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Stakeholder perspectives on environmental health-related testing

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There has been a growing literature on exposome and environmental health-related research, public acceptance, and understanding of ecological health-related testing; however, it has remained underexplored, especially in the context of rapid testing. This study aims to fill this gap by gathering insights into what key stakeholders see as the primary ethical implications, benefits, and possible risks of environment-related tests. 32 interviews were conducted with potential users, medical providers, and ethicists, asking them about their perceptions of environment-related testing, who would benefit most from the research, and if these tests might detract focus from other, directly relevant health-related factors. The study found that the main concerns among these stakeholders include test reliability, the need for tests where the ecological factor being tested has a proven causality for human health, the possibility for individuals or communities to achieve change based on the test results, and the need for tests that foster social justice.

KEYWORDS

exposome, self-testing, environmental tests, health, benefits, risks, social justice

1 Introduction

The influence that environmental pollutants have on physical and mental health has been receiving increasing attention. Nitric oxides, heavy metals, pesticides, plastics, and microplastics, and a plethora of other substances lead to environmental pollution, including pollution of air, water, and soil (1–4). In addition, a broad spectrum of non-pollutant environmental factors, such as sunlight or outside temperature, can further influence human health and well-being throughout their lifespan (5). Based on this, a growing field of research investigates the influence of the entirety of environmental factors on human health.

As a concept, the exposome has been understood as all environmental influences experienced by an individual and the biological responses associated with such external elements (6). Miller and Jones (7) provided the following definition of the exposome: "Exposome: The cumulative measure of environmental influences and associated biological responses throughout the lifespan, including exposures from the environment, diet, behavior, and endogenous processes". When first introduced, the concept was proposed as a needed complement to the genome, which considered a combination of environmental exposures, lifestyle choices, and internal biological factors (8). Under this

definition, the exposome encompasses a wide range of factors, including gut microbiota and metabolism, diet, physical activity, and environmental influences such as air quality and lead contamination in the water[1].

However, it has been notoriously difficult to clearly attribute the relevance of certain factors, be it genetic, societal, or concerning the natural environment, to human health (6, 7). There is an undeniably convoluted nature to studying environmental impacts on human health and the human genome itself. Often, knowledge or awareness is lacking concerning the relevance of lifestyle-related choices, the role of environmental factors, or evidence for the existence of contaminants in buildings, water, soil, or the air. In others, knowledge is lacking that a specific pollutant has adverse health effects. Moreover, socioeconomically disadvantaged areas are disproportionately affected by environmental pollution and other exposures, raising questions of environmental justice. Environmental justice research aims to document and alleviate disproportionate environmental burdens, enhance knowledge about environmental factors and health, and promote ecological justice (1, 3, 9–11).

Several risk management frameworks have been developed, with approaches outlined for risk assessment, management, and communication (12). Knowledge of external and internal chemical exposure is a central precondition for assessing health-related implications and developing effective risk management strategies (13). Environment-related tests that measure external exposure are an essential factor in these approaches.

In various contexts, finding out about the presence of contaminating substances can be seen as a first step towards taking remedial measures. Examples include elevated lead levels in the water, such as in the municipal water system of the city of Flint, Michigan (14), or heightened residential outdoor nitrogen dioxide (NO2) concentrations in some regions of the United States (15).

For our project, we are interested in environment-related tests that individuals can apply in their respective environments, e.g., in their homes and workplaces. Literature examining public discussions and questions around environment- and exposome-related self-testing is sparse. Still, reviews looking at current and potential future technologies of this kind exist and promise to provide public information about different types of pollutants (16). Many experiments of this kind focus on citizen science efforts to monitor air quality or toxic substances in the soil (17–19).

Currently, smartphone applications, wireless devices, and surveillance technology make it easier to collect exposure factor data such as location and activity (16). However, sensors that could also detect air pollutants, noise, and ultraviolet light are likely to rapidly expand access to this kind of monitoring in the near future. Personal sensors and testing that allow for more continuous monitoring of water and soil pollutants are likely to be further developed in the future. Given the growing awareness of the role of environmental factors in human health, the market for environmental tests and related technologies will only grow.

There has been a growing literature on exposome and environment-related research, public acceptance, and understanding of environment-related testing; however, exposome and environment-related testing have remained underexplored, especially in the context of rapid testing. Our research aims to fill this gap by gathering insights into stakeholder views regarding testing for environmental factors.

This study seeks to understand broader views on exposome and environment-related testing, particularly focusing on tests individuals can use in everyday settings, such as at home or the workplace. By examining these perspectives, we aim to better understand the challenges and opportunities associated with the development and potential adoption of environment-related tests by stakeholders.

2 Materials and methods

2.1 Interview questionnaire and data collection

The research discussed in this paper is part of a collaborative project conducted at the Illinois Institute of Technology in collaboration with researchers in the Chicago area from Northwestern University and the University of Chicago, who seek to develop a rapid test for antibiotic resistant bacteria, The ethics subproject involves three ethicists—one postdoctoral scholar who specializes in bioethics, one professor of philosophy and applied ethics, and one librarian who has worked 20 years in the field of applied ethics, and one biomedical graduate student research assistant. As the subgroup of researchers focusing on the ethical aspects of the project, our main goal of this project is to explore the perspectives of various stakeholder groups on the benefits and potential risks of rapid tests, such as the antibiotic-resistant bacteria rapid test being developed specifically for this project and also on exposome- or environment-related tests, more broadly speaking. In this, the focus is on the possible ethical implications of these kinds of tests and their introduction to the market.

The research team conducted a semi-structured interview study to better understand what potential users, s, medical providers, and ethicists see as the primary ethical implications, benefits, and possible risks of rapid environment-related tests in general and rapid antibiotic-resistant bacteria detection tests in particular.

The interviews conducted as part of this study were divided into two distinct sections. The first, which is not the focus of this paper, gathered insights into stakeholders' views on the potential concerns and benefits of a rapid test for antibiotic-resistant

[1]Exposomics, on the other hand, refers to the study of the exposome (6). Differentiate between environmental health research and exposomics, arguing that the value of exposomics is on its potential for discovery-driven research. They argue that the goal of exposomics ought to be the development of research programs designed to "motivate and demarcate an approach to studying the whole complexity of exposures that affects health and disease" (6).

bacteria. A paper discussing the first section of the interview study looking at stakeholder perspectives on the risks and benefits of the rapid test for antibiotic resistant bacteria is forthcoming. The second part, discussed here, centered on the interviewees' views on environment-related testing.

Two slightly different versions of the questionnaire were developed: one for healthcare providers and one for potential users and ethicists (see Supplementary Appendix).

In our interview study, we introduced the concept of exposome to the interviewees by referring to the Wikipedia definition of exposome. The provided definition stated, "The exposome is a concept used to describe environmental exposures that an individual encounters throughout life and how these exposures impact biology and health. It encompasses both external and internal factors, including chemical, physical, biological, and social factors that may influence human health" (https://en.wikipedia.org/wiki/Exposome). Given its less technical terminology, we opted to provide interviewees with this definition, as it is better suited for a broader audience. After discussing this definition with the interviewees, the first three questions focused on environment-related testing, and the final question, which was asked only of medical providers and ethicists with strong backgrounds in medical ethics, specifically addressed the exposome (see Supplementary Appendix I). The questions were framed to gather interviewees' thoughts in general about environment-related self tests, though many interviewees made reference to their own experiences with health and healthcare in answering the questions.

The team received IRB approval after developing a questionnaire for medical providers and potential users/ethicists (see Supplementary Appendix I for questions) and recruitment material. The differences in questionnaires sought to probe differing lived experiences of medical providers, potential users, and ethicists. It reached out via flyers on campus and in the surrounding Bridgeport and Bronzeville communities via Illinois Tech Today (the university's weekly newsletter), social media, and the Ethics Center's international mailing list. We employed a snowball sampling method to ensure that our sample represented a broad spectrum of perspectives. However, one major limitation of our study is that interviewees required access to a computer with an internet connection, as the interviews were conducted via videoconferencing. Individuals who agreed to participate in the interview received a $25 Amazon gift card. The interviews were conducted from October to December 2023 over Zoom and recorded. Then, the final transcription produced by the Zoom software was edited to take out any identifying information and for clarity. Thirty-two interviews were conducted, involving 14 potential users, 11 medical providers, and 7 ethicists.

The demographics of the interview participants can be found it Table 1.

TABLE 1 Interviewee demographics. A table with all the collected demographic information is available in Supplementary Appendix IV.

Characteristics	Number	Percentage
Interviewee category		
Medical Provider	11	34%
Ethicist	7	22%
Potential User	14	44%
Gender		
Male	15	47%
Female	17	53%
Ethnicity		
Caucasian	14	44%
African/African American	7	22%
Asian/South Asian	8	25%
Hispanic	1	3%
Multiple Ethnicities	2	6%
Age		
18–30	10	31%
31–45	11	34%
46–65	8	25%
65+	3	9%
Education Level Achieved		
High School	2	6%
BA	6	19%
Masters	9 (of these, 5 pursuing a PhD/MD	28%
Phd/MD	15	47%
Nationality		
United States of America	13	41%
European (Germany, Estonia, Netherlands, Poland)	9	28%
Africa (Nigerian)	5	16%
South Asia (India, Pakistan)	3	6%
Mexico	1	3%
Asia (South Korean)	1	3%
Do you have a chronic health condition?		
Yes	4	13%
No	28	87%
How many medical visits		
Once a month or more	2	6%
Once every three months	6	19%
Once a year or less	24	75%

2.2 Data analysis and methodology

The anonymized transcripts were loaded into Taguette, an open-source qualitative research tool for coding and analysis (20). Using the grounded theory methodology, the four team members independently coded three transcripts and then discussed and compared the results to develop a shared coding method. Categories developed in this coding system emerged through successive levels of analysis and discussion (See Supplementary Appendix II for the coding system). Following this, two team members coded each interview transcript in parallel and discussed the results. In cases where the two coders initially disagreed, an in depth discussion ensured to reconcile differences, and codes were agreed upon (Supplementary Appendix II).

As the interview consisted of two sections, one focusing on antibacterial-resistant tests and the final section on environmental-related testing, a second round of coding was needed. In this round, all four members of the research team

TABLE 2 Exposome codes answering specific questions.

Code	Total Number of code mentions	Number of Interviews	Ethicists	Medical	Potential Users
Benefits	49	28	7	8	13
Awareness of Environmental Factors	38	26	6	8	12
Beneficiaries-specific population	25	22	6	9	7
No- it will not take away focus from health	23	21	6	6	9
Beneficiaries- Everyone	12	12	3	1	8
Yes it will influence concepts of human health	11	11	2	9	0
Beneficiaries- Public health/Public Policy	8	8	3	2	3
Concerns/Risks	8	7	1	3	3
Limited impact on concepts of human health	4	3	1	0	2
Yes- it may take away focus from health factors	3	3	0	2	1
No- it will not influence concepts of human health	1	1	0	1	

looked at a) answers to the individual exposome- and environment-related questions and b) all quotations from section two that shared a code and analyzed the results independently to find themes (See Table 2 and Supplementary Appendix III). These themes were then discussed as a group.

49 codes were generated for analyzing the entire interview. The second round of coding for exposome and environment-related testing generated 32 codes.

Section 3.1 of this paper will discuss the responses to the four questions about environment-related tests. These questions concern the usefulness of environment-related tests, whether they distract from other factors that are more directly relevant to health, the benefits and beneficiaries of environment-related testing, and whether focusing on the exposome may influence the concepts of health and disease.

Section 3.2 provides an overview of topics coded from the interviews, i.e., a cross-section of the topics found in the interviews.

3 Results

In analyzing the interview results, the research team first examined respondents' answers to the questions asked in the exposome testing section and then looked at interviewee comments overall for themes. Section 3.1 discusses codes explicitly linked to the questions asked (see Table 2 for codes discussed). Section 3.2 examines the themes presented across the four questions (see Table 3 for codes discussed).

3.1 Responses to the questions

3.1.1 Question 1: do you think that tests that serve to identify environmental characteristics are useful at all?

When discussing question one, twenty-nine of the 32 individuals interviewed spoke about the benefits of exposome tests. Most of these individuals went on to elaborate on this answer. Twenty individuals spoke about how these tests would raise "awareness of environmental factors" on human health. For example:

> "I think that especially for air quality, indoor vs. outdoor. […] I can foresee in the future having to make those day-to-day decisions […] do you allow your child to go outside and play because the air quality is okay … You're having to make decisions based not on what the national database says, but more so [about] your immediate neighborhood" (Int. 1-medical).

Fifteen interviewees also spoke about the "impact of the environment on human health" and how exposome tests could help individuals seek treatment or respond to adverse environmental impacts. Several interviewees discussed the importance of understanding the environment's impact on them, but none provided more detailed insights about what they wished to learn more about.

> "So, if these tests come, you put on your faucet to see if your water is actually being filtered so they can have a good interpretation of what's going on. They have better tools to interpret the data that comes their way. It's really smart" (Int. 16-ethicist).

Eight of the twenty-nine individuals who spoke about the test's benefits predicated their answer on the premise that test users could make changes in their situation to mitigate identified harms. Most were medical providers (4) and ethicists (3).

Of the three interviewees who did not explicitly discuss the benefits of these tests, two questioned whether environmental tests would empower individuals to take action to improve their environment (Int. 17-patient and 25-medical). Another interviewee questioned whether there was enough accessible data to conduct useful environmental-related tests (Int. 32-medical).

3.1.2 Question 2: do you think measuring environmental factors could take away focus from other or more directly relevant health-related factors, like blood pressure or heart rate?

Twenty-four individuals interviewed thought measuring environmental factors would not distract from other health-related factors. Twenty specifically mentioned the impact of the environment on human health and the connection between these two factors. Seventeen of these respondents talked about the benefits of using both tests in parallel.

> "I think everything is interlinked, you know, [the] environment will eventually affect everything happening to you. Right? Your blood pressure, your heart rate, your normal biological markers in the body. They're basically influenced by the environment […] They affect each other so measuring environmental factors should be a good thing … " (Int. 29-medical).

Three interviewees thought that measuring environmental factors would distract from health-related factors. Two mentioned that some individuals often focus on external influences on their health rather than making behavioral changes, such as improving their eating habits.

> "It's easier to change the world than to change yourself" (Int. 21-medical).

Five individuals gave mixed responses, either mentioning specific populations that would benefit, such as medical patients (interview 23-patient), or issues relating to an overload of information (Int. 31-medical and 12-ethicist).

> "You know, you could Google literally anything, like there's so much information coming at you. I'm not on social media, but I would imagine […] you just get bombarded with the latest and greatest thing that's, gonna you know, revolutionize health. […] So, I absolutely think there's a lot of potential pitfalls you could go down" (Int. 31-medical).

3.1.3 Question 3: who would benefit most from environment-related tests?

When asked who would benefit most from environment-related tests, most respondents, around 25, discussed how specific populations would see the most benefits, such as individuals living near high-polluting industries or in polluted communities (10), agricultural workers (5), medical patients and individuals who have a high risk of infections or compromised immune systems (4), children (3), manufacturers looking to monitor workplace pollutants (3), athletes (1), healthcare workers (1), educators (1), and immigrants and individuals who travel (1). Interestingly, the ethicist spoke about how the manufacturers of the tests will benefit, as they can sell the tests to generate revenue.

Twelve individuals mentioned that everyone would likely benefit from using exposome tests.

> "Everybody's going to benefit, especially people who don't have the means to go to a laboratory or go to the clinic. […] So those people that can't maybe afford to go to the clinic at the time and you can do the test at home and get the same results. […] So generally, everybody is going to benefit" (Int. 5-patient).

TABLE 3 Exposome codes reflecting broad themes.

Code	Total Number of code mentions highlights	Number of Interviews	Ethicists	Medical	Potential Users
Impact of the environment on human health	63	31	7	12	12
Societal vs. Individual Responsibility	24	17	6	5	6
Can individuals make changes to mitigate harm found by test?	20	14	4	5	5
Global Concerns	13	10	3	5	2
Test Interpretation	12	10	3	1	6
Unnecessary/Irrelevant use of Test	10	8	3	3	2
Useful in medical/hospital settings	12	8	2	6	0
Wellbeing/Desire to live a healthier life	8	7	3	2	2
Combine Exposome tests with other tests	6	6	1	2	3
Correlation vs. Causation	6	6	2	4	0
Agricultural/Farming Concerns	5	5	0	4	1
Anxiety/Stress	6	5	1	2	2
Comparison to Current Lab Practices	6	5	2	2	1
Differences in population/users of test	6	5	2	1	2
Lack of data	6	4	0	3	1
Reliability of test	5	4	0	0	4
Affordability of test	3	3	1	0	2
Convenience	4	3	0	1	2
Social Justice	3	3	1	0	2
Overload of information	2	2	1	1	0

Eight individuals mentioned how public health and public policymakers would benefit from this test. This included testing city water supplies (Int. 23-medical), local governments to help improve local environments (Int. 7-patient), and regulating industrial pollution (Int. 12-ethicist, Int. 32-medical).

Five mentioned using these tests in the agricultural sector, particularly for farmers who raise livestock, where antibiotic-resistant pathogens may occur.

> "I mean, farmers have got to worry about the results of fertilizer and pesticides. So, in a farming community, it would be useful" (Int. 3-ethicist).

Others mentioned specific instances where environmental tests would be beneficial, such as testing for pollution and air quality in their house or workplace.

Three interviewees spoke about social justice, emphasizing the importance of environmental tests to help individuals gain the necessary information about their environment and act on these issues.

> "They just go and dump certain things, in certain areas, mainly the black neighborhoods, here in America. […] I think those people, because if you go to the white neighborhood, […] they won't allow this. But in some black neighborhoods, that imbalance is there because they don't have people to advocate for them, to speak for them. So that makes them like a handicap, you know, in that situation. I think those are the people that will benefit in such a program" (Int. 7-patient).

3.1.4 Question 4: do you think focusing on the exposome may influence the concepts of health and disease?

This question was only asked of the interviewees who identified as ethicists or medical providers. Twelve respondents were asked question four: all ten medical providers interviewed and two ethicists with a strong background in medical ethics.

Eight interviewees thought that focusing on the exposome would influence concepts of health and disease. Seven of these individuals spoke explicitly about the impact of the environment on human health and the intertwining of these two factors, particularly in relation to air quality issues.

> "Yes, it will give a more holistic picture of disease, where things come from. It's not very common now in primary care, just because of timing. But I think, […] if you're providing optimal care, that would be kind of something you'd think about" (Int. 28-medical).

Four interviewees thought that exposome-related testing would have a limited impact on human health and disease concepts. They spoke about the need to be more educated on how the environment affects human health (Int. 10-ethicist), the need to be educated about both the environmental hazard causing health issues and how to use the test (Int. 25-medical), and individuals ignoring behavioral and genetic causes of poor health and blaming all health issues on their environment (Int. 8-medical).

3.2 Themes that appeared in the interviews

Along with analyzing the responses to the four questions asked, the research team also closely examined the comments made by the interviewees. Through individual coding and discussions, they identified the following themes closely related to the four questions. We shall discuss these themes in detail.

3.2.1 Impact of environment on human health

In answers to all four questions, interviewees mentioned the "impact of the environment on human health". The code referenced four specific concerns and benefits related to the relationship between health and the environment.

Interviewees referenced the interconnectedness of health with examples. Some of these examples included the effect of the environment on blood pressure, increased heart rate, and cancer. Additionally, some interviewees mentioned the following environmental factors as influential to human health: radiation in basements and on airplane flights, air quality, air pollution, water quality, chemicals in the water, tropical climate, cold temperatures, noise pollution, pesticides, fertilizer (farming context), sulfur (close to industrial areas), and stress. Other interviewees, however, emphasized the need for further research to confirm or clarify the interconnectedness between health and the environment.

> "I think there needs to be more research, potentially, at least in terms of what, how big an impact things like these, you know, whatever is being measured, it actually plays on health compared to things that we know are important, like you said, like blood pressure, you know, smoking status, those kinds of things, you know, those are things that are well documented and very important for health … " (Int. 1-medical).

A group of interviewees argued that recognizing the interconnectedness between health and the environment could give healthcare professionals a clearer picture of a potential user's's overall health.

> "Those outside factors are just as important, if not more important, than just looking at the numbers that come back from a blood test. Like you would very well expect things to be different for an athlete vs. like a bread maker at a bakery. But you want to take those things into account so that you can interpret these results accurately" (Int. 26-patient).

Lastly, interviewees also stated the need to treat environmental factors and health together, given their interconnectedness.

> "There is some kind of holistic integration that goes on between humans interacting with nature. It is not a one-

> sided thing. […] Humans are interacting with nature. Nature is interacting with humans. Some of the sicknesses, some of the problems we have, we get from the environment. And so, you are concerned with being healthier. You should also be concerned with having a healthier environment. And so, they cannot be separated. It goes together" (Int. 24-ethicist).

3.2.2 Societal vs. individual responsibility

In answering the four interview questions about exposome-related testing, seventeen interviewees discussed the theme of social vs. individual responsibility, with the code appearing 24 times. The theme came up most often in question 1 (Do you think that tests that identify environmental characteristics are useful?) in 11 interviews and in question 3 (Who would benefit most from environment-related tests?) in nine interviews. Of the 17 interviews that mentioned this topic, five were conducted with medical professionals, six with ethicists, and six with potential users.

The interviews focused on who is responsible for achieving change based on exposome-related testing and how change can be achieved. Several interviewees emphasized that individuals often cannot do much with environment-related tests; it's more up to society to effect change. Interviewees believed that, aside from genetic tests, exposome-related tests are not primarily about individual lifestyles, but rather about addressing societal issues.

Interviewees mentioned a broad spectrum of institutions, communities, or entities they considered responsible for societal improvements following exposome-related tests. Hospitals and nursing homes could enhance hygiene standards and improve disinfection practices within the healthcare sector. Health professionals and educators could raise awareness of environmental factors and their influence on health. Alternatively, public health officials, city management, or governments could develop environment-related standards (for example, guidelines for building houses), public policies, and laws based on existing standards to limit pollution, provide resources, and hold accountable those who cause environmental problems. Laws allow being proactive instead of being reactive or not caring.

> "So, it is necessary that such tests are developed to call us to action, to call human activities to action. Maybe in industrial activities, maybe technological activities. So, actions could be more responsible. With such a test available, we will know as much as possible about the nature of human activities in our environment, and we can be more protective. So, it is very necessary". (Int. 24-ethicist).

Some interviewees stressed the responsibility of employers and companies towards their employees. They thought that once evidence exist to support claims of change or lawsuits against employers/companies, reducing pollution from industrial and technological settings, such as steel mills or the chemical and medical industries, would be easier. With environment-related testing available, workers can demonstrate empirical evidence of pollution, compelling employers and companies to implement change and promote social justice.

> "So, I think one major benefit here is that it would allow you to show that, for instance, there's misconduct at your workplace or in an area where there is this big factory [.] Because then you would be able actually to show it by means of this test. Listen, I have something that other people don't have. Everyone here has that, and it's not healthy. So, you need to change it. So, it might help you in a court case". (Int. 13-ethicist)

Several interviewees discussed how responsibility is shared between individuals and institutions. They said that after conducting an environment-related test, people have evidence of a problem and can use it to pressure their governments, employers, and others to bring about change.

3.2.3 Can individuals make changes to mitigate harm found by tests?

One of the significant questions raised by our discussion of ethical issues surrounding the use of exposome-related tests centered on whether individuals can make changes to mitigate harm identified by the test. Fourteen interviewees discussed this issue, with the code appearing 19 times overall. The theme appeared most frequently in questions 1 (nine times) and 3 (six times). Of the fourteen interviews that mentioned this theme, five were medical doctors, five were potential users, and four were ethicists.

Several interviewees distinguished between individuals and a group's ability to make changes based on test results, discussing how cities or workplaces could implement changes based on these tests, unlike individuals who might have less power to effect the necessary changes the test addresses. Based on the test results, stakeholders could collectively claim a reaction from governments or employers or face legal consequences.

> "Well, individual citizens? And you know I would see this more as a public service gain, than you know, corporate gain, for sure. But so, the If these kinds of tests were available, then I think it helps government be in a position to mandate and create helpful environments" (Int. 6-ethicist).

> "I think it would be very interesting for groups in some districts. They could check their surroundings and then in a group, they could claim some reaction of government or city management or something. But for an individual person, it can also be difficult because if I can't move house, I have a little problem. Sometimes it's better not to know…" (Int. 21-medical).

Others stressed that tests like these may help to set or improve standards and legal regulations.

> "Can you identify something that's […] totally identifiable and that's causing a poor outcome and is actionable? If you can find

> that, phenomenal, like lead, you know. If we can change our standards and get that lead out of the paint. Wonderful, that's amazing". (Int. 31-medical).

When discussing what individuals can do, interviewees suggested ways to change one's behavior or make changes in one's home to address environmental problems revealed by exposome testing, such as installing an air purifier to improve air quality, adding something to the water supply, or using activity-tracking watches.

However, several individuals stressed that it is often unclear and relatively challenging for individuals to make changes, especially for those who are socioeconomically disadvantaged. Several interviewees (all of them medical practitioners) stressed adverse mental effects of environmental tests if individuals can't change their lives or behaviors: "sometimes it's better not to know" (Int. 21-medical), "it's hard not to develop a panic or to feel unsafe to give the water to their children" (Int. 23-medical); "It only causes anxiety, and it doesn't benefit the patient or like the user at all" (Int. 25-medical).

3.2.4 Global concerns

This theme was mentioned 13 times in 10 interviews. Five of these were medical professionals, three ethicists, and two potential users. Quotes in this theme centered around drawing comparisons between different countries or regions, often using their home country as an example. In these comments, interviewees emphasized that tests may benefit socioeconomically disadvantaged groups and individuals. They may be particularly useful for people living in regions with high pollution levels, such as those residing in urban areas or near factories. "It's possible that things like air pollution and water quality are either in urban settings or developing countries. And so, I think it certainly could help those populations that notoriously have major health disparities". (Int. 32-medical).

Two interviews explored issues surrounding the adoption and use of these tests and how education levels and the local population's overall awareness of the environmental impact on human health may influence test use and interpretation.

> "And so, it is a rampant situation whereby you have people abusing the environment by all sorts of activities. [People] don't know, but with such a test like this, the awareness can become much more. Alright. So, I think most people who benefit from such tests are uneducated people" (Int. 24-ethicist).

Two interviewees (17 and 7-patients) also drew direct connections between issues of social justice and access and use of these tests in developing countries. (See xv. social justice).

3.2.5 Test interpretation/reliability of test/anxiety-stress/overload of information

This theme was mentioned 12 times in 10 interviews. Six potential users, three ethicists, and one medical provider spoke about test interpretation. The interviewees' main concerns centered on understanding how to use the test correctly and on individuals' inability to interpret or misinterpret test results. Interviewees expressed concern that, in some cases, this misinterpretation might lead to panic or overreaction among some users. Three users emphasized the need for education on environment-related tests to enable individuals to accurately interpret the results. "It's not so clear that many tests will be beneficial to people, especially if they don't really know how to use it properly, or if they don't fully understand the limits of the test". (Int. 12-ethicist).

The reliability of potential exposome-related tests was mentioned five times in five different interviews, with all potential user comments. This theme was closely linked to test interpretation, with users emphasizing the need for tests to be reliable. Two interviewees emphasized the importance of passing such a test, which must meet the reliability standards approved by the government (Int. 7 and 3).

A similar theme, "anxiety/stress", came up six times in five interviews, once by an ethicist and by two medical providers and two potential users. Stress can be caused by receiving test results or being unable to change their environment, such as issues with tap water or air quality. "It can be sort of paralyzing in the sense of oh, my God! There's so much stuff out there, and I don't think I can even really deal with all of it, you know" (Int. 12-ethicist). If not adequately understood, the test result may cause stress and anxiety, even if only a very low level of a dangerous substance was detected, for example, lead (Int. 3-patient). The theme of "overload of information" came up in two interviews (12-ethicist and 31-medical), with both interviewees seeing too much information as potentially misleading to users of exposome tests.

3.2.6 Unnecessary use of test

This theme was mentioned ten times in eight different interviews. Of these, three were medical providers, two were potential users, and three were ethicists. Four of these quotes also addressed issues of correlation vs. causation, and there was a notable similarity in the sentiments expressed by interviewees regarding this topic. Interviewees emphasized that the environmental factors identified do not necessarily have a causal relationship with the disease. They were concerned about the marketing of unnecessary tests to users and that exposome-related tests might lead users to focus more on environmental factors rather than essential health factors that should be addressed. Additionally, they had concerns about what individuals could do to change their situation based on the test results.

In this context, interviewees discussed irrational health concerns, unsubstantiated claims to revolutionize health, and a trend that provides a good selling point for new gadgets or unnecessary gimmicks.

> "The people who are going to benefit the most are the manufacturers who come up with something that they think they can sell and package in a particular way that will, you know, make the money? Yeah, and beyond that,

> it's not so clear that many tests will benefit people, especially if they don't really know how to use it properly or if they don't fully understand the limits of the test". (Int. 12-ethicist).

3.2.7 Useful in medical situations

The topic "useful in medical situations" arose in 8 interviews, with three doctors commenting multiple times. Of the eight, six were medical providers, and two were ethicists. In the context of questions about exposome-related tests, many interviewees mentioned that such a test could be helpful in medical contexts or hospital settings. There was a particular interest in testing patients' rooms for bacteria, as well as other areas where at-risk patients are found, such as dialysis centers and nursing homes (Int. 2-medical). Various interviewees emphasized the importance of environment-related tests for immunocompromised or other at-risk patients, such as those with asthma, diabetes, or lung-related diseases, or younger children and infants.

3.2.8 Wellbeing/desire to live a healthier life

Seven interviews, including three with ethics ethicists, two with medical professionals, and two with potential users, discussed the possibility that the expanded use of exposome-related tests could help individuals improve their well-being or assist in their desire to live healthier lives.

Two themes emerged in this context. On the one hand, interviewees emphasized the importance of caring about the environment, as it significantly impacts health and well-being. Being concerned about the environment is crucial to staying healthy (Int. 24-ethicist; Int. 18-patient). In this context, interviewees mentioned the well-being of workers (Int. 11-ethicist) and people in socioeconomically disadvantaged communities (Int. 15-patient).

The second theme can be described as the popularization of preventative medicine through gadgets and test kits. Here, interviewees discussed what they characterized as an exaggerated desire to live a healthy life, driven by smartwatches (Int. 15-patient) and the internet and social media (Int. 31-medical). These interviewees stressed that environmental tests align with this development and may further facilitate it (Int. 11-ethicist).

3.2.9 Combine exposome-related tests with other tests

Six interviewees commented on this topic: three potential users, two medical providers, and one ethicist. When asked about the potential for exposome-related testing to distract from other, more direct health issues and testing, it was noted that one test should not substitute for the other but rather work in combination. Several interviewees stated that environment-related tests should be combined with more traditional medical tests to be effective, as testing the environment alone without considering the potential users' health is invalid.

3.2.10 Correlation vs. causation

Six different interviewees mentioned the distinction between correlation and causation. Two respondents were ethicists, and four were medical professionals. No potential users discussed this theme. Quotes labeled with this code were split between those discussing the test itself and others addressing issues surrounding exposome research and the numerous interrelated causes of a phenomenon.

Comments on this theme focused on concerns about what exposome-related tests measure, whether test results enhance users' understanding of a given issue or merely provide information that might obscure the underlying causes of a problem. For instance, "There's maybe the risk of correlation and causation like, just because the test shows up with something doesn't mean it's because of something. And I will be maybe a little bit wary of that. Would you approach that? How would you deal with that?" (Int. 13-ethicist). Accordingly, a test may indicate something, but this does not necessarily mean that the identified factor has a causal role in the disease.

When discussing exposome-related tests and research, one medical professional interviewed emphasized that research into the causal role of environmental factors is complicated, as many variables are involved.

> "Yes, but I think it's contingent upon whether that environmental factor is definitively implicated in causing disease or a worse health outcome, which is tough [.] I think that's the real challenge with researching either environment or nutrition. Are there so many different variables that in any good test you control all the variables except for the one you're testing? And I think that's where environment and nutrition are notoriously difficult because you can say, Gosh! Chia seeds, they're going to decrease your risk of cancer, proving that is near impossible because you have to control everything else". (Int. 31-medical).

While many environmental factors have been scientifically proven to play a significant role in human health (such as lead exposure being associated with developmental defects in exposed children), establishing proof of causality is challenging. In other cases, potential users of environment-related tests may assume a causal influence where none has been scientifically proven to exist. While people strive to control as many environmental factors as possible to maintain their health, they may not be aware that these factors are not necessarily the only environment-related factors that play a role in their overall well-being.

3.2.11 Agricultural/farming concerns

Five interviewees commented in the "agricultural/farming concerns" category: four medical providers and one potential user. The correlation between environmental testing and agricultural/farming concerns was brought up in three different contexts. Interviews 3, 25, and 28 mentioned that, given farmers' use of fertilizers and pesticides, an exposome-related test could

prove helpful to the farming community in identifying environmental hazards. Lastly, interview 1 mentioned that the test could also benefit the animals, as the farmers could use it to verify the soil and water quality of the areas they are exposed to, which would also benefit human health.

3.2.12 Comparison to current lab practices

Five interviewees discussed the topic "comparison to current lab practices". Two were ethicists, two were medical providers, and one was a potential user. Interviewees compared the exposome test to home tests, such as COVID-19 tests, other tests that assess environmental hazards, and self-management technology that allows individuals to monitor and manage their health, as well as set health goals (e.g., smartwatches).

3.2.13 Differences in population/users of test

Five interviewees commented on this topic: two potential users, two ethicists, and one medical provider. This code appeared in answers to questions 2 and 3. It was mentioned that when interpreting test results, individual differences must be considered for a large individual variability (Int. 26-patient). In line with the fact that many different factors often contribute to a disease, one interviewee noted that certain environmental factors that lead to a health issue for one person may not affect the health outcome of others (Int. 12-ethicist). Therefore, given that potential users' responses to the environment vary, assessing and testing the potential users' surroundings would be beneficial. Interviewees who mentioned this topic were particularly interested in the positive effects of this test on vulnerable populations. Interviewee 12 argued that children and older adults may particularly benefit from environment-related tests. Interviewees 7 and 12 highlighted the potential benefits of these tests for various populations, with a focus on marginalized groups, individuals living in socioeconomically disadvantaged neighborhoods, and those residing in polluted areas.

3.2.14 Lack of data

Of the four interviewees who spoke about "lack of data", three were medical providers, and one was a potential user. A lack of data emerged in multiple contexts during the interviews: a shortage of information on environmental hazards and their impact on health and a scarcity of reliable or factual information, resulting in misinformation. Interviewees discussed the need for more scientific research on specific environmental factors influencing human health, and the need to develop specialized tests to potentially measure these factors. Moreover, it was noted that environmental hazards and exposome testing are challenging to assess due to the numerous variables that need to be considered.

3.2.15 Social justice

Two potential users and one ethicist raised arguments related to social justice when discussing who would benefit from exposome testing and whose responsibility it would be to enact change based on the results of such tests. Both potential users (Interviewees 7 and 15) mentioned the social injustices experienced by members of lower socioeconomic communities and how they could benefit from having access to exposome-related testing. Interviewee 13, an ethicist, argued that having exposome-related testing available to everyone could provide victims of hazardous workplaces with the necessary evidence to demonstrate environmental hazards. All three interviewees expressed an interest in the positive changes that environmental testing could bring due to its potential to expose dangers that tend to be ignored by individuals and communities.

> "I think of communities where maybe there's been shoddy construction because they're in a lower socioeconomic area, and so, the proper protocols may not have been followed. I mean, this could happen in a nicer neighborhood, too, but more often than not, you know, people will cut corners in areas that are of a lower socioeconomic status. So, I think, you know, the community at large could benefit from that. And if, you know, the community finds that by large most houses have unhealthy high levels of radon, or if it tests for lead paint, you know that this entire neighborhood has a high level of lead paint which could lead to, you know, bad conditions in children. Then the community itself can be active towards a solution, as opposed to just individuals" (Int. 15-patient).

In addition, interviewees discussed the responsibilities associated with the test, including the need for it not to claim too much, for people to understand it, and issues related to correlation vs. causation.

3.2.16 Affordability

Affordability emerged as a theme in the interviews, with one ethicist and two potential users addressing this concern. Two interviewees highlighted the costs of tests, noting that not everyone can afford testing, particularly if it needs to be done regularly (Int. 11-ethicist). Another interviewee (Int. 5-patient) emphasized that these tests would be less expensive than laboratory tests since people can perform them themselves, even at home.

3.2.17 Convenience

This topic arose in three interviews: one with a medical provider and two with potential users. There is a connection between arguments for convenience and arguments for having the necessary information to act. The test is labeled convenient in a way that allows people to possess knowledge about their environment and act on such information (Int. 22-medical, 7-patient). Moreover, it will enable the user to take quick action and be cost-efficient (Int. 15-patient).

4 Discussion

Many categories described in the results section can be grouped into three broader themes (see Table 4) that played a significant role in the interviews. These themes are test quality, social justice, stakeholder protections, and exposome-related self-

TABLE 4 Overview of themes.

Theme	Codes grouped into each theme
Aspects Relating to the Quality of a Test	Test interpretation, Unnecessary/irrelevant use of test (Combine exposome related tests with other tests), Correlation vs. Causation, Comparison to current lab practices, Lack of data, Reliability of test, Convenience, Overload of information
Social Justice and Stakeholder Protection	Societal vs. Individual Responsibility, Can individuals make changes to mitigate harm found by test? Global concerns, Wellbeing/Desire to live a healthier life, Agricultural/Farming Concerns, Differences in population/users of test, Affordability of test, Social Justice
Exposome Awareness and its Relation to Self-Monitoring	Impact of environment on human health, Useful in medical/hospital settings, Wellbeing/desire to live a healthier life, combine exposome-related tests with other tests, Agriculture/farming concerns, Anxiety/Stress, Comparison to current lab practices, Unnecessary/irrelevant use of test, Differences in population/users of test, Combine Overload of information

monitoring. The following sections will discuss these themes in more detail. Subsequently, differences in perspective between stakeholder groups will be addressed.

4.1 Aspects related to the quality of a test

The interview questions and the ensuing discussion about the quality of environment-related tests in this study were hypothetical, as the interviewees were not asked about or discussed specific tests or parameters. Instead, they presented their general thoughts on aspects of the quality of environment-related tests.

While several interviewees emphasized that they were willing to use environment-related tests if they were reliable, others, especially some ethicists, highlighted difficulties related to test quality. Three themes can be distinguished regarding the quality of the test: the reliability of the test itself, i.e., whether the test delivers consistent results over repeated administrations or with different users, the validity of the test, i.e., consistently measures what it is supposed to measure, and the test's usefulness, i.e., whether the information gained from the test is relevant to health.

The interconnectedness between environmental factors and human health was often emphasized, highlighting the need to raise awareness of the role of ecological factors in human well-being and health. Interviewees emphasized that tests would need to be reliable and that users would need to understand how to interpret the test results and what actions to take based on them. While interviewees emphasized the role of environmental factors in human health and the hope that environment-related tests could benefit human health, the question of what exactly is measured by the test and how the measured factors relate to human health proved critical in several interviews. As emphasized by several interviewees, given the numerous environmental and other factors that influence human health, it is challenging to establish the causal impact of a specific environmental factor on health. Several medical professionals and ethicists emphasized the distinction between correlation and causation and the need for further research into the causal role of environmental factors.

Several interviewees considered it an open question whether environment-related tests are helpful. Against this background, concerns were raised that marketing environment-related tests lead to an inadequate focus on environmental factors and foster unnecessary use of environment-related tests. In this context, several interviewees emphasized the need for quality standards to prevent the excessive use of environmental tests whose results are not beneficial but misleading.

Similar points were made in other studies and articles discussing DIY testing kits. Tighe et al., in their analysis of the effectiveness of a home test for lead in soil, paint, or dust, found that in their comparisons of home testing vs. testing done by a lab, proper sample collection by homeowners, especially in collecting paint samples, proved a significant obstacle to the sensitivity, specificity, and accuracy of results (19). However, the authors concluded that DIY testing for lead was a helpful way to prioritize homes that should receive a full Home Lead Assessment, thereby leading to actionable results from test results (p. 6). Home tests for detecting lead in drinking water are mixed, with many binary tests either overestimating lead concentrations or failing to detect particulate lead in drinking water (21).

Additionally, it is crucial to differentiate between tests for infectious diseases that detect viruses, bacteria, and other pathogens, and tests for environmental factors such as lead in the water. While several interviewees rightly emphasized the role of microbiological tests in medical contexts, this does not necessarily hold for the second type.

4.2 Social justice and stakeholder protections

Aspects of social justice were of central relevance for a broad spectrum of interviewees. The topics raised by interviewees are closely connected to those addressed in environmental justice research (9). Several interviewees discussed the role of socioeconomic disparities in determining where people live, the level of environmental pollution in this area, and what they can do about it. The costs of environment-related tests may limit accessibility, meaning that especially socioeconomically disadvantaged groups may not be able to afford them. Yet, as several interviewees stressed, socioeconomically disadvantaged groups could significantly benefit from using these tests. People living near polluting companies or busy roads, in housing situations with a high risk of lead paint and lead-containing water pipes, may be able to detect pollutants with adverse health effects in their environment and request change.

However, as rightly emphasized in the interviews, the possibility of individuals bringing about change to mitigate harm identified by environmental-related tests may be less extensive

than initially thought. Most often, it will not be possible for individuals to move to other areas or to change workplaces or employers. Accordingly, change needs to be approached at a group level; tests allow for community engagement in driving change. When paired with community-engaged research, exposome self-testing could empower individuals to participate in local movements to address environmental exposures (22).

Against this background, several interviewees discussed how environment-related tests could be beneficial if used by communities, policymakers, and regulators to learn about environment-related pollution and build on the test results to develop healthier living and working conditions. Studies on environmental health literacy have found that community engagement and education strategies must be tailored to the specific topic and population and geared to help community members understand risks and prompt action to reduce them (22). In this way, exposome-related self-testing provides evidence-based communication with key stakeholders.

Several interviewees discussed how having results from environment-related tests equates to putting knowledge in the hands of people. Evidence that something about the environment, environmental pollution, or the working conditions is inadequate and needs improvement. Research and case studies have demonstrated that presenting test results can facilitate the enforcement of environmental protection laws and regulations, which is particularly important for low-income and minority communities in their efforts to address inequalities (10, 11). In this context, however, Diaz cautions about potential adverse outcomes from policymaker efforts to combat environmental injustice, including job loss and environmental gentrification (10). Against this background, the author considers reforming environmental enforcement structures and involving communities to increase their political power as the most promising strategies (10). Meaningful involvement of community members requires not only transparency in the regulatory process but also transparency about the existence and extent of environmental harm.

Literature exploring participatory-action and citizen science research projects, which examine community exposure to environmental hazards, helps interpret our interview participants' comments. Projects looking at lead-contaminated drinking water, lead exposure in soil and paint, and radon exposure in homes all point to similar themes of the need for education, providing affordable tests at convenient locations, and the need for report backs with actionable items as key (19, 23, 24).

4.3 Exposome awareness and its relation to self-monitoring

There has been a growing awareness of the role of the environment on health, starting with the realization of the role the environment can play in the occurrence of cancer and other chronic diseases (25) and continuing as the growing effects of climate change impact on human health (26, 27). This awareness was highlighted during our interviews, with 31 interviewees discussing the topic and with most of the interviewed medical providers and ethicists arguing that this growing focus on the exposome will likely shape concepts of health and disease. As awareness of the exposome and its impact on human health grows, laypeople are expected to become increasingly interested in the possibility of environmental self-testing, particularly DIY testing. Several interviewees compared the utility of at-home environment-related tests to current DIY tests on the market, with COVID-19 tests leading the comparisons. The recent COVID-19 pandemic witnessed an exponential increase in the use of at-home tests (28), and this has arguably made the concept of DIY tests for other health-related factors seem plausible (29). This recent trend may explain the relatively positive attitudes among interviewees towards environment-related tests. Interviewees seemed particularly interested in the convenience of DIY tests and the sense of autonomy that comes with being in control of their own testing.

When considering convenience and usefulness, eight interviewees discussed the value of accessing potential users' environmental data in clinical settings, as it could provide healthcare professionals with a more well-rounded understanding of a potential user's health. Int. 12-ethicist referred to the nature/nurture debate, arguing that human health is an interplay of both. Thus, access to medical data on both the exposome and genome could prove useful. Moreover, five different interviewees also brought up the convenience that these types of tests could offer farmers, as environmental-related tests could be developed to self-track harmful substances in the soil and to keep track of antibiotics in the water, which has been a persistent problem in the farming industry (30, 31).

Many of our interviewees communicated positive attitudes towards at-home testing due to the potential this type of self-testing offers individuals. Some of the benefits mentioned were discussed in the previous section, as they concerned social justice. The answers of other interviewees aligned with the recent development of health-related self-tracking, such as tracking the number of steps, amount of exercise, blood pressure, and hours slept. People are increasingly used to collecting and tracking health-related data through wearable devices (32). The rise of these trends can be attributed to claims that self-tracking can lead to increased awareness of one's health and improve physiological outcomes (33). Throughout the interviews, some interviewees expressed enthusiasm about the possibility of tracking environmental exposures to take control of their health. Nevertheless, whether and how environment-related tests could fit into this trend remains to be seen.

On the other hand, some interviewees questioned the relevance of exposome-related testing in health. Interviewees wondered if exposome-related testing was part of a momentary testing trend on par with *health fads*. They expressed concern about potential issues in the reliability of environment-related tests, the difficulties of proving a causal role of certain environmental factors for health, and the often-limited capability of making changes based on test results. While the environment can exacerbate health conditions, many depend on the individual's genetics. Therefore, it will be necessary to carefully choose the

wording when discussing environment-related tests, i.e., to avoid hyping and over-emphasizing their health-related benefits.

Developers and researchers will need to adopt this carefulness beyond marketing efforts to ensure that the benefits of environment-related testing are not being exaggerated. This involves scrutinizing the language used in claims about the environment, environmental research, and policies (34).

4.4 Differences in stakeholder perspectives

In line with growing awareness of the relevance of including stakeholder perspectives in decision-making processes, when planning the interview study, our goal was to bring in the perspectives of different stakeholders (35, 36). By interviewing potential users, medical professionals, and ethicists, we aimed to gather a broad spectrum of responses and highlight the topic from different perspectives. While the interviewees of our study are not stakeholders actively involved in environment-related decision-making or regulatory processes, their responses are valuable in providing a broad spectrum of views and value-related considerations on environment-related DIY testing.

Overall, there was considerable overlap between the topics the interviewees from the different stakeholder groups brought up. Concerns about the test quality, reliability, and usefulness of environment-related tests were widespread, as were critical reflections on the possibilities of bringing about meaningful change based on the test results. Although the interviewees generally raised similar topics and concerns, each stakeholder group also brought a distinct perspective. Taken together, these generated a complex and interwoven network of considerations.

Medical professionals brought their experience and knowledge to the discussion, exploring the potential usefulness of exposome testing in hospital contexts and how understanding the exposome will impact our concepts of health and disease. Medical professionals also questioned whether data gleaned from these tests could be useful, given the complexities of untangling a single environmental factor that impacts health from all the factors that make up the exposome. Issues of correlation and causation were key with this group. Other medical professionals who were more skeptical discussed if test results could prove to be a distraction, as some potential users find it easier to blame outside causes of disease rather than changing diet or exercise. Medical providers were also concerned about information overload if exposome tests become widely available for home use and about individuals being able to implement actual changes based on test results. Specifically, medical ethicists focused on the adverse mental effects of this, as "sometimes, it's best not to know" (Interview 21).

Ethicists raised factors similar to those of medical practitioners, including the holistic integration between human health and the environment. However, they often focused on outside stakeholders beyond test users, focusing on how test manufacturers might unfairly benefit, especially if the tests were inaccurate, overly priced, or detected environmental factors that individual citizens could not change. Ethicists also focused on using tests in various sectors, including farming (to detect issues with fertilizers and pesticides), industry (for workplace safety), and public policy. In addition, they dwelled on the ability to make informed decisions and sometimes incorporated more theoretical reflections. Some ethicists viewed exposome-related tests as a call to action to be more aware and mitigate the impact of human activities on the environment (Interviewee 24). Others focused on the need for education to help potential users use tests properly and interpret both the results and the limitations of potential tests.

Potential users, who comprised 44% of the interviewees, discussed various issues and demonstrated remarkable insight into the ethical implications of using exposome-related tests. Potential users of the tests seemed generally positive about exposome-related testing and saw it as helpful in various situations. They discussed social justice issues, often drawing from their experiences living in polluted environments and struggling with health conditions. Based on experiences using COVID-19 self-tests and similar tests, potential users were enthusiastic about the potential of these tests. Still, they expressed concern about test interpretation and the need for clear directions for using and interpreting test results. Access to environment-related tests was also a concern, including the affordability and convenience of getting the test factored in among potential users. This reflects similar concerns from other studies from users of radon tests, who see cost and accessibility as significant issues (24, 37, 38).

Beyond the interviewee groups we identified, differences in perspective based on physical location and health status became apparent. Potential users of these tests were the most enthusiastic about the ability to self-monitor potential exposures. Individuals with existing medical conditions were specifically interested, often sharing stories of how their lives had been affected by their condition and how monitoring potential triggers could give them more autonomy. This mirrors a study conducted in 2018 looking at public interest in using a smartphone-based formaldehyde exposure detection test, which found that individuals with poorer health were generally more interested in these tests than those with fewer chronic conditions (39). Similarly, in a Canadian interview study looking at motivators for home radon testing, individuals with existing conditions or concerns about an ill family member were motivated to participate in testing (23).

Unlike other studies looking at community perspectives around exposome-related research (40), race seemed to play a small role in the perspectives on testing in our survey, with equal amounts of white and non-white interviewees expressing both enthusiasm and some level of caution about exposome-related testing, and a wide range of interviewees of different races bringing up social justice issues. Differences were more prevalent between national and international interviewees. Interviewees who either currently live or have lived outside the United States—especially in Africa and South Asia, particularly stressed the game-changing nature of exposome-related testing if it could reliably be used to raise awareness and action around cleaning up polluted areas that local communities live in. International interviewees were also

somewhat skeptical about access to these tests due to cost, ease of test interpretation, the need for education about how the environment impacts health, and users' ability to make changes based on test results.

5 Limitations

We have identified three potential limitations of the study. First, the sample size of the interviewees was relatively small and relied on a self-selected group, which could limit the generalizability of the findings. To mitigate the potential impact of the limited sample size, we interviewed diverse stakeholders—potential users, medical professionals, and ethicists —to capture a broad spectrum of responses and different perspectives on the topic.

The second limitation of this study affects the study population. First, to participate in the study, participants needed to have access to a computer with internet connectivity and the videoconferencing software Zoom, as this was the medium used to conduct, record, and automatically transcribe the interviews. Second, in retrospect, the Wikipedia definition given to the interviewees could have been made more accessible by rewording it. A handful of potential users requested clarification about this definition, and every effort was made by the research group members conducting the interview to thoroughly explain the concept; however, this limitation is inherent to the study. Our study also is extremely overrepresentative in terms of education level, with 75% of the participants having a masters or more in education. This is somewhat accounted for by the 56% of the interviewees being either an ethicist with an MA or above or a medical provider with an MD, but the potential user population was still more educated than the average population.

The third limitation concerns the context of the interviewees' answers. As previously mentioned, the interviews were conducted in a broader research project focused on a test for antibiotic-resistant bacteria. Consequently, there may have been some overlap between the two topics. We attempted to avoid this possibility by delineating when the first part of the interviews was over and by beginning the second part with a definition of the exposome and sharing examples. However, it is possible that when interviewees responded to the exposome-related questions, some might have maintained the context of antibiotic-resistant bacteria and focused their response on this type of test. This was further complicated by the fact that the interview questions did not refer to one specific kind of environment-related test but were far more exploratory in nature. Our questions were designed to elicit initial reactions to potential concerns expressed by stakeholders. Future work is needed to address the benefits and risks of specific environmental testing methods, as well as the education that medical professionals and patients need to safely and effectively use these tests.

While efforts were made to mitigate both limitations, they should be taken into account when interpreting the findings of this project.

6 Conclusion

Through this exploratory research, we aimed to uncover stakeholder views on the acceptability and understanding of exposome-related testing among a diverse audience. Based on the interview analysis, a cautious approach to developing and introducing exposome-related tests seems warranted. While several interviewees were enthusiastic about the potential benefits of these tests, others, especially some of the ethicists interviewed, were particularly critical of their usefulness and the possible risks of overstating their effectiveness. Our analysis brought forward four factors or criteria typically shared by interviewees when discussing the acceptability of exposome-related tests. These draw on goals and qualities that test developers should strive to incorporate in future research. Interviewees highlighted and distinguished the following criteria:

1. Tests with high reliability
2. Exposome-related tests where the environmental factor being tested has a proven causality for human health
3. Possibility for individuals or communities to achieve change based on the test results
4. Tests that foster social justice

As researchers and developers move forward with exposome-related tests, we recommend careful consideration of these factors to ensure their ethical development and the highest chances of acceptance by potential users and consumers.

The first and second criteria, which appeared closely in some interviews, indicate the test's reliability and relevance for health. These first two criteria establish a foundational goal for developers, where the proposed test is reliable and should explore only specific environmental factors. This implies an obligation for developers and marketing teams not to create a perceived need for exposome-related tests that do not offer significant benefits or insights into health.

The third factor argued that exposome-related tests seem most valuable when people can make changes based on the test results, whether at the individual, company, community, or government level. This points to a role for policy, governments, and standards in developing and distributing exposome-related tests.

The fourth and last factor was the fostering of social justice, which appeared throughout multiple interviews as a crucial factor for the acceptability of exposome-related tests. In the context of our interviews, social justice emerged in conversations centered on socioeconomic disparities and accessibility. Interviewees argued that tools of this kind should be easily accessible and affordable, as socioeconomic inequality resulting from unequal access must be avoided. There must be transparency regarding the test results, exposing the existence or non-existence of environmental pollutants to avoid social injustice and ensure that the stakeholders can act based on the results.

While there is enthusiasm for developing environmental tests, these criteria should be considered to ensure a successful and equitable integration into health-related practices. By prioritizing the development of needed, reliable tests and ensuring they are accessible and actionable, we can maximize their benefits while minimizing potential harms.

Future research is needed into perceptions around the public acceptability of environmental testing. It would be useful to replicate this test with a larger sample size and a stronger comparison between public perceptions between different countries. In this case, we focused our questions on environmental testing, but future studies looking more specifically at exposome testing would expand knowledge of this area and provide further guidance for the responsible development of these kinds of tests in the near future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Illinois Institute of Technology Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

KL: Software, Resources, Investigation, Validation, Writing – review & editing, Conceptualization, Supervision, Funding acquisition, Formal analysis, Writing – original draft, Data curation, Project administration, Methodology, Visualization. KV: Project administration, Visualization, Data curation, Software, Methodology, Conceptualization, Validation, Funding acquisition, Writing – original draft, Supervision, Resources, Writing – review & editing, Formal analysis, Investigation. EH: Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Validation, Resources, Data curation, Visualization, Supervision, Conceptualization, Methodology, Funding acquisition, Software, Project administration.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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