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Participatory Environmental Health Research: A Tool to Explore The Socio-exposome in a Major European Industrial Zone

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Abstract

Objectives - We show that participatory research approaches can be a useful tool across disciplines and data collection methods to explore the socio-exposome near one of the largest industrial harbors in Europe. We analyzed resident involvement in each project and their capacity to affect structural changes.

Methods - Longitudinal participatory environmental monitoring studies on lichens, petunias, aquatic systems and groundwater were conducted under the program VOCE (*Volunteers for the Citizens' Observation of the Environment*), which mobilized nearly 100 volunteers to collect and report data. A community-based participatory health survey, Fos EPSEAL was also carried out during the same period. We describe citizens' involvement in each study following Davis and Ramirez-Andreotta's (2021) 'best practice' grid. We also use residents' insights to refine understanding of the socio-exposome.

Results - The region is significantly impacted by industrial pollution and fenceline communities are disproportionately exposed. The community-based participatory health survey documented negative health outcomes among the residents, including a higher prevalence of chronic symptoms and diabetes (e.g., 11.9%) in the Fos-Berre Lagoon region than in other communities. This methodology shows the benefits of the co-production of knowledge in environmental health: not only does it enable epistemological transformations favorable to the vulnerable population, but it also triggered public action (i.e., media and public authorities' attention leading to official expertise reports, filing of collective complaints before the courts).

Conclusion - This body of multiple participatory research studies over time is a useful approach to better understand the socio-exposome and health issues in an industrial zone.

Keywords :

Community-Based Participatory Research - Environmental Justice - Exposome - Industrial Pollution - Participatory science – Socio-Exposome.

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1. Introduction

A growing number of environmental health researchers are conducting collaborative research with communities facing environmental injustices (Davis and Ramírez-Andreotta 2021). This includes community-based participatory research (CBPR) and citizen science (CS). The process of CBPR emphasizes community involvement in determining which issues are addressed through the research, the design and process of research, and action to effect change (Israel et al. 1998; Wallerstein et al. 2017). CS is scientific research conducted with non-professional volunteers, who may contribute to data collection, data analysis, or generation of theory or hypothesis. CS is commonly used in ecological research (Bonney et al. 2014; O'Fallon and Finn 2015; Ramirez-Andreotta et al. 2015). Although the degree of resident participation might vary, community-engaged research involves community oversight and resident perspectives throughout the research study, including the development of the study questions, the collection/interpretation of data, and the communication and dissemination of results. This orientation to research can strengthen research quality and benefit the community involved (Balazs and Morello-Frosch 2013; Farquhar and Wing 2003; Cargo and Mercer 2008; O'Fallon and Dearry 2002; Cohen et al. 2016). It can improve local understanding of exposure to industrial pollutants and associated health risks, leading to concrete policy changes (Castleden et al. 2017) and/or protective measures (Grineski 2006). Moreover, strongly participatory science is a way to address "undone science", which is actively produced through selective attention or chronic inattention to the public's questions about health and the environment (Hess 2016; Frickel 2014). Providing residents with relevant data to support their illness/exposures claims serves to enact a form of knowledge justice (Allen 2018). This can be especially relevant in environmental justice (EJ) communities, in which residents bear a disproportionate burden of exposure to environmental pollutants (Brown and Mikkelsen 1997; B. Allen 2003; McCormick 2009; Liévanos, London, and Sze 2011; J. Harrison L. 2011).

Developed at the end of the 19^{th} century, the industrial port zone of Fos-Berre Lagoon (Figure 1) became the largest industrial harbor in France, and the second largest in Europe, right after a boost of development in the mid 1960s (Garnier 2001; Daumalin and Gramaglia 2020). It was created as an autonomous district so that industrial siting and expansion decisions could be made by the state in consultation with industry without substantive input from the local residents (Allen 2018). The lack of power by the local citizens to have input into decisions on industrial growth or facility siting is the basic parameter of an Environmental Justice (EJ) community. Additionally, some towns in the zone, such as one of the study towns of Port-Saint-Louis-du-Rhone, have high rates of poverty (20%); high rates of unemployment (17%), and high rates of public housing occupancy (43%) indicative of a socially vulnerable population (Allen et al. 2016). The region is now characterized by numerous sources of atmospheric emissions (NOx, SOx, VOCs, organochlorine pollutants, trace metals, PAHs etc.) due to the concentration of large-scale industrial activities (e.g. petrochemical, steel industry, organic chemistry, transport or solid waste incinerator) (Sylvestre et al. 2017). Multiple health and environmental concerns have emerged in the last 40 years. New concerns arose in the 2000s after the addition of new gas terminals and the construction of the solid waste incinerator to service nearby Marseille. Under the pressure of intense public outcry (Osadtchy 2015), local stakeholders commissioned an environmental assessment of the territory, before supporting the creation, in 2010, of an independent research center devoted entirely to examining the local environment: the *Institut Écocitoyen pour la Connaissance des Pollutions* (Ecocitizen Institute for Pollution Research). Its main mission was to assess industrial pollution in all environmental areas (air, land, water, flora and fauna) and its consequences for local residents, towards the goal of characterizing the human exposome in this particular industrial context, especially since regulatory monitoring proved to be inadequate in documenting their cumulative effects.

The exposome, originally coined by Chris Wild (2005; 2012), has become an important research paradigm aiming at understanding the totality of a person's exposures within their life – and relevant health-related outcomes. In the population, especially in an industrial context, the range of exposures is particularly difficult to capture and link with the occurrence of chronic diseases (David et al. 2021). Different holistic methods have been developed to meet the challenge, which often rely on new analytical equipment such as high resolution mass spectrometry or bioinformatics. Since exposomics is the comprehensive analysis of exposure to all environmental components, researchers have been encouraged to make effort to engage impacted communities (e.g., migrants, low socioeconomic position groups with high environmental exposures, pregnant women) in participatory exposome research (Smith, de la Rosa, and Daniels 2015). Indeed, in addition to the high-tech advances to produce large volumes of data (exposomics), other approaches inspired by the human and social sciences have also emerged, where insights from environmental justice could extend the exposome concept. The idea is not only to look at the social and economic determinants of the exposome explaining the vulnerabilities of different categories of populations, including the most marginal, but to also deeply involve the local residents being studied. For example, Senier et al. (2017) proposed the concept of the socio-exposome, since empirical data have shown the limits of environmental health studies disconnected from field experiences (Brown 2007; Corburn 2007) or community members' lived experiences. The socio-exposome approach could help assess exposure at multiple levels (e.g., individual, local, global) with collaboratively-generated insider insights, thereby broadening the collective of those empowered to participate in exposome research.

Following these considerations and objectives, we designed participatory studies. First, residents were invited to assist the researchers in identifying environmental issues, design protocols and collect data on environmental and human impregnation as part of a CS program called VOCE (a French acronym for *Volunteers for the Citizens' observation of the Environment*) led by the IECP. At the same time, the cross-sectional CBPR study, Fos EPSEAL (a French acronym for *Locally Grounded Participative Study on Environmental Health*), was conducted to assess overall community health (e.g., chronic diseases and symptoms) by a team of local and international researchers. Both approaches benefited from early-stage meetings and collaboration with local communities. EPSEAL also included the additional step of co-interpretation of the socio-epidemiological results in collaborative workshops with residents.

In this article, we argue that participatory research can be an important tool to explore the socio-exposome of residents. To our knowledge, this was the first time that the socio-exposome was investigated in a heavily industrial context where there were already strong citizen-science alliances. We first present the findings from these complementary participatory research studies, providing the socio-exposome levels (e.g., individual, local or global) investigated. Then, we consider the level of residents' involvement in progress towards environmental health justice and scientific knowledge across a major industrial European zone. Finally, we offer recommendations to improve the socio-exposome and related environmental exposures in the context of the Fos-Berre Lagoon context and beyond.

2. Methods

2.1. Industrial port zone of Fos-Berre Lagoon

Both the VOCE and Fos EPSEAL studies took place in the region of the Fos-Berre Lagoon, which is home to approximately 400 000 residents (Figure 1). On its west bank sits the industrial core zone of Fos-sur-Mer (about 10,000 hectares). In this section of the Mediterranean coastline (i.e., the Gulf of Fos), there are multiple industrial facilities, such as steel mills, refineries, petrochemical and organic chemistry plants, a liquefied natural gas terminal plus industrial and residential solid waste incinerators. These activities are associated with intense road, maritime, and air traffic.

2.2. Citizen Observatory of the Environment (VOCE)

The IECP relied on the concerns and questions raised by residents about local industrial pollution, changes in biodiversity and climate change to develop studies that would provide them with some answers (IECP n.d.). After multiple environmental controversies sparked local outcry and activism, VOCE was established in 2014 to support ongoing communication and co-learning between scientific activities and local communities. It was quickly acknowledged by the *REPERE* Commission on participatory sciences created by the French Ministry of Ecology, Sustainable Development and Energy (REPERE n.d.), certifying that the methods employed effectively integrated the experiences and knowledge of citizens. The program helped train a network of volunteers dedicated to monitoring the environment (including flagging industry violations, biodiversity loss, etc.) and the dissemination of scientific knowledge in the community.

Through their professional or recreational activities (e.g. hiking, hunting, fishing, etc.) or in their everyday lives, volunteers could participate in studies at varying levels, such as in the preliminary phase (e.g., sharing preliminary observations or historical land use information, taking part in field reconnaissance, selecting sentinel species, defining protocols, etc.) or operational phases (such as observing, sampling, collecting, disseminating). Different compartments of the environment (e.g., air, soil, freshwater, saltwater) were investigated (Figure 1). VOCE provided support to the volunteers. The participants kept in touch with each other and with the scientists through annual reports, meetings and presentations. Today, its network consists of approximately 100 volunteers, including over 50 active members collecting and reporting data at least once a year.

2.2.1. Air biomonitoring

Lichen biodiversity (VOCE) - Lichens have long been used as a bioindicator of air quality (Nimis, Scheidegger, and Wolseley 2002; Dron et al. 2016). In France, lichen diversity has been studied using standardized methods (AFNOR 2014, EN 16413). This approach relies on the identification of the different species and frequent observations over time. For VOCE, data were collected on 4 faces of 10 trees of a given site, using a grid (5 meshes, 10x10 centimeters) at 1 meter high to avoid cross-contamination with the ground. In each mesh and for each face, the presence or absence of a lichen species was recorded on a scale of 0 (absence) to 5 (presence in each mesh). This protocol has been adapted for the monitoring of lichen diversity by non-professionals. Volunteers were free to choose their monitoring station(s), which were generally close to their home, and were trained to identify lichen morphology (e.g., crustose, foliose, fruticose) and four particular species which they had to identify on the 4 faces of 5 deciduous trees using the 5-meshes grid. These species were selected beforehand by the scientists according to their presence in the region and their sensitivity to air pollution (Table 1 – see Dauphin et al. 2018; Gramaglia and Dauphin 2017). The sites investigated represent different exposure profiles, including urban, industrial and rural environments (Figure 1).

Petunia growth **(VOCE)** - Volunteers were also invited to participate in the Volatile Organic Compounds (VOCs) biomonitoring study (full methodology described in Dauphin et al. 2018). Several volunteers showed strong interest in this particular study, selecting 16 monitoring sites (Figure 1). Over 8 weeks (April-June 2014 and 2015), 102 seeds of *Petunia Hybrida* (6 by site) were germinated under similar conditions and randomly planted at each site under identical conditions (e.g., same potting soil and clay balls). The frequency of watering (using bottled water from the same company) was 205 ml per pot every 2 days. All the plants had full sunlight. Volunteers were trained to take weekly measurements of six different aspects: 1) the number of fresh flowers, 2) dead flowers, 3) shoots, 4) dead leaves, 5) measure the length of the plant, and 6) the diameter of flowers. Finally, the dry-weight of each plant was measured at the end of the study period. This experiment was repeated by the volunteers the following year, accompanied by passive VOCs samplers.

2.2.2. Marine monitoring

Marine biodiversity **(VOCE)** - As part of the FOS SEA project, members of a diving club were asked to go snorkeling to monitor the diversity of benthic fauna and flora in the Gulf of Fos at 6 sites (Figure 1). Participants characterized the benthic flora and fauna according to a procedure developed with scientists to meet research objectives as well as field constraints (i.e. restricted/limited access to certain areas of the marine ecosystem). The method involved checking the presence/absence of certain species and conducting abundance measurements in 50x50 square centimeter plots, with a minimum of ten quadrants per plot.

Hydrological parameters **(VOCE)** - Residents pressed for water monitoring in the Gulf of Fos, as they expected that industrial salt discharges could have serious impacts on the local marine ecosystem. Thus, hydrological measurements (i.e., temperature, pH, salinity, levels of oxygen and chlorophyll-a) were taken monthly by volunteers, who were also boat owners, using a CTD (Conductivity Temperature Depth) probe in 5 locations across the Gulf of Fos on the whole water column (Figure 1).

Biomonitoring contaminants in fish - A major concern of the residents was the contamination of fish and seafood in the Gulf of Fos, where much professional and recreational fishing occurs. Volunteering fishers and recreational boaters participated in different parts of this biomonitoring program by choosing the most adapted sentinel species, as well as disseminating the results and analyses (Dron et al. 2019). For example, the European conger (*Conger conger*) was proposed to help identify an organism that is sufficiently sedentary and well distributed in the area, but also carnivorous, to account for the phenomena of bioaccumulation of contaminants – contrary to the species chosen for regulatory monitoring. The European conger was also locally consumed but was not widely for sale, making it a “cosmopolitical” fish on the bioaccumulation survey (Gramaglia and Mélard 2019). Muscles of 24 different species of congers caught in Gulf of Fos (Figure 1) were analyzed for numerous organic compounds (PCBs, PAHs, PCDD/Fs), metal elements (e.g., Arsenic, Mercury), and stable isotopes ($\delta^{15}N$, $\delta^{13}C$) (see Dron et al. 2019 for further details on methodology).

2.2.3. Groundwater surveillance (VOCE)

The Crau groundwater is the largest freshwater reserve of the region. It supplies drinking water to around 270,000 inhabitants, including 100,000 people who reside in 15 surrounding cities. The VOCE program teamed with the SYMCRAU organization (the local *Crau groundwater management body*, in French) in charge of the protection of the freshwater resources of the region (SYMCRAU n.d.). Their shared objective was to measure periodically the groundwater level of residential wells and boreholes, expanding the existing network (SYMCRAU-BRGM) in order to better understand the evolution, fluctuations and circulation of the waters and anticipate drought (Figure 1), as the greater Provence-Alpes-Cote d'Azur region is expected to face major stress on water supply in the next few years.

2.2.4. Soils and plants monitoring (VOCE)

The VOCE program also investigated the transfer of industrial atmospheric and terrestrial contaminants into living organisms (Austruy et al. 2021). In particular, we evaluated the quality of cultivated soils and vegetables in the town of Port-Saint-Louis-du-Rhône in order to assess the potential environmental and health risks associated with gardening (by ingestion of contaminated soils particles or vegetables) in urbanized and industrialized areas. Individual and community gardeners participated at several stages: 1) to select the sampling sites and vegetables species, 2) to develop the cultivation procedure, 3) to maintain the crops and, 4) to monitor and collect vegetables and soil samples. Several metals (As, Cd, Co, Cr, Cu, Ni, Pb, Sb, V, Zn, Al, Fe) and organochlorine compounds (PCDD-Fs and PCBs) were measured in soils and vegetables on 3 sites with contrasted anthropogenic influence (rural and industrial-urban areas) (see Austruy et al. 2021 for further details on methodology).

2.3. Human biomonitoring

Following the VOCE program's environmental monitoring research, a cross-sectional biomonitoring study, INDEX, was conducted by the IECP, in 2016. In the wake of concerns raised by residents, it aimed to investigate whether proximity to the center of the industrial zone (city of Fos-sur-Mer) induced overexposure to industrial contaminants compared to living 40 kilometers further away (the control site was Saint-Martin-de-Crau) (Figure 1). The study aimed to document some of the determinants of this exposure, such as individual physiological factors, diet, type of housing, leisure activities and history of smoking. A questionnaire was administered to a random sample of 138 persons (n=80 in the exposed area and n=58 in the reference one). Blood serum and urine samples were collected to measure a large range of chemicals (trace metals, PCBs, PCDD/Fs, benzene, and PAHs) (see Jeanjean, Goix, et al. 2021; and Jeanjean et al. 2022 for further details on methodology). Industrial workers were excluded from this cohort.

2.4. Community-based participatory health survey (Fos EPSEAL)

The cross-sectional health participatory survey Fos EPSEAL investigated the health of residents having the same exposure (Fos-sur-Mer/Port-Saint-Louis, illustrating the core industrial zone) and a reference area (Saint-Martin-de-Crau) (Figure 1) (Allen et al. 2016; Cohen et al. 2018; Jeanjean, Lees, et al. 2021). Residents were randomly selected for in-person surveys. Two of these towns are closer to industrial sites: Fos-sur-Mer (n=536 participants) and Port-Saint-Louis-Du-Rhône (n=281 participants). People in these towns live near multiple industrial facilities and have been studied in past decades for possible health risks associated with environmental pollution (OREP 1996; Pascal-Bensa et al. 2012; Mantey, Pascal, and Cortaredona 2019). The third town on the periphery, Saint-Martin-de-Crau (n=439 participants), was the same one used in the INDEX biomonitoring study; selected for comparison.

A community-based participatory survey was conducted among a population-based random sample of residents of these areas. Data were collected in 2015 in Fos-sur-Mer and Port-Saint-Louis-du-Rhône (further details available in Cohen et al., 2018) and in 2018 in Saint-Martin-de-Crau (further details available in Jeanjean et al., 2021). In the health questionnaire, participants were asked whether a doctor or other health professional had diagnosed them with health issues, including diabetes. We used questions that had been validated in other contexts for assessing health outcomes (Cohen et al. 2018).

Diabetes was a chronic health issue that has been understudied in environmental health research in industrialized areas, but that was identified by the community members as a matter of concern. Participants who reported having been diagnosed with diabetes also reported the type (i.e., Type I or Type II). A substantial proportion (between 12.9% to 14.6%) were uncertain of the type of diabetes they had. Our direct age- and gender-standardized analyses were restricted to just those participants who reported Type I or Type II diabetes. Prevalence estimates were stratified by gender and 10-year age groups and weighted by the reference population in that group (French metropolitan population, Insee, 2017).

2.5. Citizen involvement and (socio)-exposome levels

In order to present the diversity of participation approaches that have been used in the region, we described the degree of residents' involvement of each study following best practices as categorized by Davis and Ramírez-Andreotta (2021) in a critical synthesis review of participatory research for environmental justice. We also discuss existing classifications of the exposome (Wild 2012) and expand it to the socio-exposome classification, with a close attention to environmental exposures; a focus on environmental justice; and a strong commitment to citizen–science alliances (Senier et al. 2017).

3. Results

The following sections provide an overview of the environmental participatory research conducted over the last decade in all areas of the environment and the socio-exposome levels explored (Table 2).

3.1. Air quality biomonitoring

Biomonitoring of air quality was conducted seasonally by volunteers through longitudinal measurements of different aspects of *Petunia hybrida* growth. Flower growth differed according to site exposure. Physiological deformities were linked to proximity to industrial facilities and heavy road traffic, while no impacts were observed among petunias along the seashore (Villarino et al. 2014; Dauphin et al. 2018). Random controls conducted by the scientist showed little differences with the volunteers' measurements (<4 % for all the seven parameters). This study was time-consuming for volunteers, taking about 2 to 3 hours per week, and the results remained difficult to interpret on a scientific basis without atmospheric data at each lichen or petunia site. Therefore, the second study focused on the most consistent measurements, and the frequency of measurements was reduced to keep volunteers at a reasonable level of involvement. Passive samplers were added for the data analysis. Residents were receptive to the findings from volunteer-collected data, which were disseminated through local community-based organizations.

Lichen diversity was monitored based on the emergence or disappearance of lichen species from the selected sites. Volunteers' comparisons between sites directly informed the measurement of total air quality in the selected locations. *Xanthoria Parietina* (most resistant to pollution and nitrophilic species) is the most commonly found species in Fos-sur-Mer and Martigues (industrial/urban area), but was observed to be less abundant at these two sites. The frequency of *Physcia Biziana* (a nitrophilic species) increased in urban and agricultural sites. *Flavoparmelia sp.*, which is relatively sensitive to pollution, was rarely identified in these sites, but was the dominant species in Grans and Le Tholonet (rural sites). Finally, *Ramalina sp* (the most sensitive species to pollution) was only found at the rural/control sites. Interestingly, these results were similar to the scientists' results, validating both the methods and volunteer measurements (Dron et al. 2017). The volunteers continue to be informed of the results through a yearly report. Recently, concerns arose at the sudden loss of diversity in the rural site, leading to follow-up by the scientific team. This method could also be used to monitor environmental impacts from an industrial fire, and further underscores the utility of resident involvement.

3.2. Marine monitoring

The development of a marine biodiversity monitoring program arose after 2-3 years of discussion between volunteers and scientists who wanted to develop a methodology that could be conducted in a reasonable time for divers and would lead to consistent scientific results. The sites were selected to be representative of the different types of marine environments existing in the Gulf of Fos: euryhaline and eurythermal environments; muddy sands; infralittoral pebbles; infralittoral phytophilous algae. The volunteers actively participated in designing the procedure, and changes to the diving frequency and the monitoring of sentinel species are still under consideration. To date, the results indicate that the benthic fauna (out of fish) includes 13 families and 43 species (Figure 2). Some species were encountered at all sites such as *Balanus sp.*, *Mytillus galloprovincialis*, *Anemonia viridis*, *Paracentrotus lividus* or *Patella sp*. The most abundant and diverse families were gastropods and arthropods. Temporal (between October and July) and spatial variations across sites are the result of physico-chemical variations and of site exposure to water currents and waves (results not presented here). These data were used as a reference following an accidental release of ferric chloride from an industrial site near one of our benthic diversity monitoring locations. The scientists were able to rely on the description of the benthic diversity of the area and to follow up on the evolution of the benthic fauna after the accidental release.

The accumulation of monthly water monitoring data over the course of several years allowed for documenting consistent annual trends (e.g., expected seasonal variations in temperature (i.e., warmer in the summer) and chlorophyll-a (which blooms in spring and autumn)). Further longitudinal data could provide even greater detail into these trends (Figure 3). In addition, better knowledge of the longitudinal hydrological variations in the Gulf of Fos could lead to findings on sea acidification and warming in coming years or decades. The conclusions drawn from the study data also shed light on the variations of water characteristics among freshwater entries (Rhône river, Berre Lagoon) and meteorological influences. Even though this study did not respond specifically to the residents' concerns about impacts of salt discharges, reported resident satisfaction was high thanks to greater understanding of their environment from annual reports and presentations. However, the initial concern has not vanished, and an extension of the study to monitor the effects of the salt discharges is currently being discussed.

3.3. Groundwater surveillance

The measurements taken by the volunteers of their own wells and boreholes across the region (Figure 1) strengthened the spatial precision of the existing map of the region, thus providing better scientific knowledge and understanding of the changes to the groundwater level (Figure 4). Therefore, groundwater elevation measurements were updated by the VOCE program. Active participation and monthly reporting allowed the volunteers to measure their own water resources, which is of major concern to them. Overall, this should lead to improved management, with greater shared knowledge between residents, stakeholders and scientists.

3.4. Soil and plants monitoring

In the vegetables and soils, the toxicity was mainly caused by the vanadium, cobalt, cadmium, and lead, as well as As and PCDD/Fs for soils. Results suggested that population exposure to pollutants in soil/plants was mainly caused by vegetable ingestion (Austruy et al. 2021). This work pointed out that the proximity of vegetable crops to highly developed areas has led to long-term exposure of vegetables and soils to air pollutants, leading to bioaccumulation in the food chain and thus posing a risk for human health.

3.5. Human monitoring

Much of the exposure variability was attributed to individual physiological factors, diet, type of housing, leisure activities and history of smoking. However, after adjustment for these confounders, we found that particular behaviors were significantly associated with a higher accumulation of industrial pollutants among residents of the industrial port zone compared to residents living further away, as a result of their interactions with an environment contaminated by industrial activity, including: gardening (PCBs), consumption of home-grown vegetables (Cadmium), personal consumption of poultry products (Vanadium), and consumption of local seafoods (PCBs, PCDDs/Fs), (see further details in Jeanjean, Goix, et al. 2021; Jeanjean et al. 2022).

3.6. Health survey

Baseline demographic details - The sample was 58% women and 42% men, with an average age of 53 (SD: 17.9) years. There were some differences between the participants and the demographics of the towns. Women and people aged 65−79 were over-represented. People without any diploma were underrepresented and people with a high school degree were over-represented. These imbalances were consistent across the three areas and did not affect our comparisons. Moreover, we accounted for gender and age imbalances using direct age- and gender-standardized standardization. The number of people per household and the time spent at the current address were very close to those of the town census. Self-reported smoking among respondents (30.1%; 95% CI: 27.1–33.3%) was slightly lower than the proportion of smokers in the surrounding Southern region (33%) and in France (34%) (more details about the study population are available in (Jeanjean, Lees, et al. 2021). A large number of collaborative workshops, groups and public meetings were also conducted (28 workshops in Fos-sur-Mer and Port-Saint-Louis in 2016, and 19 in all towns in 2019; see Allen et al. (2019) for more details).

Overall health - Study participants who lived in the industrial fenceline zone (i.e., residents of Fos-sur-Mer and Port-Saint-Louis-du-Rhône) had higher rates of nose and throat problems (adults and children), eye irritation, chronic skin problems and headaches (adults) than people who lived further away (residents of Saint-Martin-de-Crau) (Jeanjean, Lees, et al. 2021; Lees et al. 2022). Similarly, diabetes prevalence was elevated in the industrial towns, corroborating the serious concerns raised by local stakeholders in the industrial area on the prevalence of Type 1 diabetes. We also found that for some health issues, there was a higher prevalence across all three towns, when compared to national data. Additionally, the anthropological qualitative research produced from an extended presence in the field corroborates quantified results, revealing a continuous and everyday presence of illness and death for the residents (Lees and Ferrier 2022). The intent of the Fos EPSEAL method was to combine epidemiological (quantitative) and ethnographic (qualitative) approaches to co-produce knowledge with residents (Lees et al. 2022; Lees and Ferrier 2022; Lees 2018). Additionally, social inequality, observed through employment, financial resources and levels of education, seemed to consistently shape health inequality in the industrial fenceline zone (Fos-sur-Mer, Port-St-Louis), whereas these observations are less clear in the town of Saint-Martin-de-Crau (Lees et al. 2022). Our findings on diabetes serve as an instructive example of the value of combining qualitative-quantitative methods and collaborative analysis approaches.

Focus on diabetes - One of the most important local concerns was the elevated prevalence of diabetes. In particular, the standardized self-reported prevalence of all types of diabetes was 11.9% (95% CI: 9.7, 14.0) of respondents in Fos-sur-Mer and Port-Saint-Louis. Of these, 10.9% report being diagnosed with Type I diabetes, 77.7% with Type II, and 11.4% did not know what type of diabetes they had or if it was another type of diabetes (e.g., gestational diabetes) (Figure 5). In Saint-Martin-de-Crau, 7.9% (95%CI :5.6, 10.2) of participants reported diabetes. Among these, 12.2% report having been diagnosed with Type I and 73.2% with Type II and 14.6% were unaware of the type of diabetes. The difference between the standardized prevalence in Fos-sur-Mer and Port-Saint-Louis was higher, but not statistically significant, compared to Saint-Martin-de-Crau. In comparison, the prevalence of diabetes in France is approximately 5.6% (see more details in

Supplementary Materials), which is lower than the prevalence of diabetes in the center of the industrial zone (Fos-sur-Mer and Port-Saint-Louis) (Mandereau Bruno and Fosse-Edorth 2017).

In the focus groups, participants generated hypotheses to explain these findings. They noted that residents could be exposed to endocrine disrupting chemicals via industrial processes and/or pesticides, which could affect the occurrence of diabetes as an endocrine disease. They also wondered if air pollution could contribute to the development of autoimmune diseases (Ritz 2010; Zhao et al. 2019), including Type I diabetes (Lanzinger et al. 2018). Residents were generally interested in better understanding the cocktail effects of the different sources of environmental pollutants that could be related to health outcomes like diabetes.

3.7. Citizen involvement and practices

Both VOCE and Fos EPSEAL methodologies had high levels of residents' involvement in the research process. In all studies, research questions were informed by local experiences, knowledge and concerns. Community involvement was embedded either in the development of protocols and data collection and/or collaborative data analysis, depending on the study. Some of the project partnerships lasted over 8 years, some are still ongoing. Solid and trustful partnerships could be built, especially since some members of the IECP and the Fos EPSEAL team were members of the same communities as residents.

Most VOCE studies were intended to be longitudinal (i.e., groundwater monitoring, lichens diversity, hydrological parameters, marine and rivers biodiversity). They have been community-led since the creation of the IECP in 2010. VOCE is an inclusive program: it ensures that a wide range of actors, including decision-makers and activists, play a leading role. In some cases, they identified the research priorities, waiting for the scientists to make the measurements they requested. In others, depending on their will and skills or training, they were involved in data collection and interpretation. The IECP is now a well-established local non-profit organization that offers recurring opportunities for scientists and residents to collaborate and produce new knowledge on pollution, leading to breakthroughs in understanding and regulation from large data sets on the whole of the Gulf of Fos – when previous data documented some environmental compartments and sites individually. Fos EPSEAL engaged both residents and experts throughout the study, from initial interviews, public meetings, and design of the survey instrument to involving everyone in the analysis and interpretation of the data (Allen et al. 2019; Allen 2020). Multiple public scientific meetings and collaborative workshops on data report-back and trainings were held.

Finally, both VOCE and Fos EPSEAL made a point of translating their results to be comprehensible to the public and catalyze action. They managed to do so by shedding a new light on the problems they tackled. Some studies (i.e., lichens diversity, INDEX and Fos EPSEAL) challenged official knowledge by highlighting the political significance of the environmental and health issues they documented – which had been previously under-monitored.

7.a. 3.8. Exposome and socio-exposome levels explored

This mix of cross-sectional and longitudinal studies with varying citizen involvement explored a subset of the environmental components of the exposome and socio-exposome (Table 2). Each of the main domains of the exposome (Wild 2012) were investigated:

1) **General external** (climate/natural environment) - The groundwater levels and marine hydrological parameters were monitored for climate change-induced impacts.

2) **Specific external** (air pollution, soils, plants, water and sea fauna contaminants) - Outdoor air quality was assessed using the lichens bioindication and petunias growth. Contaminants were measured in soils, plants and fish.

3) **Internal** (intrinsic properties, medical outcomes, background characteristics) - Both cross-sectional human biomonitoring and the participatory health survey investigated a wide variety of internal components. For example, INDEX used a large range of confounders in the statistical models (including physiological, morphological, lifestyle, socioeconomic features, type of housing and leisure activities) to measure internal levels of biomarkers. Fos EPSEAL investigated a large range of medical outcomes (such as cancers, autoimmune and respiratory diseases, symptoms, etc) and collected various other background individual variables (i.e, physiological, socioeconomic, occupational).

We were consistent with the socio-exposome framework because of our close attention to environmental exposures (i.e., the exposome), our focus on environmental justice (capturing the forms of collective action that help communities), and our strong commitment to citizen-science alliances along the process (Senier et al. 2017). This made it possible to diversify the sources of pollution to be studied, as well as the methods - leading to the production of results which can complement and substantiate the findings from other studies and improve overall research rigor. Resident inputs provided a more detailed, meaningful and accurate characterization of the socio-exposome in the Gulf of Fos offering insights for understanding socio-exposomes in other industrial regions. Following the socio-exposome levels classification (Senier et al. 2017), each of the socio-exposome main levels were explored:

1) **Global forces** (climate) - here, by monitoring the groundwater levels and marine hydrological parameters

2) **Local** (physical & political) - the physical environment was investigated through outdoor air quality, which was assessed using the lichens bioindication and petunias growth methods. Contaminants were also measured in soils, plants and fish. Regarding the political environment, public engagement was also studied in the Fos EPSEAL project (Cohen et al. 2018).

3) **Individual** (molecular, body and social & physical) - molecular (contaminants), body (comorbid health conditions) and social environment (educational attainment, age, gender, household level, health behaviors, etc.) were collected either in the INDEX or Fos EPSEAL study, or both.

Regarding both classifications that overlap at some points, the socio-exposome levels ("Local" and "Individual") differ from the exposome domains ("Specific external" and "Internal") by capturing the political and social environments.

4. Discussion

Biomonitoring evidence from these participatory (CBPR and CS) showed that the Fos–Berre Lagoon region was contaminated with industrial pollution (through trace metals, organochlorine and PAHs) in the air, soil, water and vegetation (Table 2), and that fence line communities are contaminated with chemical pollution (Adams et al. 2018). Moreover, EPSEAL underlined deteriorated health indicators in the region, while collaborative workshops demonstrated tangible, positive contributions from the residents in the co-production of locally relevant and sought-after environmental health knowledge (Allen et al. 2019).

Necessity of citizen involvement **-** We brought together findings from several long-term participatory studies (CS and CBPR) in an industrial region. Following common participatory standards (such as project development and community engagement or data translation and policy engagement) (Davis and Ramírez-Andreotta 2021) (Tables 2 and 3), these studies produced a rich specter of knowledge: from the evaluation and surveillance of pollution and its spread to multiple areas of the environment (e.g., atmosphere, soil, sea and groundwater, flora, fauna) and impacts on overall community health. Although the degree of the residents' involvement was not as systematic in the VOCE program as compared to Fos EPSEAL, the VOCE program bore the mark of the volunteers' influence and capacity to reorient priorities and development of research endeavors (i.e. the change of sentinel species for marine water quality). The IECP projects were always inspired by resident concerns and significant efforts were done to share results publicly (public meetings were scheduled at each occasion) (Austruy et al. 2021; Dron et al. 2019; Jeanjean et al. 2021; Goix et al. 2018). In contrast, Fos EPSEAL study organized more than 60 workshops that created space for residents, workers and doctors to discuss scientific results, procedures and recommendations for further action (Allen et al. 2019). These participatory and other community-oriented research studies have shown that the residents need to be represented in all parts of a study. The plurality of approaches in these diverse projects increases the richness of the results, supplements expert approaches and increases the potential for residents' claims and interests to be heard.

New environmental/ecological knowledge **(VOCE)** - The lichen monitoring study (conducted annually since 2015) continues. The *Petunias* studies showed higher volatile organic compounds (VOCs) concentrations at sites closer to industrial facilities and a physiological response of *Petunias* to atmospheric VOCs exposure. This air quality biomonitoring is a complementary approach with existing instrumental approaches. It shows direct impacts of different air quality on living organisms, and provides straightforward results to the volunteers on their exposure based on where they live.

The fauna benthic observations showed a lower diversity in the eastern Gulf of Fos with degraded habitats. Monitoring the water levels of the Crau aquifer added precision to the existing measurements from the local SYMCRAU network. Finally, the long-term follow-up on some environmental measurements (such as dissolved O_2, Cl, salinity, temperature, levels of groundwater, diversity of species) contributed to better knowledge of local trends that may be related to climate change. These data can be used in scientific studies and allow for long-term monitoring of different environments and biota.

Local environmental exposures and health concerns **-** Before conducting a participatory health study, IECP scientists first assessed the human exposure to industrial atmospheric pollutants such as organochlorine pollutants, trace metals, and PAHs (Jeanjean et al. 2021; Jeanjean et al. 2022). The INDEX community-oriented human biomonitoring survey which accounted for relevant confounders (e.g., individual physiological factors, diet, housing characteristics, leisure activities and history of smoking), showed that particular behaviors such as gardening, consumption of home-grown vegetables, and consumption of local seafoods were significantly associated with a higher accumulation of some contaminants (e.g. organochlorine pollutants and heavy metals including cadmium) among residents of the industrial port zone compared to residents living further away (Jeanjean, et al. 2021).

At the same time, Fos EPSEAL showed that the prevalence of numerous illnesses, including diabetes among adults living in all areas of the industrial zone was higher than it was for France (Cohen et al. 2018; Jeanjean, Lees, et al. 2021). Additionally, participants who lived closer to the center of the industrial zone may have had a higher prevalence of diabetes than people on the periphery of the industrial zone. Only a few regions in France have a Type I diabetes registry; these findings suggest that it may also be worth having diabetes registries in industrial zones. Although the relatively small sample size limits the generalizability of our estimates, the elevated prevalence of diabetes in this industrial area was further bolstered by qualitative evidence. First, local primary care physicians had voiced concerns about diabetes among their patients even before the study. Their insights, shared through our community-based participatory process, initially led us to measure diabetes in the Fos EPSEAL study (Allen et al. 2019). Endocrinology specialists at the nearby hospital also agreed that the general practitioners' anecdotal observations could be indicative of a larger trend. While there are many determinants of diabetes (e.g., genes, nutrition, socioeconomics, demographics), the presence of, for example, endocrine disruptors in industrial pollutants and pesticides could also have played a role in the development of diabetes (Butalia et al. 2016). Our results on diabetes, and in particular Type I, raise the question as to whether local exposures could be affecting autoimmune and other diabetogenic reactions.

By triangulating across our quantitative and qualitative data collected through a community-based participatory health study, we increased understanding of, and community trust in, our findings as accurately reflective of illness, including diabetes, in the industrial zone, and the necessity to further investigate illness etiology in this region and other environmentally polluted areas. Indeed, emerging research on links between diabetes and air pollution has increased the body of evidence regarding air pollution's adverse effect on Type 2 (Yang et al. 2020) and pediatric Type I (Elten et al. 2020). Interestingly, a recent local study reported a link between cadmium atmospheric exposure and hospitalization for all types of diabetes (Pérez et al. 2021) and the study INDEX, conducted beforehand by the IECP (Jeanjean et al. 2022), showed that residents of the coastal industrial zone were overexposed to cadmium through consumption of home-grown vegetables. Finally, the regional health observatory (ORS PACA) reported high prevalence of diabetes (all types) in the coastal industrial zone (ORS PACA).

***New knowledge practices/dissemination of scientific expertise and social advancements* following the participatory process -** These environmental and health studies received and still receive important media attention. Researchers have remained in touch with media outlets since the creation of the IECP. The Fos EPSEAL project received substantial media attention (Duarte, Cohen, and Allen 2020) due to its focus on residents' health and because the residents themselves spoke directly with the media using their co-produced science as evidence.

It is difficult to measure definitive outcomes of participatory science. It appears that collaborative research projects, supported by community-based environmental organizations, might have pushed formal channels to pursue actions and led to substantial positive outcomes such as: policy, structural and behavioral changes, increase in self-efficacy among residents, new involvements, assets, priorities and plans for action, and increased awareness (Davis and Ramírez-Andreotta 2021). The regional health authorities requested the French national agency for epidemiological issues (Santé Publique France) to review the EPSEAL study in 2018 to question the validity of its results. The National Agency for Food, Environmental and Occupational Health

Safety (ANSES) also released a briefing regarding the biomonitoring study INDEX. At the same time, the advisory body of the French Ministry of Ecology (CGEDD) gave a report in 2018 (for which the CBPR research team was interviewed) on pollution and health around the Fos - Berre Lagoon, stating that although there have historically been efforts to reduce levels of atmospheric pollution (i.e., PM, ultrafine PM and O_3), there are still substantial health risks (CGEDD 2018). Its experts then publicly recognized that the overall health status of the residents of the industrial port zone was “weakened”.

It can be noted that residents came up with a list of recommendations that they sought to bring to the attention of local and national authorities during the Fos EPSEAL workshops. One of them was about preventive health and social policies in response to the environmental burdens caused by one of the largest industrial harbors in Europe. It has still not been addressed. However, the residents’ request to create a regional cancer registry (Lees et al. 2022), has recently been accepted by the state agencies (PPA 2019). The existing cancer registry, REVELA13, reports incidence of three types of cancers (kidney tumors, bladder tumors, and acute leukemia) (Mantey, Pascal, and Cortaredona 2019); The registry needs to be expanded to track all cases and types of cancers and other environment-related diseases, such as Type I diabetes and other autoimmune diseases, as well as any diseases that residents wish to track.

Meetings to converge various industrial actors involved in the region (e.g., representatives from industry, the state, and the union, scientific experts) have increased in frequency in part due to media coverage and social pressure fueled by the publication of some of the studies mentioned in this article. These meetings are organized by the Department for the Prevention of Industrial Pollution (Secrétariat Permanent pour la Prévention des Pollutions Industrielles, SPPPI – see Daumalin 2020), an organization created 40 years ago to organize steps toward pollution reduction and which now manages a discussion forum called “REPONSES” (translated: “ANSWERS”) launched in 2019 to collect and respond to residents’ concerns.

Residents of Fos-sur-Mer also engaged in several judicial proceedings (La Provence 2019). First, a collective of residents mobilized to present individual complaints to the court (Tribunal de Grande Instance d’Aix-en-Provence), against unnamed industries for “reckless endangerment.” Second, fourteen residents of the industrial zone have taken several industrial facilities to court (ArcelorMittal Méditerranée, Dépôts pétroliers de Fos, Esso refinery and Kem one) for “abnormal disturbances in the neighborhood.” Finally, a civil complaint was also lodged against the state for its failure to exercise its role in protecting the health and safety of the local population.

In 2018, the state fined one of the largest industrial emitters of air pollution in the coastal industrial zone for its VOCs emissions. More recently, in summer 2021, the judicial tribunal sentenced the same emitter for 36 environmental infractions (between 2013 and 2018) regarding air, water, and industrial exhaust treatments. This follows several years of court proceedings that dealt with charges brought by the nonprofit France Nature Environment against the industrial emitters (Daumalin and Gramaglia 2020). These court decisions, although carried out without any real consultation with local groups, appeared in the press and helped publicize the environmental and health problems of Fos - exposing the laxity of the local authorities who, although they had the measurement data available, had not taken any sanctions. They precede more recent collective criminal and civil complaints, bringing together the nonprofit ADPLGF (Association de Défense et de Protection du Littoral du Golfe de Fos) and residents. However, if the first lawsuits were won, because they were based on monitoring and referred to exceeding standards, the outcomes of future lawsuits are more uncertain. On 7 April 2022, the Court of Aix-en-Provence dismissed the plaintiffs' case on the grounds that the neighborhood disturbances they complained about were “acceptable,” with “foreseeable consequences” and presented “no abnormal consequences”

(Reporterre 2022). Further court rulings are expected. In discussions with key residents, it is clear that participatory studies were an important catalyst for their legal battles. However, they were not too optimistic about their chances of ever winning their cases. Instead, they viewed the lawsuits as a way to constantly keep the issue of environmental health in the press and at the forefront of citizens, politicians, and regulators' consciences. The lawsuits, supported by participatory science, served as a loudspeaker for the residents' concerns. In sum, this participatory process led to:

- New knowledge-making practices, dissemination of scientific expertise (generation of locally relevant new environmental knowledge on the basis of an extensive network of new bioindicators – some chosen in consultation with fishers and residents; production of environmental health knowledge based on the experiences and interpretations of local residents; articulation of complementary fields of knowledge on complex environmental health problems; strengthening of expert knowledge with local knowledge) (Allen 2018).

- Social transformations (media and public authorities' attention leading to official expertise reports, increased regulatory surveillance of polluting industry, development of a regional cancer registry, organization of a rarely gathered multi-actor consultation group, and filing of collective complaints before the courts).

Limitations - The main three domains of the exposome (general external, specific external and internal) and levels of the socio-exposome (individual, local and global) were only partially explored and incorporated through single studies, instead of a more holistic inclusion of all domains (Juarez et al. 2014). However, these Fos-Berre Lagoon projects focused on both quantitative and qualitative data to account for the residents' experiences and exposures in one industrial harbor. The researchers were deeply involved with the community, in accordance with the CBPR value of direct contributions to resident-led environmental justice activism. One limitation of our approach is that not all studies were longitudinal (i.e. Fos EPSEAL, INDEX) and were not conducted on the same timeline (from 2010 to 2020). For greater research rigor, the mix of cross-sectional and longitudinal data should ensure that exposures relative to critical windows of development (from pregnancy to senescence) are captured. Since some samples were collected by volunteers without extensive formal research expertise, there could have been data collection errors. However, our use of this standard during the Petunias study (Dauphin et al. 2018) produced very satisfying results. Lichen monitoring stations were also verified occasionally, upon volunteers' request (if they have some kind of doubt) or when very contradictory results were observed. Volunteers' observations were always confirmed by experts. Finally, participants were trained for monitoring to limit potential bias. We believe that volunteer-based sampling provides relatively reliable data and is not too noisy to be informative (Schmeller et al. 2009).

Future Directions - A longitudinal, participatory health follow-up study with the residents is necessary to maintain the community-academic link, regularly update residents on their exposures, and incorporate new resident concerns and priorities. Efforts should be made to get a broader, more cohesive and more exhaustive approach to the socio-exposome levels across the lifespan (with specific windows such as pregnancy, childhood etc.), coupling conventional tools along with innovative technologies and interdisciplinary approaches (Haddad, Andrianou, and Makris 2019; Dennis et al. 2017), following gold standards and methodological quality assessment tools (Zeng et al. 2015). Other specific groups of components should be included in future analyses. For example, regarding the internal/individual level (genetic, metabolic and micro biota profiling, politics, socioeconomic approaches, mental health, etc.), the specific external domain (e.g., infectious agents, noise exposure, or emerging pollutants such as PFAS), or general external domains (e.g., street connectivity, vegetation, blue spaces, psychological and mental stress, health programs and policies and economic investments).

There is a real necessity to substantiate statistical data with the lived experiences of pollution (Brown 2007). This is not only to adapt studies to the questions asked by residents, but also to get a glimpse of realities, sometimes complex ones, that the experts have difficulty grasping with their quantitative instruments and limited community insider knowledge. Beyond trust, regular visits to exposed communities tend to change researchers' practices. It is no longer a question of measuring from a distance, but of understanding a situation from the inside in order to document the socio-exposure at the level of the residents by including considerations that could otherwise go unnoticed, but which degrade their quality of life and therefore health. This is what the EPSEAL investigators were able to do. It is also what the sociological ECOLEX study, which complemented INDEX, has also brought to light in terms of the experiences of nuisances and pollution on social practices, relations and well-being (Gramaglia, Jeanjean and Goix 2022). All studies on the Fos-Berre Lagoon highlighted the degraded livability of industrial zones.

Continuation of long-term partnerships - We posit that this long-term research has positively impacted not only the participants but the overall community as well. As previously described by several authors, benefits included the improvement of research quality (Balazs and Morello-Frosch 2013; Cargo and Mercer 2008; O'Fallon and Dearry 2002) and community understanding of health risks and behaviors (Loh et al. 2002; Sullivan et al. 2018; Thompson, Sugg, and Runkle 2018). We aim to continue to pursue this long-term commitment in order to better observe and understand significant community structural changes (Davis and Ramírez-Andreotta 2021) previously observed by several research teams, such as changes to zoning and economic policies, political power or community mobilizations, the built environment, public services, and environmental policy enforcements (Asada et al. 2018; Frohlich and Abel 2014; Rütten and Gelius 2011; Wilson 2009). Specifically, efforts should be directed toward community capacity building such as continued training of residents in participatory science. The VOCE program provides regular training for volunteers and the Fos EPSEAL project team gave several trainings on CBPR and participatory epidemiology to transmit the methodology to researchers, public health officials and activist-stakeholders in the field. This program had a long-term commitment to the region only ending in 2022 after eight years of engagement. The VOCE program is also engaged in a long-term commitment: researchers are employed indefinitely by public funding. Public meetings are regularly organized, where new results are translated for a large audience, increasing community understanding of health risk and behavior, and more broadly environmental health literacy awareness. Additionally, decision makers have been involved in the debate through the administrative committee (VOCE), collaborative workshops (Allen et al. 2019) and public meetings. A more active collaboration and mutual feedback among all stakeholders could also be encouraged in order to help formalize health and ecological initiatives. Recent studies engaged the most relevant stakeholders in industrially contaminated sites, within a large hydrocarbon industrial hub actively operating in Cyprus (Kleovoulou et al. 2021). The authors evaluated the stakeholders' perceptions of the environmental and public health risks and recommended actions associated with the hydrocarbon activities, and assessed their understanding and interest towards exposome-based technologies. Although extensive community engagement lengthens the research process, it is ultimately beneficial and demonstrates the need for longitudinal research and research funding that allows for continued engagement.

French national interest in participatory processes regarding environmental health has risen in recent years (Laurent et al. 2021). Our local approach is part of this positive emerging trend

(AirCitizen n.d.; Ambassad'Air n.d.; Bottollier-Depois et al. 2019; Jondreville, Lemercier, and Gascuel 2018; Languille et al. 2020; Mihăiţă et al. 2019; Perrey 2016; Rouen respire 2020; Calvez 2018). This research is, to our knowledge, the first microlocal and continuous community-based research structure in France to characterize the multiple pathways of industrial exposure in all the areas of the environment (e.g., air, soil, plants, humans). These projects support an integrated and strongly participatory approach (Allen 2018) to address complex health issues at the human, animal and environmental interfaces, converging toward Ecohealth and Onehealth systems-focused approaches (Harrison et al. 2019).

5. Conclusion

These participatory approaches have investigated different domains of the socio-exposome in all environmental compartments (air, soils, plants, waters and humans) using different methodologies and disciplines, capturing a large-range of exposures and producing a glimpse of the global socio-exposome mapping of the industrial area. This is an important local start for understanding what has happened in a particular industrial context with multiple sources of pollution. It helped residents to better comprehend and predict the manifold components of environmental health. Finally, the findings and resulting epistemological transformations and public actions highlighted the need to develop long-term partnerships with community members, advocating for progressive and precautionary policies. These inclusive and reflexive approaches would be particularly relevant to deploy in other industrial zones: elsewhere in France, but also around the world.

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Data availability statements

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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