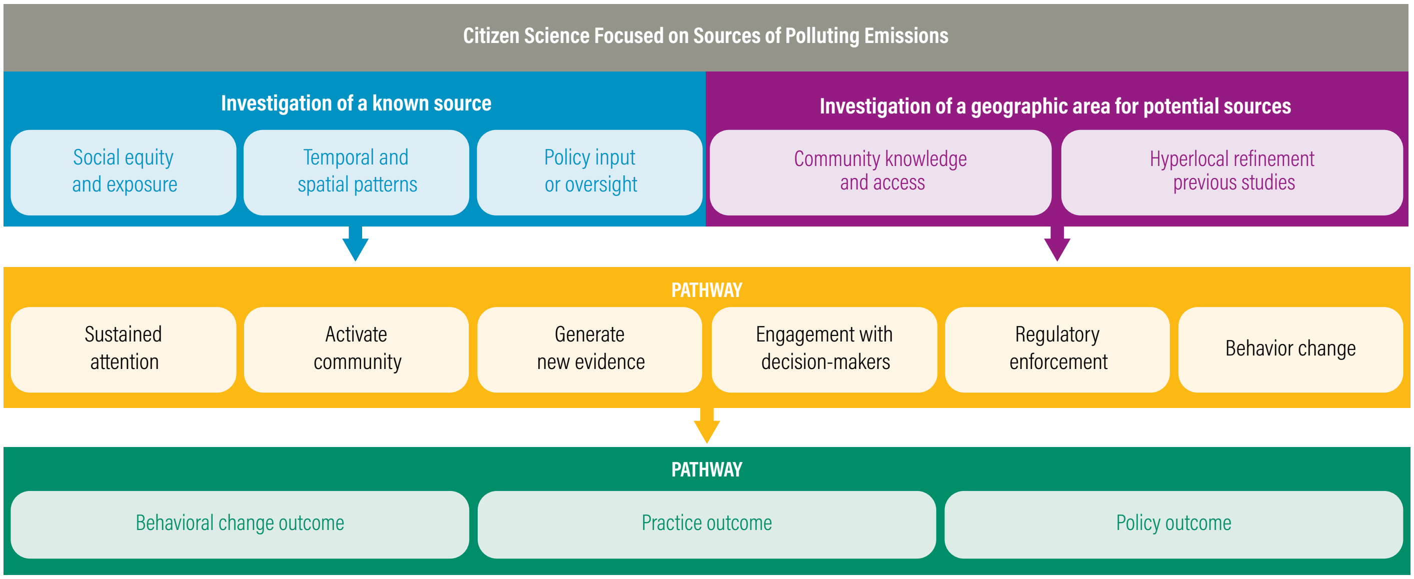
A wide range of policy, practice, and behavioral outcomes directed at specific sources was documented in the case studies. In addition to improved public attention to and understanding of the scientific issues around sources of emissions, increased engagement between community members and policymakers and scientists, including the formation of new networks, was also achieved. Examples of specific outcomes include the documented reduction in ambient levels of toxic hexavalent chromium, a crackdown by regulators on coke plant pollution, governmental agreement to use health impact assessments in pollution mitigation plans, documentation of cancer risk from diesel emissions, the redesign of walking groups and vehicle drop-off/pick-up points to minimize exposure, confirmation of suspected hot spots for exposure and the upgrading of transit services and enforcement of anti-idling laws in response.

Challenges to addressing source awareness stemmed from poor understanding of the complexity of urban air pollution and community frustration over the inability of monitoring studies to definitively identify specific sources without follow-up apportionment studies. Frustration also arose in cases where limited or no action was taken as a result of the new data. In studies that looked to characterize potential pollution sources, researchers had to address conflicts between interpretation of the monitoring data results and community perceptions.

Conclusion

Based on this review, the author created a typology for how pollution sources are addressed in citizen science initiatives, which is presented in Figure ES-1.

Figure ES-1 | **Typology of Citizen Science for Sources of Polluting Air Emissions**



The case studies reviewed begin to outline the positive role that citizen science can play in fostering source awareness. Data collection and engagement do not directly activate regulatory and political action, but data are difficult to ignore. Data provide critical context for public attention and a persuasive case for policymakers and polluting companies to act. Further research could focus on opportunities for the following:

- Develop innovative participatory approaches to collect hyperlocal source activity data for emission inventory and modeling and other source apportionment techniques, especially for sources not typically included in emission inventory estimates.
- Create new platforms and strategies organized according to sources of pollution for communicating pollution emissions, including apportionment data. This could help community participants target their advocacy and engagement goals and address the root causes or sources of air pollution rather than just harm reduction.
- Investigate how different socio-political contexts and different regulatory agency capacities can shape source awareness approaches.
- Expand new methodologies that document the connection between source-specific emissions, exposure, and differentiated impacts on women, children, and other vulnerable populations.

1. INTRODUCTION

As evidence of air pollution's deadly health and ecosystem impacts continues to mount, an increasing number of nonscientists are deepening their efforts to collect and use local air quality data. The involvement of the public in gathering, analyzing, and sharing environmentally related scientific information—broadly referred to as citizen science—is not new. But the emergence of new low-cost monitoring technology along with smartphone and websites apps has greatly expanded the diversity of citizen science air quality projects now feasible.

Citizen science does not have a single, unified definition—one researcher has identified over 34 definitions from a variety of influential actors and documents (Haklay et al. 2021). A common theme is public participation in scientific research, but approaches vary by objective, function, approach, and type of actor involved (Vohland et al. 2021). Alternative names for citizen science include community-based participatory research (CBPR), participatory sensing, community-based monitoring, crowdsource mapping, and participatory science.[1]

Citizen science approaches are employed in diverse fields and settings such as the social sciences, education, organizational science, nursing, and public health (Holkup et al. 2004). This variety highlights how the influence of stakeholders and organizations, country contexts, and understanding can drive the definition of citizen science, and in turn, shape how projects are structured and run (Vohland et al. 2021).

Air-quality citizen science initiatives encompass this variety, using different combinations of monitoring technologies, methods, and partnerships, depending on the objectives and scale, motivations, and specific pollutants of concern (Ceccaroni et al. 2021). The diversity of air quality citizen science initiatives is illustrated in Table 1.

The rapid growth of citizen science offers important opportunities to develop collaborative policy solutions that reduce environmental health burdens and deepen public awareness (Hubbell et al. 2018). Citizen science initiatives have proved an effective mechanism for expanding data transparency, especially the availability of local spatial-temporal data, in areas with little or no regulatory monitoring (Mahajan et al. 2021). Studies have also highlighted how the involvement of citizens can raise public awareness and knowledge about the dangers of air pollution and build capacity to engage around impact concerns (Schaefer et al. 2020). Participatory research can help build trust with local community representatives and provide a valuable forum for addressing the concerns of vulnerable or marginalized communities with low access to resources, opportunities, and agency (Teufel-Shone et al. 2019). The collection of hyperlocal data with low cost sensors can help fill regulatory monitoring gaps, complement regulatory compliance and enforcement and other policy outcomes, and provide new avenues for civil society advocacy (Wyeth et al. 2019). Evidence also suggests that participation can lead to behavior changes as an outcome of engagement (Mahajan et al. 2021).

But citizen science initiatives are not without challenges (Hecker et al. 2019). Documented issues include data quality and sensor management, project operational and organizational problems, sustainability and long-term funding, and uncertainty over how to incorporate citizen science outcomes into regulatory air pollution control policies and practices (Hubbell et al. 2018). The influence of citizen science in government decision-making is not well documented because of concerns around equipment accuracy and data quality as well as policy requirements limiting its use as an official data source for documenting compliance with pollution limits (Wyeth et al. 2019). Further, failures or adverse impacts of citizen science initiatives are not commonly published, creating selection basis in evaluations. Professional scientific skepticism and concerns over community-based inclusion, bias, exploitation, and practicability have also been raised (Lowry and Stepenuck 2021).

As interest grows in citizen science as a pathway for positive environmental impact and public engagement, it is essential to understand how citizen science leads to outcomes on the ground. But because of the vast array of project types, it can be difficult to talk about conditions under which initiatives are successful. Different projects will achieve different outcomes and impacts based on multiple factors including geographic scale, depth of participant engagement, timeline, available resources, and project partnerships (Ceccaroni et al. 2021). To address this challenge, researchers have used a wide range of analysis frameworks including process-based

Table 1 | **Range of Citizen Science Approaches**

OBJECTIVE	LEVEL OF PARTICIPATION	DATA COLLECTION	SENSOR MONITORING METHODS
Education and Information	Citizens as data collectors or personal exposure subjects	Low cost sensors	Fenceline monitoring captures emissions near the periphery of industrial facilities.
Hotspot Identification and Characterization	Citizens as basic interpreters or source of collective knowledge	Websites and smartphone apps	Fixed-site monitoring measures air quality with static instruments at a given location.
Personal Exposure	Citizen participation in problem definition and data collection methodology	Perception and behavior change surveys	Grab sampling refers to collection of an immediate air sample at a specific time, usually for analysis in a laboratory.
Supplemental Regulatory Monitoring	Collaborative science citizen participation in problem definition, data collection, and analysis	Image and odor perception crowdsourcing (human-reported data)	Mobile monitoring is typically performed with equipment housed in trailers, cars, and even backpacks, which are moved around to different locations.

Source: Adapted from Wyeth et al. 2019; Commodore et al. 2017; Williams et al. 2014.

and outcome-based evaluation (Schaefer et al. 2020), organizational contexts (Anderson et al. 2020), and impact analysis (Bonney 2021). Others have defined environmental change impacts (Noordwijk et al. 2021) or unpacked co-creation and citizen participation elements (Blake et al. 2020).

1.1 Citizen Science and Awareness of Air Pollution Sources

Despite the explosion of citizen science initiatives, the level of public understanding surrounding sources of air pollutants remains low. People across seven European countries dramatically underestimate the contribution of the agri-food sector to air pollution (Maione et al. 2020). In California, wild-fire press releases and public complaints published in regional newspapers were poorly correlated with actual air quality (Cisneros and Schweizer 2018). In China, one researcher found a mismatch between the different types of industrial, agricultural, transportation, and domestic pollution sources in the Beijing-Tianjin-Hebei region and the willingness of people to pay for pollution controls on those sources (Wang et al. 2019). Another found that age, education level, and international travel experience impacted awareness of air pollution sources in Nanchang (Liao et al. 2015). And finally, Vital Strategies' analysis of three years of media content in South and Southeast Asia found that public discourse around the sources of air pollution did not center around important drivers like power plants and waste burning, but around traffic emissions, an important, but less significant source of pollution (Mehta and D'souza 2019).

Part of the challenge may lie in the complexity of the chemical and physical dynamics and ability to communicate technical information to non-scientists. In one California case study, for example, despite the public release of air quality data, residents in the San Joaquin Valley community had a preference for non-technical explanations of poor air quality (Ramírez et al. 2019). In this case they indicated that the data presented were hard to understand and lacked actionable steps they could take to mitigate their health risk (Ramírez et al. 2019).

Effective air quality management is a complex process that involves a broad suite of regulations and standards, management tools, and monitoring networks designed to control anthropogenic emissions and reduce public exposure to polluted air. This includes executing detailed source apportionment studies and models that characterize the specific air pollutants released from different sources and the complex spatial, meteorological, and temporal interactions that determine the contribution of local, background, and transboundary air pollution sources in any given airshed. These methods depend on having an inventory of sources and emission estimates along with meteorological data or analysis of filter samples where chemical profiles can be matched with those of emissions from different sources (Heimann et al. 2015).

Researchers are using many new source apportionment techniques and models, but only a few have collected and incorporated residential and especially individually based pollutant data in their analyses (Williams et al. 2009). Without a clear understanding or application of the processes used to connect emissions to a source, regulators or impacted communities will find it hard to target root cause interventions. They also cannot build pressure for policies that hold specific polluters accountable to legal pollutant limits or best practices.

This absence of clear, broad-based, and personally relevant knowledge about the sources of pollution is a significant obstacle to cleaner air. More research is needed on the tools and approaches that can help shift air pollution control strategies from an accurate accounting of ambient concentration of priority pollutants to a targeted focus on the sources of air pollution emissions. Growing source awareness can and should leverage the growing number and documented success of citizen science projects.

This paper helps unpack how citizen science initiatives reflect sources of air pollution based on a purposive literature review of case studies. Specifically it outlines a typology of citizen science initiatives that attempt to address air pollution sources and provides recommendations for possible approaches that strengthen participatory science focused on sources of pollution.

2. METHODOLOGY

The selection of published case studies was based on the following criteria:

- Studies that involved partnerships between civil society and community members with government representatives, air quality professionals, and/or academic scientists or researchers.
- Utilization of a citizen science methodology where local community members and/or civil society organizations played a role in one or more of the attributes of citizen participation—problem definition, data collection, data analysis, public and/or policy engagement, and/or as a source of collective knowledge.

- Air pollution monitoring was a primary objective.
- Identification, characterization, or awareness of sources of pollution was incorporated into the study.

Case studies for review were identified through a word search using Google, EBSCO Discovery Service, Science Direct, and Google Scholar platforms. Word searches using a combination of terms such as "citizen science," "community-based participatory research (CBPR)," "participatory science," "environmental justice monitoring," and "community-based monitoring," as well as "air pollution," "air pollution monitoring," "sources of pollution," "source identification," and "source apportionment."

After identifying more than 75 potential case studies, 33 were selected for analysis (listed in Appendix A). Some relevant case studies were not accessible online or did not provide enough detail about the citizen science or elements to be included. An analytical framework was developed and used to organize information collection in an Excel spreadsheet. The framework is presented in Table 2.

Table 2 | **Case Study Analytical Framework**

FIELD CATEGORY	FIELD NAME	DESCRIPTION
Summary	Reference link/source	Hyperlink to study
	Title of study	Name of study
	Project description	Brief project summary based on abstract
	Timeframe	Year study conducted
	Location	Geographical location of study
	Citizen monitoring tag	Type of monitoring and citizen science elements included in study. **Type of monitoring** included personal exposure, fence-line monitoring, and residential monitoring (fixed site monitoring, grab sampling, and mobile monitoring). Near-road and school monitoring is noted where relevant.
	Citizen science tag	**Citizen science elements** include objective and participation elements
	Pollution tag	Name of specific pollutants being investigated
	Source of pollution tag (primary or secondary)	How sources of pollution were addressed in project. **Primary** indicates studies where identification of sources or characterization of pollutants from known sources was a primary objective. **Secondary** indicates studies where sources of pollution were investigated or mentioned but not addressed as a primary objective.
Stakeholders	Demographics of community	Summary of community demographic information provided
	Specific problems addressed	Summary of specific problem or concerns expressed by community members, including sources of concern such as explicit framing as an environmental justice issue
	Air pollutants/concern	Specific pollutants of concern, if mentioned
Project goal and implementation	Type of outcome desired (policy, practice, or behavior change)	Outline of outcomes or outputs achieved
	How project was organized, including leadership, coalitions, and targets	Description of how project was conducted, including the general role of community partners
	Types of partnerships created	Specific names of project partners
	Implementation challenges recorded	Challenges with citizen science elements and/or partnerships recorded

Table 2 | **Case Study Analytical Framework, Continued**

FIELD CATEGORY	FIELD NAME	DESCRIPTION
Source of pollution investigation	General source category investigated	General description of type of source of pollution investigated if recorded. Categories include general ambient characterization, mobile, stationary, area, or natural category
	Specific source, if identified	Name of source, if identified (both point and non-point)
	History of compliance and enforcement of point sources (if relevant)	Enforcement and/or compliance information about sources of pollution, if recorded.
	Monitoring approach details	Additional details about specific monitoring approach or approaches utilized
	Citizen science element details	Additional details about citizen science elements utilized
Outcome achieved	Policy, practice or behavior change, none	Description of outcomes or outputs achieved where relevant
	How data was translated into action	Additional details on how data collection was used
	Long-term goals/next steps	Additional detail on next steps or long-term impact recorded where relevant

2.1 Caveats

This analysis is based on a targeted sample and is not suitable for hypothesis testing. With the rise in low-cost sensor technology and other strategies to collect pollutant concentration data, citizen science is changing rapidly. New technologies are regularly developed, and new approaches make it easier to document and locate emitting activities. It is likely that some relevant case studies were missed or published after the data collection was completed. Thus, the list of analyzed case studies should be considered a snapshot and not comprehensive.

In addition, numerous other studies incorporate local community monitoring but do not fit the criteria for evaluation because community residents were not engaged in any element of the project design or the monitoring was not conducted in partnership with researchers or scientists. These included

- personal exposure studies where non-scientist residents were the data collection subject but had no other involvement;
- monitoring studies conducted solely to determine the accuracy of fixed-location monitoring or the quality of specific low-cost sensor equipment; or
- civil society campaigns that collected sensor information for advocacy without the involvement of scientists or other experts.

Pollutant or exposure results from the selected case studies were not taken into consideration in the analysis. Excluded information includes details on the specific monitoring technology or platform used, including placement, calibration or maintenance of sensors that impacts the quality of data. It also excludes findings around pollutant concentrations and, where collected, chemical composition of particulate matter (PM).

3. INSIGHTS AND DISCUSSION

3.1 Characterization of the 33 Case Studies

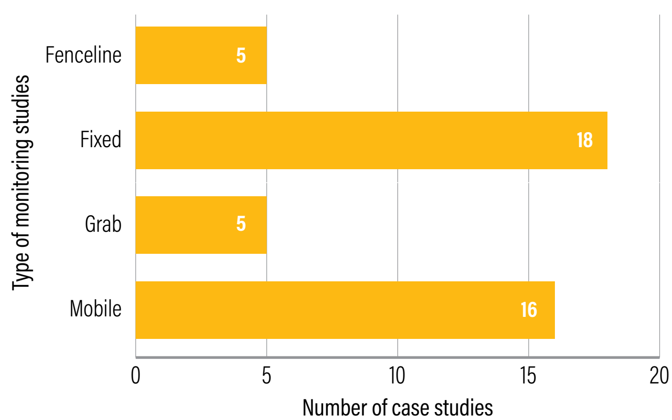
The case studies reflect the diversity of monitoring objectives and citizen science approaches employed in citizen science projects. A wide range of pollutants was investigated, including nitrogen oxides (NO and NO_2), sulfur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM_{10} and $PM_{2.5}$), black carbon (BC), ozone (O_3), hydrogen sulfide (H_2S), methane (CH_4), formaldehyde (HCHO), and other volatile organic compounds (VOC).

A range of monitoring approaches was used to capture the combination of transport-based and stationary emissions either suspected or known to be a major source of exposure (Figure 1). Studies included 16 cases of walking or bike-based mobile residential monitoring and 18 cases of fixed residential monitoring. Eight studies used a combination of both mobile and fixed monitoring, while three measured both indoor and outdoor air pollution levels.

Multiple citizen science objectives were observed across the cases, although strengthening public awareness and knowledge around air quality was a key goal in all of the studies reviewed. Most specified two goals, including 24 cases where the objective was both hotspot and personal exposure monitoring, 26 cases where hot spot and supplemental regulatory monitoring was the goal, and 24 studies where the objective was personal exposure and supplemental regulatory monitoring. As illustrated in Figure 2, the scope of citizen participation also varied, with half utilizing community members as data collectors and 14 applying collaborative science elements that maximized involvement of community members in the project design, data collection, and analysis. Surveys were the most common approach used to collect additional information from community participants (in 9 cases), while uploading information to web based platforms (6 cases), workshops and meetings (5 cases), and interviews and focus group discussion (4 cases) were also utilized.

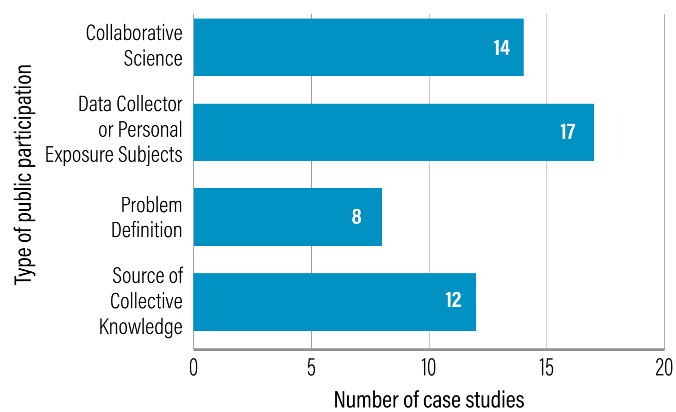
Seventeen of the studies included emission source identification or characterization as a primary objective; 13 focused on a known hot spot point source or targeted geographic area (Figure 3). There was no major difference in monitoring approaches or citizen science elements used in secondary case studies where emission source awareness was not a stated goal.

Figure 1 | **Monitoring Approach Used in Case Studies**



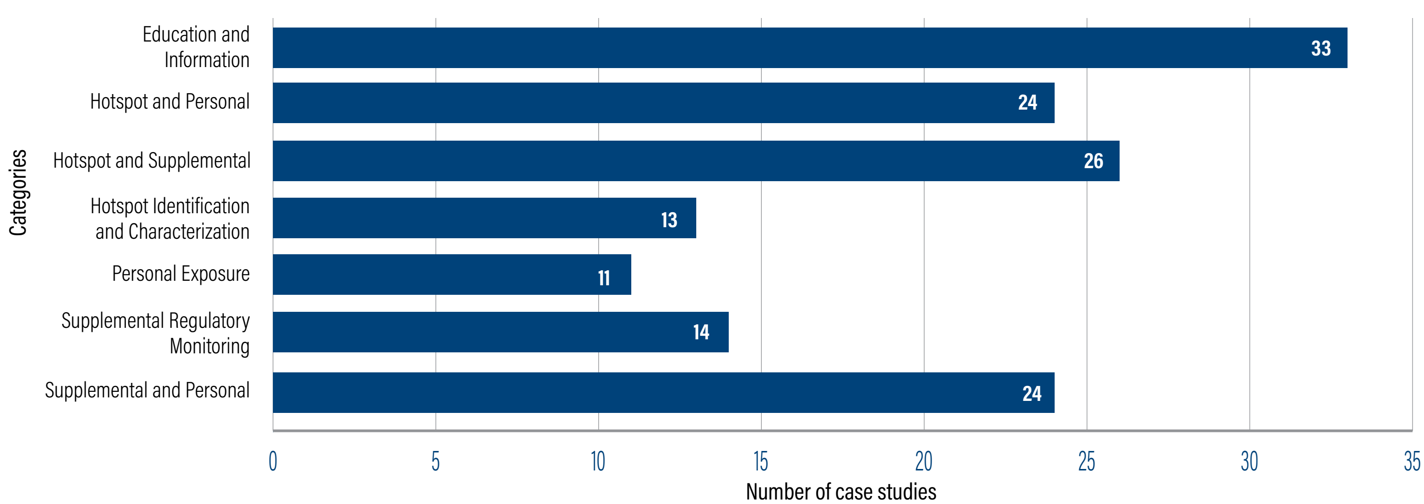
Note: Definitions can be found in Table 1: Range of Citizen Science Approaches.
Source: Author.

Figure 2 | **Range of Citizen Participation Approaches**



Source: Author.

Figure 3 | **Citizen Science Objectives**



Source: Author.

3.2 Seven Insights

1. **The 33 case studies indicate that the use of citizen participatory monitoring outside Europe and the United States is still quite limited.**

Of the 33 studies, 24 were conducted in the United States, including 9 in California alone, and 6 were located in European countries. Three case studies in Kenya, Myanmar, and Canada were also identified. These results reflect documented trends in the greater use of citizen science in developed countries, especially the United States and Europe, than in developing countries, which often have fewer resources or opportunities to use these approaches (Pocock et al. 2019; Rathnayake et al. 2020). Researchers have suggested that limited networking, organizational, and collaboration capacities, including the lack of volunteer participation, are the most common reasons why large-scale citizen science programs are rarely found in developing countries (Requier et al. 2020). Limited air quality monitoring networks and calibration capabilities, unreliable power supplies, lack of spare parts, low commitment, lack of data storage, and the impact of politics also likely contribute (Commodore et al. 2017).

2. **Citizen science initiatives targeted sources of air pollution in two main ways. The first approach characterized known emission sources to encourage accountability to citizens' concerns. The second focused on specific geographical areas and leveraged local knowledge and access to identify or characterize potential sources that needed more regulatory focus.**

In 15 studies, research focused on a known source of air pollution. Sources included industrial facilities such as oil and mining sites, a steel refinery, waste piles, hog operations, and previously identified air pollution "hot spots" with high density traffic and multiple industrial facilities. One study specifically focused on car emissions from a school's pickup and drop-off process. The specific goals and strategies for investigating these known sources focused on three general themes:

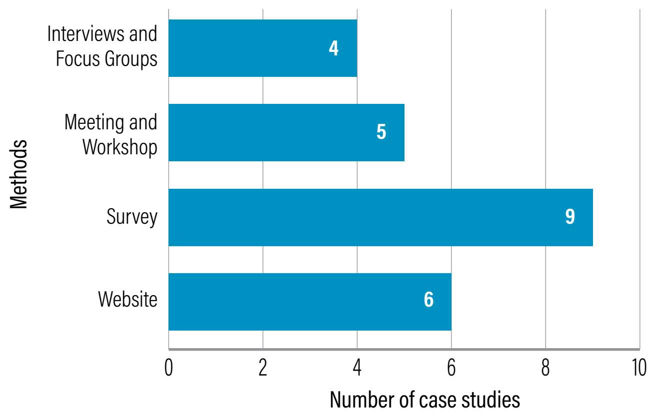
- **Social equity and personal exposure:** Identification of social equity issues surrounding personal exposure where pollutant monitoring data were linked with citizens' health histories and experiences dealing with the sources (Shamasunder et al. 2018; Wing et al. 2008; Macey et al. 2014; Brody et al. 2009; Rickenbacker et al. 2019).
- **Temporal and spatial patterns:** Characterization of temporal and spatial patterns associated with the emissions from specific point or area sources (D'Addario 2015; Williams et al. 2009; Buonocore et al. 2009; Kumar et al. 2020; Liberda et al. 2015; Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019; Hasheminassab et al. 2020; DEC 2019).
- **Policy input or oversight:** Investigation into regulatory compliance or additionally needed regulatory action based on exposure and emission characterization (Phenrat 2020; Williams et al. 2009; Brody et al. 2009; Hammond et al. 2008; Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019).

In Myanmar, for example, previous efforts by villagers in the Ban Chaung, Dawei District to collect data on the burning waste heap were interpreted as clear evidence of past poor waste management and fire suppression by the mining company (Phenrat 2020). New data allowed the community to influence enforcement decisions, elevate democratic capacity, and empower marginalized individuals and communities to advocate for scientifically appropriate mitigation options (Phenrat 2020). In San Diego, California, the work of the Environmental Health Coalition (EHC) and its partnership substantially impacted air quality regulatory action, including passage of an amortization ordinance and a law to limit the operation of a truck-driving school adjacent to the local elementary school, as well as the securing of funds for a feasibility study for an industrial park outside the city limits (Minkler et al. 2010).

Nine studies provided insights into potential sources of emissions associated with exposure. This included investigation into hyperlocal sources suspected by community members of being the source of emission exposure (West et al. 2020; Hsu et al. 2020). Citizen surveys were commonly used by outside researchers to collect local community knowledge about potential emission sources for evaluation (Figure 4) (West et al. 2020; Williams et al. 2009; Downs et al. 2010; Hasheminassab et al. 2020). An example of this approach is provided in Box 1.

Studies seeking to identify potential pollution sources used people's knowledge of their local environs to create a more accurate picture of sources contributing to bad

Figure 4 | **Citizen Perception Data Collection Methods**



Source: Author.

air quality. Potential sources were also identified through refinement of general studies or existing regulatory information (Johnston et al. 2020; Williams et al. 2009; THE Impact Project 2009; Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019). Studies yielded insights into local-scale emission variability not easily captured by ambient regulatory monitors located outside of the community or away from known sources, or by larger-scale modeling efforts (Kaufman et al. 2017; West et al. 2020; Kimbrough et al. 2019; Downs et al. 2010; Minkler et al. 2010; Macey et al. 2014). In many cases, more precise citizen knowledge of the mix and spacing of sources contrasted with state

Box 1 | **Particulate matter pollution in an informal settlement in Nairobi: Using citizen science to make the invisible visible**

The case study investigated perceptions of personal exposure to air pollution among informal settlement dwellers of Makuru, Kenya. The Stockholm Environment Institute, based at the University of York, was approached by Muungano Wa Wanavijiji (MWW) to assist with a monitoring campaign. MWW is a community-based organization affiliated with Slum Dwellers International.

MWW had received multiple complaints from residents about air pollution. Mukuru, an informal settlement located within Kenya's largest industrial area outside of Nairobi, is dominated by small and medium-size industries, including food processing, power generation, chemical processing, battery manufacturing, plastic production, and scrap metal recycling. Residents live in small, crowded, semi-permanent rented structures made of tin, and poorly ventilated.

In order to sample a variety of locations and occupations within the informal settlement, a female roadside vendor, male door to door grocer, a female second-hand clothes hawker, two women involved in community development work, and a young man involved in a community clean-up campaign were selected and trained to carry the air quality monitors. Monitoring efforts found significant differences in $PM_{2.5}$ exposure between individual workers that could be partially explained by spatial differences in concentration identified within the settlement.

A wide range of community residents was interviewed, including street vendors, restaurant owners, shop owners, carpenters, factory workers, and housewives. Residents discussed their perceptions and knowledge of air pollution, sources, and whether they thought they could influence their exposure to pollution. The perception survey was conducted by six research assistants recruited by MWW from the local community, each matched with an experienced researcher.

During the mobile monitoring activities, community champions were able to describe the areas surrounding particularly high or low readings and identified the locations of many potential point sources not possible to identify through other means such as aerial photographs or maps. In addition, unaccompanied researchers would likely have gotten lost in the maze of densely packed buildings, so community member identification of sources was critical. Community knowledge about personal activities such as cooking practices, waste burning habits etc. was useful in understanding pollution from background sources (vehicles, dust, domestic emissions).

Identification of potential sources of pollution exposure was accomplished despite the fact that the resident questionnaires found limited evidence of change in people's knowledge about air pollution over the duration of the project and no change in how polluted they thought the air was (either indoor or outdoor). There was some evidence from the questionnaires that the campaign encouraged more conversations about air pollution in the wider settlement population. The multistakeholder workshops provided a new and much-needed forum to bring together for the first time community members, local policymakers and government officials, and researchers to discuss air pollution, including a forum for discussing odors after dusk and feelings of helplessness about air pollution. A key outcome from this engagement was the formation of the Kenya Air Quality Network (KAQN), as participants realized there was a need for an ongoing multistakeholder forum to discuss air pollution in Kenya.

Source: West et al. 2020.

efforts that were limited by access to and negotiation with property owners, availability of electrical power sources, and location of fixed monitoring sites (Macey et al. 2014).

A number of the studies hope to help target further air monitoring efforts based on these insights (Kaufman et al. 2017; Hsu et al. 2020; Kimbrough et al. 2019) and help community members better understand the sources of air pollution contributing to their personal exposure, as well as the links to asthma, cancer, and cardiovascular disease (Loh et al. 2002; Johnston et al. 2020; Minkler et al. 2010; Rohlman et al. 2015; THE Impact Project 2009; DEC 2019). In many cases, however, while the studies proved a powerful method of engaging people in local air pollution issues, links between an emission source, elevated exposure, and specific health impacts were beyond the scope of the study objective.

3. **Only a limited number of studies incorporated source apportionment or exposure modeling. However, the data helped connect regulatory action to sources of community concern and highlighted the need for further investigation**.

Of the 33 case studies, only 2 incorporated source apportionment analysis (Hasheminassab et al. 2020; Williams et al. 2009), while 2 other studies mentioned the need for or planned future analysis (Kaufman et al. 2017; Kimbrough et al. 2019). These studies highlight how local citizen science data can contribute to the creation of more accurate apportionment models and provide new insights on the sources of pollution of concern to community members, especially regarding health impacts.

In Detroit, researchers conducted a PM source apportionment study based on monitoring data collected by the local civil society partner, Community Action Against Asthma (CAAA). CAAA worked with scientific partners to identify and address the environmental triggers for asthma among children residing in southwest and east Detroit. The PM study revealed that approximately 60 percent of the $PM_{2.5}$ mass was attributed to secondary sulfate/coal combustion sources, approximately 30 percent to vehicular sources, and 1–5 percent to local industrial sources (Hammond et al. 2008). The South Coast Air Quality Management District collected and analyzed over 5000 samples for hexavalent chromium Cr (VI) during a three-year period as part of a monitoring campaign in the city of Paramount, California while engaging in extensive community outreach to inform the community about the air monitoring results and ongoing enforcement efforts and actions.

The need for more detailed analysis became apparent over the course of the citizen science project conducted in the Ironbound community in Newark, New Jersey. As a potential next step, Ironbound Community Corporation (ICC) members recommended performing ongoing saturation monitoring with passive sensors to support source apportionment-type studies (Kaufman et al. 2017). Similarly, researchers in the Kansas City Transportation and Local-Scale Air Quality Study (KC-TRAQS) focused primarily on characterizing sources of pollution in the broader southeast Kansas City, Kansas. However, they planned to use the initial data monitoring as a framework to characterize emission source attributions and estimate near-source exposures in future studies (Kimbrough et al. 2019).

4. **An environmental justice framing was commonly used to discuss disproportionate exposure and associated potential health risks due to proximity to air pollution sources.**

Citizen engagement in air quality monitoring efforts was driven by community concerns about health and disease burdens. High asthma and other respiratory disease rates were the focus in 10 studies, cardiovascular disease in 4 studies, and cancer risk in 5 studies. In some cases, air pollution community concerns were based on sensory perceptions such as bad smells (Hsu et al. 2020; West et al. 2020; Wing et al. 2008; Macey et al. 2014; D'Addario 2015; Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019; DEC 2019) or visible smoke or haze (Phenrat 2020).

The majority of reviewed studies took place in communities that are both poor and majority people of color; two studies were in Indigenous communities (Canada and Myanmar). Pollution sources are frequently located in marginalized communities where residents have less social capital and structural power to advocate for themselves and their environment (Cushing et al. 2015). This environmental justice lens was explicitly referenced in 11 of the US-based studies reviewed, including six initiatives from California, and reflects a growing trend in citizen science. These studies attempted to recognize and address disproportionate exposure, high density of pollution sources, and community health concerns. They also prioritized community inclusivity, participatory project design, and empowerment as a strategy for addressing structural inequities (Ceccaroni et al. 2021). The studies recognized the need for more low-cost community monitoring because of community perceptions that regulatory monitors do not reflect local air quality and that monitoring data are not displayed during elevated pollution events (English et al. 2017).

In a California study involving a Latino community in San Diego, the community organization Environmental Health Coalition helped community members think through their priorities and policy strategies. Their success was due to strong in-house research and training and active engagement of *promotoras de salud* (women lay health promoters) as co-researchers and policy-change advocates. This led to researchers highlighting the importance of empowerment, co-learning, community capacity building, and balancing research and action as important goals of citizen science (Minkler et al. 2010).

In Pittsburgh, Pennsylvania, an interdisciplinary effort between University of Pittsburgh faculty and students, community liaisons, and local organizations developed an Environmental Justice Community Alert Matrix (EJCAM) to facilitate both citizen science and community engagement (Rickenbacker et al. 2019). This framework included both participatory research around mobile air quality monitoring via a bicycle campaign and development of Community Action Teams and involvement of the Urban Transition Cities Movement (Rickenbacker et al. 2019). Researchers concluded that scientific partners must first understand community perceptions of environmental health benefits to inform and guide the process of goal-setting and that bottom-up principles are important when addressing environmental justice issues and should be developed through a long-term process (Rickenbacker, et al. 2019).

Finally, in a study in 16 communities living near hog farms in Tillery, a predominantly African American rural community in eastern North Carolina, participants gained confidence and a greater sense of legitimacy by seeing their experiences and views embedded in a scientific process in which they participated (Wing et al. 2008). Community members felt empowered through connections with a privileged and previously inaccessible professional research team when their experiences became contextualized in scientifically observable patterns (Wing et al. 2008).

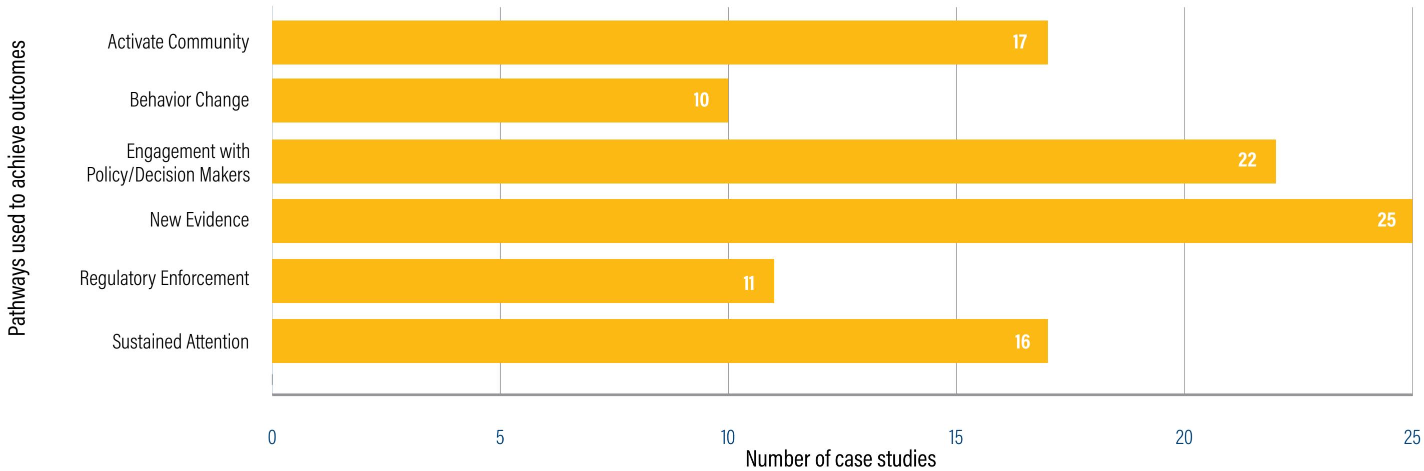
5. **The collection and public sharing of monitoring data alone was insufficient to spur outcomes. The citizen science initiatives reviewed utilized multiple pathways to transform the data into action.**

Given the range of citizen science methods used to monitor air quality, it should not be surprising that a wide variety of approaches is used to achieve impact (Vohland et al. 2021). This evaluation identified six different pathways to achieve outcomes targeting sources of pollution. The pathways can be categorized as follows:

- **Sustaining attention to a pollution source:** Raising the community level of awareness around sources of pollution included efforts to improve understanding of environmental health associated with pollution levels and personal exposure. Sustained attention was also strengthened through tools or platforms, print and social media, or public awareness-raising activities by both scientific and citizen project leaders.
- **Engaging with policy and/or decision-makers:** Opportunities or forums for engagement with policymakers and community leaders about community concerns were created where the evidence collected was used to discuss specific sources of pollution. Such engagement was also found in projects where government officials were co-leaders and/or funders.
- **Activating Communities:** Many of the case studies showcase how civil society participants activated communities interested in collecting more data and information about sources of air pollution, including the creation of networks and lasting partnerships with scientific researchers.
- **Connecting Data to Policy Reform or Enforcement:** Many of the studies used the collected pollutant and disproportionate-impact data to target needed policy reforms or stronger enforcement, including citizen documentation of violations of pollution limits and evidence of the need for stronger health protection measures.
- **Highlighting New Evidence:** Improved modeling inputs and the discovery of important potential hyperlocal emission sources helped identify sources of pollution exposure.
- **Inciting Behavior Changes:** Many of the studies hoped to change the behavior of study participants or larger-community members as a result of their new understanding of air pollutant sources or impacts.

Relationships connecting citizen science with scientific partners and multistakeholder networks helped address decision-maker concerns around the scientific validity and

Figure 5 | **Change Pathways Used to Achieve Outcomes**



Source: Author.

sustainability of the data and source targets. Combining other sources of data such as regulatory monitoring, pollution exposure, and health impact data with citizen science data also helped integrate comprehensive community concerns into regulatory processes.

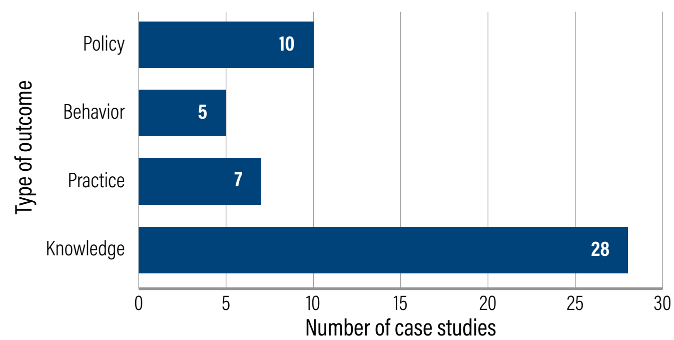
The six pathways are mapped to specific case study examples in Appendix A. In general, most initiatives used two or three pathways to achieve outcomes. Figure 5 provides an overview of pathways used in the reviewed case studies.

6. **Outcomes connected to specific sources of pollution included the recognition of new sources, stronger enforcement or development of new control policies and stronger compliance or new mitigation action by polluting companies. These outcomes were achieved in cases where community-based organization leaders had clear objectives for how to use citizen monitoring data, and when academic or government researchers and community organizations took the time to build trust and a vision for co-leadership.**

The reviewed case studies achieved a variety of different outcomes (Figure 6).

Most of the case studies documented more public attention to air pollution, deeper participant awareness of the technical and scientific issues surrounding air quality, and an increased capacity to speak about and engage policymakers around their concerns. Formal multistakeholder

Figure 6 | **Type of Outcome Achieved**



Source: Author.

networks were formed in a number of cases and follow-up monitoring studies were proposed or implemented as a result of these initiatives.

The studies had outcomes directly impacting known or potentially new sources of pollution. In eight cases, the objective was stronger enforcement or compliance targeting known polluting sources (Hsu et al. 2020; Hasheminassab et al. 2020; Phenrat 2020; Minkler et al. 2010; Brody et al. 2009; THE Impact Project 2009; Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019). In one case, the campaign provoked conversion of diesel transit buses to compressed natural gas, the relocation of a local transit bus yard, and the upgrading of transit services (Loh et al. 2002). In three cases, new sources of pollution were identified and recognized by regulators (Hammond et al. 2008; THE Impact Project 2009; English et al. 2017). Vehicle drop-off/pick-up points were modified and vegetation barriers installed to minimize exposure in another case study (Kumar et al. 2020). Other outcomes achieved included a small reduction in car use in combination with more bike use and walking and keeping children indoors when the air quality is poor (Huyse et al. 2019; English et al. 2017).

In some cases, citizen science initiatives targeting source awareness led to tangible enforcement and policy actions. In the United States, the West Oakland case study shows the local Bay Air Quality Management District specifically partnering with community-based organizations to create an action plan to take regulatory action and involve the many relevant regulatory agencies (Clift 2018). In the city of Paramount, California, different agencies, local businesses, and the community collaborated transparently with the city government, and as a result, several facilities made a range of improvements through voluntary actions, rule amendments, and compliance and enforcement measures. These changes substantially reduced ambient levels of Cr (VI) in the area (Hasheminassab et al. 2020).

Health Risk Assessments (HRAs) of the rail yards in West Long Beach/Wilmington and San Bernardino showed that they ranked among the highest in the country in terms of cancer risk from diesel emissions. The finding confirmed the experience and concern of local residents. With help from THE Impact Project, community partners called public meetings to explain the HRA findings and begin seeking stronger mitigation plans (THE Impact Project 2009). As a result, the government officials have expanded the use of this HRA tool as part of planning for the I-710 Freeway, one of the largest infrastructure projects in the country—the first time an HRA has been required for an interstate highway project (THE Impact Project 2009).

In other case studies, successful engagement and advocacy stemmed from getting the monitoring data to the appropriate decision-maker and presenting it in an accurate and accessible manner, tailored to the community concerns. For example, in the Smell Pittsburgh campaign, residents documented their perceptions and the impacts of pollution odors, cross-referenced with air quality data from monitoring stations (Hsu et al. 2020). They then used these data to deluge the local health department with 11,000 complaints, forcing regulators to publicly answer for the air quality problem (Hsu et al. 2020). In response, Allegheny County Health Department officials defended their air quality efforts and announced a plan to crack down on coke plants, the likely source of the odor and pollution in the area (Clift 2018).

Media engagement played a role in achieving impacts. In California, the EHC effectively used media advocacy, including articles in the *San Diego Union Tribune*, popular city blogs, and stories in EHC's newsletter *Toxinformer*, published in English and Spanish, to enable the "front and center" participation of *promotoras* and other residents. The campaign highlighted residents' proximity to diesel sources and adverse effects including childhood asthma and stunted lung development (Minkler et al. 2010). In Richmond, California, testimony and media coverage of the citizen science findings led the Richmond Planning Commission to attempt to restrict high-sulfur crude oil refining (Brody et al. 2009).

Effective public and technical expert partnerships were also key to achieving outcomes because of the need to ensure data quality. Training of resident researchers focused on the proper use and maintenance of monitoring equipment and route selection. Data considerations related to benefits and limitations of the sensors, information about sources, sites, and potential exposures (Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019; Kaufman et al. 2017). Support with interpreting results, disseminating findings, and commitments to longer-term training after the project also provided a mechanism for building the community's ownership of the study and confidence in its own data (Rickenbacker et al. 2019; Wing et al. 2008).

In many cases, researchers reported that incorporating time to build trust rather than jumping into monitoring was critical for joint decision-making, defining equitable involvement of community investigators, and co-learning. This was true for marginalized communities, who often have a distrust of research because they have not been engaged as research partners or haven't perceived direct benefits from research findings (Teufel-Shone et al. 2019). It was also true for academic or government partners who recognized the benefits of monitoring to build trust in policy processes, create effective information exchanges around technical complexity, and help focus pollution control agency attention on problem areas and sources (Fowlie et al. 2020). Developing funding proposals was one trust-building opportunity recognized, as it provided an opportunity for discussion around context, concerns, the integration of expertise, and locally acceptable research designs and data-collection methods (Teufel-Shone et al. 2019).

7. **Challenges to addressing source awareness stemmed from residents' poor understanding of the complexity of urban air pollution and community frustration over the inability of monitoring studies to definitively identify specific sources without follow-up apportionment studies. Challenges also stemmed from cases where limited or no action was taken as a result of the new data.**

Clearly incorporating the identification or characterization of pollution sources into the design of a citizen science project will help drive source specific outcomes, but it cannot remove the inherent limits of citizen science approaches. As illustrated in this review, the complexity of quantifying source contributions doesn't always align with the time and energy needed for relationship-building or the fact that sensor data is often not used for chemical characterization or other methods (such as satellite-derived estimates) that connect air quality with specific sources.

Researchers who tried to characterize potential pollution sources had to address conflicts between their interpretation of the monitoring data results and community perceptions. For example, in the Nairobi case study, drainage, garbage, and waste were frequently, but incorrectly, mentioned as key sources of air pollution in perception surveys. Participants also indicated that they thought indoor air quality was 'very good' even though monitoring data suggested that indoor cooking was a significant source of exposure to PM (West et al. 2020). In the Oregon and Ohio study that measured personal chemical exposure, location, and respiratory function associated with industrial and transportation sources, community members wanted to discuss additional concerns unrelated to the proposed project (Rohlman et al. 2015). In this case, researchers highlighted the challenge of keeping conversations relevant while also serving as an environmental health resource.

In Worcester, Massachusetts, consensus around exposure data collection was arduous and conflict-laden as community partners did not want to produce results subject to uncertain interpretation (Downs et al. 2010). In the process of communicating AirBeat's purposes and data to the public, the project team experienced tensions around communicating the links between asthma and outdoor air pollution (Loh et al. 2002). Some of the research partners felt that the community partners and the media overstated the degree to which diesel pollution contributed to or caused asthma. They felt the public was being misled into believing that diesel pollution was the main source of the asthma problem (Loh et al. 2002).

In other studies, community members expressed dissatisfaction with how the monitoring data could be used by policymakers or how the broader political context limited the impact. In the Ironbound, New Jersey, study, for example, community members did not understand that the CSAM pod data did not represent exposure measurements of regulatory quality that could lawfully mandate follow-up actions or impact a risk of health impacts (Kaufman et al. 2017). This resulted in the need to revise the analysis plan to accommodate comparison of CSAM pod data with regulatory-equivalent monitoring data during the validation phase. This, in turn, created conflict over who was expected to perform this task (Kaufman et al. 2017). In the Richmond, California, study while the monitoring results appeared to influence deliberations of the Richmond Planning Commission in favor of stopping refinery permit changes that could increase harmful pollutant emissions, the city council revised that decision after the oil refinery company offered Richmond $60 million in mitigation benefits (Brody et al. 2009).

In Myanmar, the field investigation helped residents make an informed recommendation about the most appropriate corrective action to address pollution from the burning waste heap. However, the mining company chose a different option and did not install any long-term monitoring system. Since this was same correction action recommended but ignored in 2017, the affected villagers doubt whether it will be successful this time (Phenrat 2020).

Many of the case studies documented common problems found in participatory monitoring studies, including lost, poorly maintained, or inoperable sensor equipment, limited distribution of sensors, and small sample sizes impacting comparisons across populations (Hecker et al. 2019). Self-selection and self-assessment biases in surveys used to collect perceptions were also noted (Hsu et al. 2020; Shamasunder et al. 2018; West et al. 2020) as were labor-intensity and the time needed to include community co-design and engagement elements (Hasheminassab et al. 2020; Minkler et al. 2010; Downs et al. 2010; THE Impact Project 2009).

4. CONCLUSION

Citizen science techniques are being employed to monitor specific air pollution sources, especially known hot spots, and to identify potential hyperlocal sources missed by regulatory-based monitoring. These initiatives employ targeted pathways that help shift the focus away from merely characterizing air quality towards

- recognizing new sources;
- fostering stronger enforcement or the development of new control policies for targeting known sources;
- strengthening the evidence of exposure to and health impacts from specific source emissions; and
- provoking stronger compliance or new mitigation action by polluting companies.

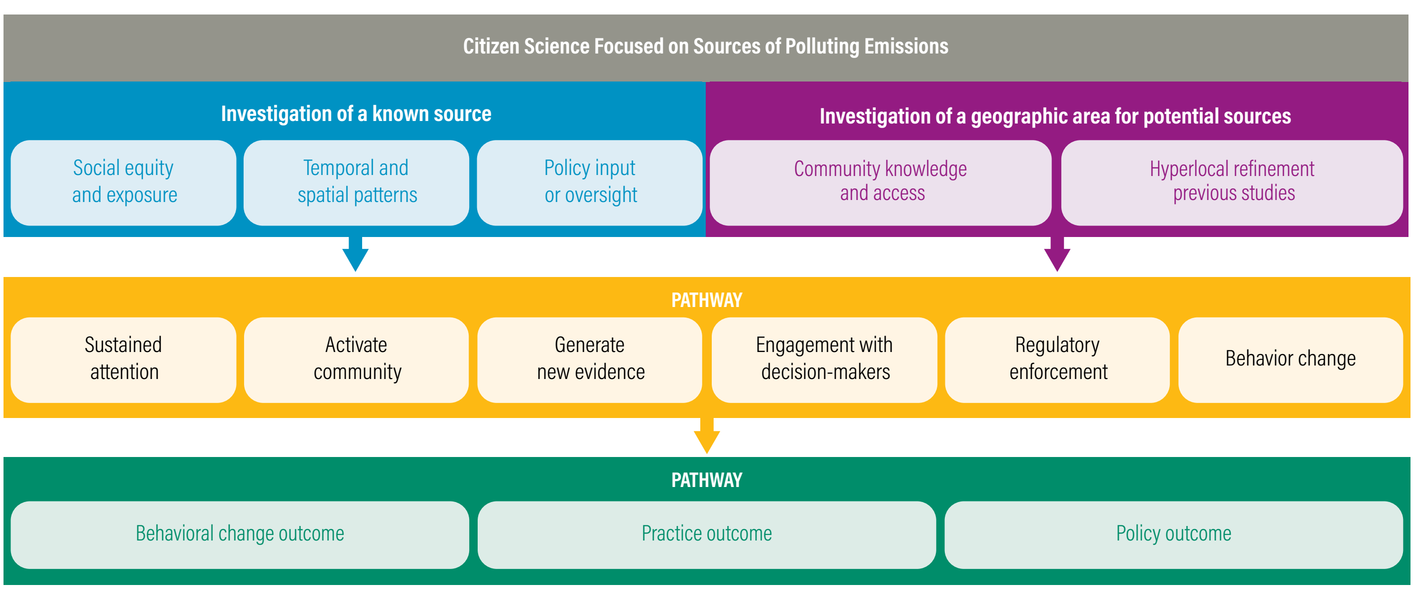
Based on these findings, a typology of citizen initiatives focused on sources of air pollution is outlined in Figure 7.

A focus on sources of pollution not only helped local residents deepen their scientific knowledge of the sources in their community, but also strengthened their ability to engage policymakers and advocate for scientifically based health protections targeting specific sources of concern. Initiatives accelerated the creation of networks and lasting partnerships with researchers and atmospheric scientists and raised source awareness by increasing the transparency and accessibility of source-specific emission data through new forms of communication. Monitoring data were also used to improve modeling outputs. The focus on sources further motivated community-based partnerships and helped empower local residents to target the sources of emissions contributing to personal exposure and health impacts.

While these examples begin to outline the positive role that citizen science can play in fostering source awareness, and what it looks like in practice, very few follow-up source apportionment studies using pollutant filter samples were conducted, and no examples of citizens contributing to emission inventory source activity estimates or other source apportionment activities could be found. This lack of specificity hindered the ability of researchers and community members to make definitive connections between sources and health impacts, especially in urban environments where local and transboundary pollutant mixtures contribute to ambient air pollution. Taking action to mitigate pollution from specific sources was further limited by the broader political economy that shapes enforcement and public health policy compliance and the lengthy complex processes needed to form meaningful, trusted relationships with local actors.

While the number of citizen science-based initiatives in the Global South appears to be growing, the context-specific outcomes and citizen science approaches employed in the United States and Europe may limit scaling and replication of successful examples. It is critical to consider the specific challenges for citizen science in

Figure 7 | **Typology of Citizen Science for Sources of Polluting Air Emissions**



the Global South, including where citizen science might be driven by international organizations as part of their data gathering or development work or the ability to use citizen science as more than a data collection tool in difficult political contexts (Ceccaroni et al. 2021; Rathnayake et al. 2020). These challenges can reinforce power imbalances seen in other research settings and can limit capacity building and citizen opportunities for more effective engagement with policymakers. Private companies have also invested in citizen science initiatives raising important ethical considerations such as power relations, market expansion motivations for involvement, and legal issues such as data protection, informed consent, and intellectual property rights (Tauginienė et al. 2021).

Further, the goals and objectives for citizen science, especially to address disproportionate impacts and perceived injustice, do not just focus on documentation but on action, making issues of power and control central to the approach (Ceccaroni et al. 2021). For citizen science to play a role in strengthening source awareness, scientists and researchers must wrestle with how best to generate science that translates into tangible results beyond robust pollutant data collection. In turn, community leaders and residents must accept that because of the complexity of atmospheric chemistry, it is difficult to make simple and direct connections between health, exposure, and obvious sources of air pollution. Scientifically valid methodologies are needed to create an accurate picture of air pollution risks and effective mitigation strategies.

Policymakers and government regulatory agency officials must wrestle with how best to incorporate the results of participatory initiatives, not only the monitoring data but the regulatory and policy gaps identified through community engagement. The reviewed case studies document that expanded monitoring at the neighborhood level built trust in the policy process and helped focus government agency attention on problem areas and sources. It would seem the positive relationships developed by working together on citizen science initiatives could be further leveraged to prioritize ongoing community engagement mechanisms in regulatory forums. Planning for and conducting source apportionment studies after the citizen science component and reporting back results could serve as a model for deepened engagement with communities and policy decision-makers. Data collected from citizen science projects can also be used to in combination with other data sources to enhance predictive models or be applied in other contexts to produce more robust estimates.

Researchers have identified future citizen science applications such as measuring hazardous air pollutants (HAPs), establishing community emergency alert systems, examining multimedia pollution or cumulative risk assessments, and even supplementing environmental data collection gaps and the limited monitoring capacity of governmental agencies to address the environmental impacts of armed conflicts (Commodore et al. 2017; Kaufman et al. 2017; Weir et al. 2019). Further development of a typology of citizen science initiatives that focus on source awareness could also support new approaches like the following:

- Development of innovative participatory approaches to collect hyperlocal source activity data for emission inventory, modeling, and other source apportionment techniques, especially for sources not typically included in emission inventory estimates.
- Creation of new platforms and strategies organized by sources of pollution to communicate pollution emissions, including apportionment data. This could help community participants target their advocacy and engagement goals and address the root causes or sources of air pollution rather than only harm reduction.
- Investigation into how different sociopolitical contexts and different regulatory agency capacities should shape source awareness approaches.
- New methodologies that document the connection between source-specific emissions, exposure, and differentiated impacts on women, children, and other vulnerable populations.

APPENDIX A. OVERVIEW OF CITIZEN SCIENCE CASE STUDIES

Table A-1 summarizes the 33 case studies discussed in this paper. It highlights key analytical framework elements used to understand how citizen science initiatives focus on the sources of air pollution. These elements include the following:

- The objective of the overall study
- The citizen science elements, including the type of monitoring, citizen science objectives, and participation methods included in each study
- The pathway used to achieve outcomes
- The specific source awareness goal and outcomes achieved

Table A-1 | **Overview of Citizen Science Case Studies**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Particulate matter pollution in an informal settlement in Nairobi: Using citizen science to make the invisible visible Nairobi, Kenya (West et al. 2020)	Quantify individual exposure within one informal settlement in Nairobi while raising awareness of the issue among community members and policy-makers	Fine particulate matter ($PM_{2.5}$)	▪ Mobile residential citizen monitoring with GIS tracking ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Residents engaged in collaborative science utilizing survey and workshops	▪ Sustained attention ▪ Activated community ▪ Engagement with policy/decision makers	Residents identified the locations of many potential point sources not possible to identify through other means due to density of area and community knowledge Strengthened engagement with policymakers and formation of the Kenya Air Quality Network (KAQN)
hackAIR: Towards Raising Awareness about Air Quality in Europe by Developing a Collective Online Platform 30 countries in Europe (Kosmidis et al. 2018)	Creation of a centralized air quality data hub, hackAIR, that enables citizens to contribute to air quality monitoring; data from official air quality monitoring stations are combined with air pollution estimates from sky-depicting photos and from low-cost sensing devices that citizens build on their own. Additionally, a data fusion algorithm merges air quality information from various sources to provide information in areas where no air quality measurements exist.	PM_{10} and $PM_{2.5}$	▪ Personal exposure characterization goals ▪ Mobile residential citizen monitoring ▪ Building awareness goals ▪ Residents as data collectors ▪ Citizen observatory ▪ Residents were source of collective knowledge	▪ Behavior change	Raised awareness of sources of ambient air pollution

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Community-Based Monitoring and Air Quality: Citizen Scientists as Data Collectors in the University Village Community and Quantifying the Effects of Nearby Industrial Practices in West Berkeley and Albany, California University Village, California, USA (D'Addario 2015)	Residents in a fenceline community were involved in parallel odor perception surveys and community-based air quality monitoring to collect data on pollutants believed to come from a nearby steel foundry to determine spatial and temporal emissions patterns and levels of air pollutants.	Volatile organic compounds (VOCs), including formaldehyde	▪ Building awareness goals ▪ Residential grab sampling and fenceline citizen monitoring ▪ Supplemental regulatory monitoring goals ▪ Residents as data collectors and source of collective knowledge through odor surveys	▪ New evidence for policy	Goal to characterize a known source of air pollution Identified patterns in emissions from odor perception survey data that weren't evident from institutional monitoring efforts Methylene chloride emission concentrations found exceeded regulatory limits
A Citizen Science and Government Collaboration: Developing Tools to Facilitate Community Air Monitoring Newark, New Jersey, USA (Kaufman et al. 2017)	EPA's Office of Research and Development (ORD) worked collaboratively with EPA Region 2 and the Ironbound Community Corporation (ICC) to measure local gaseous and particulate air pollution levels by using a customized low-cost sensor pod designed and fabricated by EPA.	$PM_{2.5}$, nitrogen dioxide (NO_2), temperature, and relative humidity	▪ Residential fixed site citizen monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Residents engaged in collaborative science through multiple telephone, webinar, and in-person meeting ▪ Development of a citizens toolkit	▪ Activated community ▪ Engagement with policy/decision makers	Goal to identify potential sources of air pollution Participants were able to use this information and data collected to formulate ideas for future studies that demonstrated need to understand sources including performing saturation monitoring with passive sensors for source apportionment-type studies; and using targeted sensor placement strategies near potential hotspots

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
From Asthma to AirBeat: Community-Driven Monitoring of Fine Particles and Black Carbon in Roxbury, Massachusetts Boston, Massachusetts, USA (Loh et al. 2002)	A collaborative development of AirBeat, a real-time air pollution monitoring system designed to answer community questions about whether there are pollution "hotspots" in Roxbury and the degree to which diesel emissions are contributing to health problems.	$PM_{2.5}$, ozone (O_3), and black carbon (BC)	▪ Residential fixed site citizen monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Residents engaged in collaborative science through community outreach via youth education and training and outreach via website and telephone ▪ Media engagement and outreach using results	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement ▪ Behavior change	Goal to identify potential sources of air pollution Data begin to confirm suspicions that Dudley is a hotspot for $PM_{2.5}$ and that diesel emissions significantly increase the pollution levels Recommendations were adopted in the final study, including enforcement of the anti-idling law in Dudley Square, conversion of diesel transit buses to compressed natural gas, relocation of a local transit bus yard, and upgrading of transit service to Dudley Square
Youth Engaged Participatory Air Monitoring: A 'Day in the Life' in Urban Environmental Justice Communities Los Angeles County, California, USA (Johnston et al. 2020)	A Day in the Life program engages youth in collecting data that they can then analyze and use to take action. Academics partnered with Los Angeles–based youth environmental justice organizations to combine personal air monitoring, participatory science, and digital storytelling to build capacity to address local air quality issues.	$PM_{2.5}$	▪ Mobile residential citizen monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Residents engaged in collaborative science and supplemented with building capacity, environmental health literacy, technical skills, storytelling skills, and collaboration between scientists, youth, and environmental justice organizations	▪ Activate community ▪ Engagement with policy/decision makers ▪ Behavior change	Goal to identify potential sources of air pollution Youth participants brought up several potential sources of $PM_{2.5}$ that they felt could affect them at home or at schools, including trucks and heavy freeway traffic, the activities at the Port of Los Angeles and Long Beach, oil extraction sites, and petroleum refineries

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Societal impact of the citizen science project "CurieuzeNeuzen Vlaanderen Flanders (Flemish Region of Belgium); and Antwerp, Europe (Huyse et al. 2019)	The "CurieuzeNeuzen Vlaanderen" (Curious Noses), project mapped the air quality across the region of Flanders (Belgium). The project mobilized 20,000 citizens to measure NO_2 air quality levels in front of their house	NO_2	▪ Fixed passive residential citizen monitoring ▪ Building awareness goals ▪ Data collectors and source of collective knowledge through online questionnaires ▪ Outreach and engagement via surveys to volunteers not selected for monitoring ▪ Crowdsource data on web platform	▪ New evidence ▪ Engagement with policy/decision makers ▪ Behavior change	Raised source awareness about traffic-related air pollution More than 50% of the respondents of the CurieuzeNeuzen groups state that they use the car less, and a similar percentage indicates that they bike more and walk more
Smell Pittsburgh: Engaging Community Citizen Science for Air Quality Pittsburgh, PA, USA (Hsu et al. 2020)	Community members report and track where odors are frequently concentrated. All smell report data are publicly accessible online. These reports are also sent to the local health department and visualized on a map along with air quality data from monitoring stations.	Fine particulate matter ($PM_{2.5}$), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), hydrogen sulfide (H_2S), wind direction, and wind speed	▪ Residential fixed site citizen monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Residents as data collectors and source of collective knowledge and problem definition ▪ Utilized odor perception surveys and mapping of data on website and post hoc and predictive event notifications	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Goal to characterize coke and steel plants as a likely source of air pollution Due to the sheer volume of complaints received and its qualitative nature, the Allegheny County Health Department has been using statistical analysis and data mining techniques to identify pollution zones and track significant changes to local air quality
Community-Based Health and Exposure Study around Urban Oil Developments in South Los Angeles Los Angeles County, California, USA (Shamasunder et al. 2018)	In partnership with *Promotoras de Salud* (community health workers), the project gathered household surveys near two oil production sites and tested the capacity of low-cost sensors for localized exposure estimates within two 1500 ft. buffer areas (West Adams and University Park) surrounding oil development sites.	Methane	▪ Fixed residential and fenceline citizen monitoring ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Residents as data collectors and source of collective knowledge through use of bilingual surveys	▪ Sustained attention ▪ Activate community ▪ New evidence	Goal to characterize known sources of air pollution—AllenCo oil site in University Park and Jefferson Drill Site in West Adams Answer community questions and effort to seek a safety buffer between sensitive land uses and active oil development

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
The Imperial County Community Air Monitoring Network: A Model for Community-based Environmental Monitoring for Public Health Action Imperial County, California, USA (English et al. 2017)	Creation of a network producing real-time particulate matter data from 40 low-cost sensors throughout Imperial County	PM_{10} and $PM_{2.5}$	▪ Fixed residential monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Explicit about environmental justice approach ▪ Residents engaged in collaborative science through including decisions on placement of monitors	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement ▪ Behavior change	Used to identify "hotspots" and to show how wind direction and transport of the pollutants affects PM levels Schools using the data to determine when the air quality is poor enough that schoolchildren should remain indoors
High time-resolution and time-integrated measurements of particulate metals and elements in an environmental justice community within the Los Angeles Basin: Spatio-temporal trends and source apportionment City of Paramount (LA), California, USA (Hasheminassab et al. 2020)	South Coast Air Quality Management District conducted an extensive air monitoring campaign in this community to identify and address sources of airborne particulate hexavalent chromium (Cr (VI)) and other toxic metals	Airborne particulate hexavalent chromium (Cr (VI)) and other toxic metals	▪ Grab sampling, and fixed site continuous, residential monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Explicit about environmental justice approach ▪ Personal exposure characterization goals ▪ Residents as data collectors and source of collective knowledge ▪ Community outreach and engagement throughout project	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Monitoring locations were selected (and adjusted over time) strategically to monitor emissions from target facilities and assess community exposure to toxic metals Source apportionment studies conducted South Coast AQMD conducted emission testing at target facilities and took aggressive inspection and enforcement actions to identify the high emitters and reduce their emissions Several facilities made a range of improvements through voluntary actions, rule amendments, and compliance and enforcement measures. These changes substantially reduced ambient levels of Cr (VI) in the Paramount area

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
The Kansas City Transportation and Local-Scale Air Quality Study (KC-TRAQS): Integration of Low-Cost Sensors and Reference Grade Monitoring in a Complex Metropolitan Area. Part 1: Overview of the Project Kansas, USA (Kimbrough et al. 2019)	The spatial and meteorological effects of $PM_{2.5}$, and black carbon pollutants on potential population exposures were evaluated at multiple sites using a combination of regulatory grade methods and instrumentation, low-cost sensors, citizen science, and mobile monitoring	$PM_{2.5}$, black carbon	▪ Mobile and fixed residential monitoring ▪ Building awareness goals ▪ Residents as data collectors	▪ New evidence	Goal to characterize potential emission source attributions and estimate near-source exposures Identified multiple emission sources, including residential, light industrial and commercial facilities, and transportation sources (railyards, passenger cars, diesel trucks), drive the $PM_{2.5}$ and BC concentrations in the study area
Citizen-Based Air Quality Monitoring: The Impact on Individual Citizen Scientists and How to Leverage the Benefits to Affect Whole Regions Spain, Italy, and Austria (Schaefer, Kieslinger, and Fabian 2020)	Collect data from CAPTOR nodes sensing devices in three different European regions by reaching citizens willing to install the low-cost sensors, and collaborate with the researchers	O_3	▪ Fixed residential monitoring ▪ Building awareness goals ▪ Residents as data collectors and source of collective knowledge through interviews ▪ Data on website platform	▪ Behavior change	Raised awareness about the existence and sources of ozone
Shared Air/ Shared Action (Sasa): Community Empowerment Through Low-Cost Air Pollution Monitoring Chicago, IL, USA (Griswold et al. 2020)	EPA funded project to monitoring air quality in four diverse communities in Chicago, using low-cost portable air pollution sensors, with 8 partners, 4 of which are local community organizations	PM, NO_2, O_3	▪ Mobile residential monitoring ▪ Building awareness goals ▪ Engaged residents in collaborative science including community involvement in project design	▪ Activate community ▪ Engagement with policy/decision makers	Knowledge gained enabled communities to be on a more level playing field with the City when discussing air quality, including advocacy around toxic cloud that engulfed Little Village community when City of the Chicago failed to plan or notify community during planned implosion of the Crawford Coal Plant

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Community Citizen Science for Risk Management of a Spontaneously Combusting Coal-Mine Waste Heap in Ban Chaung, Dawei District, Myanmar Ban Chaung, Dawei District, Myanmar (Phenrat 2020)	This study empowers the affected villagers to make risk management decisions via a community citizen science approach to identify hotspots at the waste heap releasing gaseous pollutants that may exceed acceptable levels and make an informed decision about the most appropriate corrective action that should be taken by the mine.	CO, NO_2, SO_2, nitric oxide (NO), VOC, H_2S, ammonia (NH_3), hydrogen cyanide (HCN)	▪ Grab fenceline monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Engaged residents in collaborative science, including using historical community data, knowledge, and survey of health impacts	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Goal to characterize a known source of air pollution—a coal-mine waste heap operated by a company with a history of poor compliance and ineffective mitigation Community meaningfully participated in and influenced risk management decision based on scientific information
The Design and Field Implementation of the Detroit Exposure and Aerosol Research Study Detroit, Michigan, USA (Williams et al. 2009)	The US EPA conducted the Detroit Exposure and Aerosol Research Study (DEARS) to evaluate and describe the relationship between air toxics, particulate matter, PM constituents, and PM from specific sources. The impact of regional, local (point and mobile), and personal sources on pollutant concentrations and the role of physical and human factors were investigated.	PM_{10}, $PM_{2.5}$, $PM_{2.5}$, particle-bound nitrate, elemental and organic carbon (EC, OC), formaldehyde, acetaldehyde, and acrolein, VOCs, particle-bound SVOCs, nitrogen dioxide, sulfur dioxide, and ozone	▪ Fixed and mobile community, residential monitoring ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Residents as data collectors and source of collective knowledge	▪ New evidence ▪ Engagement with policy/decision makers	Goal to characterize known sources (automotive, industrial, and natural sources) of air pollutant concentrations at the community, neighborhood, and potentially the personal level Source apportionment studies conducted not only ambient PM constituents but also VOCs, SVOCs, and potentially even the information gained from the personal and residential survey information

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Integrating Epidemiology, Education, and Organizing for Environmental Justice: Community Health Effects of Industrial Hog Operations North Carolina, USA (Wing et al. 2008)	A repeat-measures longitudinal design, community involvement in data collection, and integration of qualitative and quantitative research methods helped promote data quality while providing opportunities for community education and organizing	PM_{10} and semivolatile PM_{10}, $PM_{2.5}$ (with subsequent filter analysis for endotoxins), and hydrogen sulfide	▪ Fenceline continuous monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Personal exposure characterization goals ▪ Engaged residents in collaborative science including community odor perception survey and interviews ▪ Shared information with broader community	▪ Sustained attention ▪ Activate community ▪ New evidence	A framework for how community residents interpreted and responded to exposures from the industrial swine operations was developed—mainly to help them understand and manage such exposures Participant involvement allowed the collection of real-time data on malodors that would not otherwise be possible
Air Concentrations Of Volatile Compounds Near Oil And Gas Production: A Community-Based Exploratory Study Arkansas, Colorado, Ohio, Pennsylvania, and Wyoming, USA (Macey et al. 2014)	Grab and passive air samples were collected by trained volunteers at locations identified through systematic observation of industrial operations and air impacts over the course of resident daily routines	VOCs	▪ Fenceline, Grab monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goals ▪ Residents as data collectors, source of collective knowledge, and problem definition through community impact data collection and project design	▪ New evidence ▪ Regulatory enforcement	Goal to characterize a known source—emissions from unconventional oil and gas development and production The research team identified eight volatile compounds that exceeded ATSDR minimal risk levels or EPA Integrated Risk Information System cancer risk levels Community-based research helped improve the spatial and temporal resolution of air quality data including sources of public health concern at each site as well as identify mixtures, their potential emissions sources, and the cumulative and synergistic effects

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Participatory Testing and Reporting in an Environmental-Justice Community of Worcester, Massachusetts: A Pilot Project Worcester, Massachusetts, USA (Downs et al. 2010)	Residents and researchers tested fourteen homes for air and water hazards. Monitoring of neighborhood particulates by residents and researchers using real-time data was also implemented.	$PM_{2.5}$, radon, mold spores	▪ Fixed indoor and mobile ambient outdoor air monitoring ▪ Building awareness goals ▪ Residents engaged in collaborative science including personal exposure modeling in subsequent study	▪ New evidence ▪ Engagement with policy/decision makers	Goal was to help identify potential sources Monitoring of neighborhood PM increased awareness of environmental health risks, particularly asthma
A community participatory study of cardiovascular (CV) health and exposure to near-highway air pollution: study design and methods Boston, Massachusetts, USA (Lane et al. 2016; Fuller et al. 2013)	The Community Assessment of Freeway Exposure and Health (CAFEH) is investigating the relationship between traffic-related ultrafine particles (UFP) and biomarkers of CV risk. University researchers partnered with community and more than 700 residents from three near-highway neighborhoods in the Boston metropolitan area in Massachusetts, USA. A second study analyzed blood samples from 408 living in three near-highway and three urban background areas in and near Boston, Massachusetts.	Traffic-related ultrafine particles as measured by particle number concentration (PNC)	▪ Mobile residential monitoring plus models to link with activity data ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Residents engaged as data collectors and source of collective knowledge through biomarker (blood) sampling and surveys	▪ New evidence ▪ Engagement with policy/decision makers	CAFEH was developed as a direct response to community concerns about air pollution, and community members have engaged government officials using partner expertise and lessons learned from project to address the impacts from specific potential sources of concern

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Sí Se Puede: Using Participatory Research to Promote Environmental Justice in a Latino Community in San Diego, California San Diego, California, USA (Minkler et al. 2010)	To document anecdotally reported high rates of respiratory conditions in the community through the use of geographic information system mapping, surveys, and air monitoring to document numerous noncompliant auto body and paint shops and local air quality	UFP	▪ Residential mobile monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Supplemental regulatory monitoring goals ▪ Residents as data collectors; source of collective knowledge through surveys, interviews, and recruitment of parents at local school	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers	Academic research coupled with survey findings helped shine a spotlight on asthma and its likely relationship to poor land use planning, including findings regarding the relationship between proximity to diesel sources and adverse childhood health outcomes Both quantitative data from university-based colleagues and a *promotora*-led survey of residents received good media coverage and frequently were cited in testimony before the City Council and other bodies to help capture the key concerns and priorities of residents and in turn help shape regulatory action
Linking Exposure Assessment Science With Policy Objectives for Environmental Justice and Breast Cancer Advocacy: The Northern California Household Exposure Study Richmond and Bolinas, California, USA (Brody et al. 2009)	Study gathered information on community health concerns in two communities; analyzed indoor and outdoor air for 153 compounds, including particulates and endocrine disruptors; and compared with state monitors	$PM_{2.5}$, polycyclic aromatic hydrocarbons, elemental carbon, metals, and sulfates	▪ Fixed indoor & outdoor monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Personal exposure characterization goals ▪ Supplemental regulatory monitoring goal ▪ Residents engaged in collaborative science through meeting and collection of community health concern information	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Goal to characterize known sources (Chevron oil refinery and truck, rail, and marine shipping corridors)—breast cancer connection to cumulative effects and specific sources of indoor pollution originating from outdoor emissions Testimony and media coverage based on findings impacted regulation of high-sulfur crude oil refining

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
The Influence of Traffic on Air Quality in an Urban Neighborhood: A Community–University Partnership Boston, MA, USA (Buonocore et al. 2009)	Monitored multiple air pollutants at a community site in the Mission Hill neighborhood with support of local high school students	Ultrafine particles, $PM_{2.5}$, PAH "polycyclic aromatic hydrocarbons", black carbon, nitric oxide (NO)	▪ Fixed and mobile community monitoring coupled with traffic characterization ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Residents as data collectors sharing results with community	▪ New evidence ▪ Behavior change	Goal to characterize a known source—traffic Residents used findings to modify designed walking group routes that minimized air pollution exposures based on the data collected
A Community-Based Approach to Developing a Mobile Device for Measuring Ambient Air Exposure, Location, and Respiratory Health West Eugene, OR and Carroll County, OH, USA (Rohlman et al. 2015)	Project goals was to develop a community to measure personal chemical exposure, location, and respiratory function associated with community concerns over air pollution from industrial and transportation sources, increased incidence of asthma and impact of unconventional natural gas drilling on local air quality.	VOCs and SVOCs	▪ Mobile monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Personal exposure characterization goals ▪ Residents as data collectors; source of collective knowledge; problem definition through focus groups	▪ Activate community ▪ New evidence	Used previous studies to identify community concerns around specific sources Preliminary research indicated that a wide range of VOCs are emitted from unconventional natural gas drilling sources
A primary school–driven initiative to influence commuting style for dropping off and picking up of pupils Merrow Guildford, Surrey, England (Kumar et al. 2020)	A primary school co-designed a study with local community and researchers to generate data and provide information to understand the impact of pollution levels and identify possible mitigation measures to address traffic hotspot zones in and around school premises, owing to the congestion and engine idling during drop-off/ pickup hours.	$PM_{2.5}$, PM_{10}, CO_2	▪ Fixed monitoring ▪ Building awareness goals ▪ Residents engaged in collaborative science	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Behavior change	Goal to characterize a known source—traffic Modified the drop-off/ pick-up points away from classroom entrances and installed evergreen vegetation barriers to help limit the transport of emissions from main roads to school premises

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Sources of ambient fine particulate matter at two community sites in Detroit, Michigan Detroit, Michigan, USA (Hammond et al. 2008)	A source apportionment analysis was conducted using $PM_{2.5}$ data collected by the Community Action Against Asthma (CAAA) project in Detroit, Michigan. CAAA used a community-based participatory research approach to identify and address the environmental triggers for asthma among children	$PM_{2.5}$, elemental and organic carbon, trace element species, and black carbon	▪ Fixed monitoring (seasonal) ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Supplemental regulatory monitoring goal ▪ Residents engaged in collaborative science	▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Goal to characterize a known source Source apportionment identified sources included secondary sulfate/coal combustion, motor vehicle, oil combustion/refinery, iron–steel manufacturing/waste incineration, and automotive electroplating sources Interventions to reduce exposures based upon findings and relevant exposure metrics used by CAAA to address health impacts and non-attainment issues
Mining in subarctic Canada: Airborne $PM_{2.5}$ metal concentrations in two remote First Nations communities James Bay Ontario, Canada (Liberda et al. 2015)	Airborne particulate matter arising from upwind mining activities is a concern for First Nations communities	$PM_{2.5}$, trace chemicals including local sources of crustal material (dust) from unpaved roadways (Aluminum, Calcium, Magnesium, Silica and Titanium), and possible mine materials (Chromium, Copper, Iron, Potassium, Manganese, and Nickel	▪ Mobile fixed residential monitoring ▪ Building awareness goals ▪ Personal exposure characterization goals ▪ Residents engaged as data collectors	▪ Sustained attention ▪ New evidence	Goal to characterize a known source—mining activities Determined that even though communities are remote and isolated from urban and industrial pollution sources, Attawapiskat First Nation has significantly enhanced levels of particulate matter, and it is likely that some of this arises from upwind mining activities

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Final Report Summary—CITI-SENSE (Development of sensor-based Citizens' Observatory Community for improving quality of life in cities) Europe: Barcelona (ES), Belgrade (RS), Edinburgh (UK), Haifa (IL), Ljubljana (SI), Oslo (NO), Ostrava (CZ), Vienna (A) and Vitoria-Gasteiz (ES). (CORDIS, European Commission 2016) An evaluation tool kit of air quality micro-sensing units (Fishbain et al. 2017)	The CITI-SENSE project developed and tested components of environmental monitoring and information systems focused on the citizens' immediate environment regarding urban air quality, environmental quality of urban public spaces and indoor air quality in schools	NO, NO_2, O_3 and $PM_{2.5}$	▪ Mobile monitoring and development of "Citizens' Observatories" ▪ Building awareness goals ▪ Residents as data collectors; source of collective knowledge, and involved in problem definition	▪ Activate community ▪ Engagement with policy/decision makers ▪ Behavior change	App allowing users to share their perception of air quality, and of the dominant source, heightened awareness of sources Additional effort attempted to evaluate ability to use sensor data for source identification The citizens of Ostrava worked with local NGOs to address long-standing issue of air pollution due to industrial emissions to heighten their impact on the political landscape
A Combined Citizen Science–Modelling Approach for NO_2 Assessment in Torino Urban Agglomeration Torino, Italy, Europe (Bo et al. 2020)	Combined approach between an urban dispersion model (SIRANE) and a citizen science campaign (#CHEARIATIRA) for the assessment of NO_2 concentrations	NO_2	▪ Residential fixed monitoring ▪ Building awareness goals ▪ Supplemental regulatory monitoring goal ▪ Residents as data collectors and engaged in problem definition and sensor placement	▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers	Following the observed high concentration at sensitive receptors, passive samplers have been installed in over 90 schools

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Owning Our Air: The West Oakland Community Action Plan West Oakland, California, USA (Bay Area Air Quality Management District and West Oakland Environmental Indicators Project 2019)	Air District partnered with the West Oakland Environmental Indicators Project and a community-based Steering Committee to develop Owning Our Air: The West Oakland Community Action Plan, which will serve as a blueprint for improving air quality in this community.	Diesel particulate matter (Diesel PM), fine particulate matter ($PM_{2.5}$) and cancer risk from toxic air contaminants	▪ Mobile monitoring (hand held & car based) ▪ Building awareness goals ▪ Supplemental regulatory monitoring goal ▪ Residents engaged in collaborative science including active development of official AQMP	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Goal to characterize known sources—mobile sources on the surrounding roadways and freeways, serve Port of Oakland, stationary and area sources Integrated community work into effort to quantify sources Identified 84 strategies for reducing pollution and four Further Study Measures including moving pollution sources away from residents, adopting health-based land use policies, lowering emissions from the largest sources, increasing the use of clean trucks, and reducing exposure
Albany South End Community Air Quality Study 11 locations around NY State, USA (DEC 2019)	The Department of Environmental Conservation's Community Air Screen (CAS) program helps community groups and interested citizens collect air samples. The results help DEC and participants understand air quality concerns.	VOCs, Formaldehyde (in Seneca Falls only)	▪ Fixed indoor & ambient outdoor monitoring ▪ Building awareness goals ▪ Residents as data collector and engaging in problem definition	▪ Sustained attention ▪ New evidence ▪ Engagement with policy/decision makers	Included investigating known sources and community concerns DEC staff provided education on the many sources of air contaminants

Table A-1 | **Overview of Citizen Science Case Studies, Continued**

PROJECT OR INITIATIVE	OBJECTIVE	POLLUTANT	CITIZEN SCIENCE ELEMENTS	PATHWAY FOR CHANGE	SOURCE AWARENESS ELEMENTS AND OUTCOMES
Neighborhood Assessment Teams: Case studies from Southern California and instructions on community investigations of traffic-related air pollution Trade, Health, Environment: Making the Case for Change Southern California, with case studies in Long Beach, Wilmington, Riverside, and San Bernardino (Truax et al. 2013; "THE (Trade, Health, Environment) Impact Study—Including Health Effects in the Goods Movement Discussion" n.d.)	THE Impact Project partners and A-Team members work together in multiple communities to used P-Trak devices to measure ultrafine particle pollution and counted traffic	Ultrafine particulate matter (UFP)	▪ Grab mobile monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Supplemental regulatory monitoring goal ▪ Residents engaged in collaborative science including sensor placement through meeting and workshop	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Known sources investigated—goods movement including rail and truck/highway and port traffic A formal report attributed 70% of total cancer risk to diesel emissions in communities impacted by goods movement THE Impact Project successfully increased community and policymaker awareness of the negative impacts of diesel truck and locomotive air pollution and expanded use of Health Risk Assessments Finding helped deepen understanding that community also faced numerous other air pollution sources such as oil refineries and manufacturing plants
Creating environmental consciousness in underserved communities: Implementation and outcomes of community-based environmental justice and air pollution research Pittsburgh, Pennsylvania, USA (Rickenbacker et al. 2019)	Interdisciplinary effort between university faculty and students, community liaisons, and local organizations to develop the Environmental Justice Community Alert Matrix (EJCAM) including elements of both citizen science and community engagement	Nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon dioxide (CO_2), carbon monoxide (CO), particulate matter, black carbon (BC), relative humidity (RH), ozone (O_3), temperature, formaldehyde (HCHO), and total volatile organic compounds (TVOC)	▪ Mobile bicycle monitoring ▪ Building awareness goals ▪ Explicit about environmental justice approach ▪ Residents as data collectors and engaged in problem definition	▪ Sustained attention ▪ Activate community ▪ New evidence ▪ Engagement with policy/decision makers ▪ Regulatory enforcement	Known sources investigated including additional data based on known point and mobile sources Resulted in resident involvement in management of new housing developments, and pollution control schemes in conjunction with the local Urban Redevelopment Authority

ABBREVIATIONS

ACE	Alternatives for Community & Environment
ATSDR	Agency for Toxic Substances and Disease Registry
BC	Black carbon
CAAA	Community Action Against Asthma
CAFEH	Community Assessment of Freeway Exposure and Health
CBPR	Community Based Participatory Research
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr (VI)	Hexavalent chromium
DEARS	The Detroit Exposure and Aerosol Research Study
EHC	Environmental Health Coalition
EJCAM	Environmental Justice Community Alert Matrix
H_2S	Hydrogen sulfide
HAPs	Hazardous Air Pollutants
HCHO	Formaldehyde
HRAs	Health Risk Assessments
ICC	Ironbound Community Corporation
KAQN	Kenya Air Quality Network
KC-TRAQS	Kansas City Transportation and Local-Scale Air Quality Study
MWW	Muungano Wa Wanavijiji
NO	Nitrogen oxide
NO_2	Nitrogen dioxide
O_3	Ozone
PAH	Polycyclic Aromatic Hydrocarbons
PM_{10} and $PM_{2.5}$	Particulate matter where particles are less than 10 micrometers in diameter (PM_{10}) and less than 2.5 micrometers in diameter ($PM_{2.5}$)
SO_2	Sulfur dioxide
THE Impact project	THE (Trade, Health, Environment) Impact Project
UFP	Ultrafine particles
VOCs	Volatile organic compounds

ENDNOTES

1 This paper uses the term *citizen* science to broadly reflect this variability.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

Our Challenge

Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT

We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.

ABOUT CLEAN AIR CATALYST

Clean Air Catalyst is a flagship program launched by the USAID and a global partnership of organizations led by WRI and Environmental Defense Fund, Inc. The program focuses on building capacity for locally tailored solutions that curb air pollution, tackle climate change and improve human health.

Clean Air Catalyst

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