Designing Public Health Surveillance for Urban Air Quality in LMICs: Community Insights, Technology Acceptance, and System Design for Low-Resource, High Vulnerability Settings

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

This thesis contains three manuscripts that have been submitted for publication. Exceptions to sole authorship:

Chapters 4 and 5: The primary author, Shahan Salim, was responsible for designing the study and data collection. Chantelle Ramsundar assisted with the study design, interview guide, and thematic analysis. Dr. Warren Dodd assisted with study design and the interview guide. Enkhuun Byambadorj, Azjargal Tsogtsaikhan, and Ariundelger Ariunsaikhan reviewed the interview guide and the manuscript to ensure the questions and language was appropriate for the local context. Drs. Zahid A. Butt and Plinio Pelegrini Morita supervised manuscript writing and revisions. All authors contributed to the article and approved the submitted version.

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Abstract

Climate change is tightening exposure windows and widening inequalities in urban air quality, especially across low- and middle-income countries. Many cities lack dense regulatory networks, timely analytics, and trusted communication pathways, which means signals arrive after decisions are due. Grounded in Ulaanbaatar, Mongolia, this thesis begins by asking how people make sense of pollution in their daily lives, what actions are realistically available, and which institutions are expected to respond. These lived accounts specify what usable guidance must deliver in contexts where resources are limited and risks are uneven. Guidance must be fast, intelligible, transparent about uncertainty, and aligned with social roles and constraints that vary.

A second qualitative strand examines technology acceptance of digital monitoring and early warnings. It identifies what confers legitimacy, including credible data provenance, visible accountability, and delivery pathways that match capabilities such as low connectivity, limited time, and competing obligations. Together, these qualitative insights establish system requirements and the conditions under which guidance is likely to be acted upon.

Based on these insights and in partnership with UNICEF Mongolia, the thesis designs, develops, and evaluates a real-time air quality pipeline for Ulaanbaatar. Low-cost sensors feed an automated device to database workflow that stabilizes sparse and noisy inputs. A sequence modeling approach produces continuous predictions with calibrated error suitable for communication and decision support under intermittent power and limited connectivity. Evaluations suggests the system performs reliably under these constraints and can be adopted within existing civic workflows.

The integrated contribution is a pathway from qualitative insights to deployable infrastructure that supports proportional protection. The thesis advances empirical understanding of disproportionate risks in an LMIC city, delivers a validated and operational monitoring and prediction pipeline build from locally derived requirements, and offers policy and design guidance that ties technical accuracy to local relevance and shared accountability so that evidence arrives in time to reduce harm.

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Dedication

قَالُواْ سُبْحَـٰنَكَ لَا عِلْمَ لَنَآ إِلَّا مَا عَلَّمْتَنَآ ۖ إِنَّكَ أَنتَ ٱلْعَلِيمُ ٱلْحَكِيمُ

سورة البقرة

Exalted are You; we have no knowledge except what You have taught us. Indeed, it is You who is the Knowing, the Wise

Surah Al-Baqarah

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List of Acronyms and Abbreviations

Acronym	Expanded form
AI	Artificial Intelligence
AQI	Air Quality Index
ATT	Attitude toward use
BI	Behavioural Intention
CNN	Convolution Neural Network
CO / NO_2 / O_3 / SO_2	Carbon Monoxide / Nitrogen Dioxide / Ozone / Sulfur Dioxide
DALY	Disability-Adjusted Life Year
EPA	(U.S.) Environmental Protection Agency
ER	Emergency Room
ETL	Extract, Transform, Load
EU	European Union
GCN	Graph Convolution Network
GBD	Global Burden of Disease
GIS	Geographic Information Systems
HBM	Health Belief Model
IoT	Internet of Things
JSON	JavaScript Object Notion
KPI	Key Performance Indicator
LMICs	Low- and Middle-Income Countries
LSTM	Long Short-Term Memory

MAE	Mean Absolute Error
MBA	Master of Business Administration
MSE	Mean Squared Error
NDJSON	Newline-Delimited JSON
NGO	Non-Governmental Organization
PEOU	Perceived Ease of Use
PM / $PM_{2.5}$ / PM_{10}	Particulate Matter (≤ 2.5μm / ≤ 10μm)
PMT	Protection Motivation Theory
PU	Perceived Usefulness
R^2	Coefficient of Determination
RMSE	Root Mean Squared Error
RTM-EWS	Real-Time Monitoring-Early Warning System
SD	Standard Deviation
SDGs	Sustainable Development Goals
SEM	Social Ecological Model
TAM	Technology Acceptance Model
TPB	Theory of Planned Behaviour
UTC	Coordinated Universal Time
UTAUT	Unified Theory of Acceptance and Use of Technology
VM	Virtual Machine
WHO	World Health Organizations

List of Mongolia Specific Terms and Context

Term	Definition
Agaar Neg	Civic platform that aggregates and shares air quality information in Mongolia.
Bagakhangai	Outlying district of UB located to the southeast of the city core.
Baganuur	Outlying district of UB known for coal mining to the east of the city core.
Bayangol	Central district of UB.
Bayanzurkh	Eastern district of UB.
Breathe Mongolia	Civil society group focused on clean air advocacy and data transparency.
Chingeltei	Northern district of UB.
ECDC	UNICEF Early Childhood Development Center used as a community site in Bayanzurkh.
Ger	Traditional round dwelling.
Ger area	Peri urban settlements of gers with limited infrastructure and solid fuel heating.
Khan Uul	Southern district of Ulaanbaatar.
Khoroo(s)	Sub district administrative units within UB similar to wards.
MNT	Mongolian togrog, the national currency.
MSAP	National multi sectoral action plan on air pollution and health in Mongolia.
NAMEM	National agency that operated Mongolia's reference air quality monitoring network.
Nalaikh	Outlying district of UB to the southeast.

NCPH	National public health agency under the Ministry of Health responsible for surveillance, prevention programs, and health promotion across Mongolia.
NPRAEP	National programme on reducing air and environment pollution in Mongolia.
People in Need	International non-governmental organization active in Mongolia.
Refined coal briquettes	Manufactured household fuel promoted after 2019 raw coal ban.
Right to Breathe	People in Need project focused on clean air and community engagement.
Songinokhairkhan	Western district of UB.
Sukhbaatar	Central district of UB.
Ulaanbaatar	Capital city of Mongolia, also referred to as UB.
UNICEF Mongolia	United Nations Children's Fund country office and project partner.

Preface

This thesis is submitted at a time when climate change has become the defining public and global health challenge of our existence. Around the world it is debated, denied, and even weaponized as political leverage. Yet while leaders argue, the consequences are felt most clearly in daily life. They are not abstract. They touch the basics of survival: the air people breathe, the food they eat, and the security of their homes. The political struggle is loud, but the health crisis is quiet and relentless.

The lived reality is far from diplomatic tables. If you are poor, climate does not arrive as policy language. It arrives as a child coughing through the night when the air is heavy. It is a parent stretching medicine because the price rose again. It is choosing between fuel and food when the cold comes early. It is a day of wages lost because the road floods. It is skin rashes from standing water and headaches from smoke. It is a stomach that will not settle because the water is not clean. It is heat that pushes a tired heart. It is a clinic line that begins before dawn and still moves slowly because staff are few and supplies are thin. It is a classroom where the air stings and concentration frays. It is a grandmother who stays inside for days because the air outside burns the throat. It is the bus fare to reach care and the meal that must be skipped to pay it. It is quiet sales of small belongings to cover the week after a harvest fails. It is families crowded into one room when the roof leaks and the infections that spread in close quarters. It is a fatigue that does not lift because every season brings a new hazard.

These harms do not fall evenly. Exposure, sensitivity, and capacity to adapt are not shared in equal measure. Infants and older adults face higher risk. Pregnant people face additional risk. Outdoor workers breathe the worst air and feel the highest heat. People in crowded housing or informal

settlements live closer to smoke, flood, and contamination. When power fails, vaccines warm and insulin spoils. When transport is disrupted, care is delayed. What begins as a climate hazard becomes a chain of health problems that reaches from body to household to community.

This thesis is about monitoring and early warnings, and it is about how people experience air pollution in daily life. These pages contain data, methods, and analysis. They measure exposure and describe patterns that can be acted upon. They ask simple but urgent questions: How does air pollution shape the everyday choices people make about work, food, and care? Can warnings reach the people who need them most, not just those who are easiest to reach? Do families trust and act on the information they receive? And how can monitoring and early warnings be designed to reduce, not widen, the inequalities that already exist? The chapters report results with tables and figures, and they are careful about uncertainty. The aim is practical. The work is written for people who plan services, design programs, and make policy with limited means and the need to act.

I ask you to read these pages in that spirit. The numbers are instruments. The models are tools. They are useful only if they help someone breathe easier, drink safely, keep food on the table, reach a clinic on time, and return home to a roof that holds. As you read, remember that behind each line of text and each confidence interval is a life in motion. A parent counting breaths at midnight. A grandparent who cannot manage the stairs today. A neighbor whose chair is no longer filled at the clinic. Keep these people in view while you turn the pages.

The measure of this work is simple. If the evidence here moves decisions from later to sooner, from generic to context specific, and from unequal to fair, then it has done its job.

1. Introduction

1.1. Air Pollution and Human Health: Burden and Mechanisms

Air pollution is one of the most pervasive environmental risk factors to human health. Unlike many other exposures, it is unavoidable: every individual breathes ambient air daily, and the quality of that air profoundly shapes health outcomes. The past two decades have seen a substantial increase in epidemiological evidence demonstrating the adverse health effects of both outdoor (ambient) and indoor (household) air pollution. The Global Burden of Disease (GBD) 2019 study estimated that exposure to outdoor air pollution contributed to 6.67 million deaths (95% UI 5.90-7.49) and 213 million disability-adjusted life years (DALYs) worldwide, while indoor household air pollution accounted for 2.31 million deaths (95% UI 1.63-3.12) and 91.5 million DALYs (95% UI 67.0-119).[1] These burdens place air pollution on par with other leading risk factors, such as tobacco smoking, alcohol use, and high body mass index, underscoring its global significance as a determinant of health.

Epidemiological studies have linked exposure to air pollution with a wide array of acute and chronic diseases. Respiratory illnesses such as asthma and chronic obstructive pulmonary disease (COPD),[2] cardiovascular outcomes including ischemic heart disease and stroke,[3–5] and adverse pregnancy outcomes have all been associated with both short- and long-term exposure.[6,7] Evidence further suggests that exposure during pregnancy can contribute to developmental harms, including low birth weight, preterm birth, and cognitive and behavioral problems in children.[8–11]

The pathogenicity of air pollution lies in its composition. Air pollution is a complex mixture of particulate matter (PM), gases, and other toxic constituents.[12] Fine particulate matter (PM2.5) is of particular concern due to its ability to penetrate deep into the lungs and enter the bloodstream,

triggering systemic inflammation and oxidative stress.[13,14] Other common pollutants include nitrogen dioxide (NO_2), Sulphur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO), each of which has distinct pathways of harm.[15–17] These pollutants act through multiple biological pathways, exacerbating respiratory and cardiovascular diseases and contributing to chronic conditions throughout the life course.

1.2. Cascading Consequences of Air Pollution

Beyond direct harms to human health, air pollution also interacts with climate systems in ways that amplify risks and create destructive feedback loops. Greenhouse gases, including carbon dioxide and methane, contribute to rising global temperatures.[18,19] Meanwhile, short-lived climate pollutants like black carbon and tropospheric ozone both worsen air quality and contribute to global warming.[20] These interactions exacerbate climate extremes, prolong heatwaves, alter rainfall patterns, and disrupt agricultural cycles.[21–23] They also reshape the geography and seasonality of infectious diseases, which are exacerbated by higher temperatures and altered precipitation, thereby expanding the range of vector-borne illnesses such as malaria and dengue.[24] In parallel, climate-induced shocks to agriculture undermine crop yields, raising concerns about food insecurity, malnutrition, and cascading health effects.[25]

These environmental disruptions rarely remain confined to the ecological or health level; they often have significant social consequences. Food insecurity and loss of livelihoods create pressure that forces migration and displacement, particularly in regions where drought, flooding, or declining agricultural productivity erode the viability of rural life.[26] Such displacement can lead to homelessness, increased exposure to violence, and breakdown of community safety nets.[27] Women and children face heightened vulnerabilities in these contexts, including increased risks of gender-based violence in unstable or resource-scarce environments.[28,29] The tertiary consequences

illustrate how the impacts of air pollution reverberate through social, economic, and political systems, linking environmental exposures to cycles of instability and inequity that extend far beyond conventional measures of disease burdens.

1.3. Disproportionate Impacts and Global Inequities

Over recent years, the global distribution of exposure has shifted. While household air pollution has declined due to transitions away from solid fuel use in some regions, ambient air pollution has remained persistently high or increased in rapidly urbanizing and industrializing LMICs. As a result, people in LMICs bear a disproportionate burden, accounting for 91% of the total global deaths associated with air pollution.[30] Future increases in urbanization, particularly in rapidly developing regions, together with an ageing population, are expected to intensify exposure levels and enlarge the populations most vulnerable to air pollution.[31,32]

Air pollution, and subsequently climate change, disproportionately affect vulnerable groups, particularly children in low-income populations, globally. In Canada, low-income communities and communities of colour face disproportionately high exposure to particulate matter and other pollutants.[33] According to the WHO, one-third of the global burden of disease is caused by environmental factors, and children under five years of age bear more than 40% of that burden despite constituting only 10% of the global population.[34] Similarly, 88% of the global disease burden attributable to climate change falls on children, primarily in socially and economically disadvantaged populations.[35]

The consequences of these inequities are profound. Each pollutant can exert multiple and cumulative adverse effects throughout the life course and across generations, with associated economic costs that are staggering. For example, preterm births attributed to PM have been

estimated to cost $4.33 billion in the United States and $1.6 trillion in the WHO European Region.[36,37] In LMICs, such costs are even more devastating, given the already limited healthcare and social protection systems.

1.4. Surveillance as the Missing Link

Despite decades of epidemiological evidence on the harms of air pollution, a critical gap remains in surveillance and early warning. In most contexts, air pollution is monitored through a limited number of government-operated stations, which have limited coverage and delayed reporting. These infrastructures are insufficient for real-time risk communication, leaving segments of populations unaware of acute exposure events and unable to take protective measures. Additionally, while these reference stations provide highly accurate measurements, they are expensive to purchase, install, and maintain, and require regular calibration by trained engineers.[38] As a result, monitoring networks are typically sparse. Many large cities operate only a handful of stations to cover entire metropolitan regions, falling short of international guidelines.[38,39] For instance, the WHO recommends one monitoring station per square kilometre, while the EU Clear Air Directive suggests one per 20,000 inhabitants.[38] Such standards are rarely met in LMICs, where financial and logistical barriers limit the expansion of the network. They result in patchy surveillance that overlooks localized exposure dynamics.

1.5. From High-Cost Monitoring to Ubiquitous, Low-Cost Technologies

The advancements, accessibilities, and cost-effectiveness of ubiquitous and commercially available air quality sensors allow us to collect continuous and real-time data. Compact and relatively inexpensive, these sensors can be deployed at a higher density than traditional monitoring stations, providing more granular spatial and temporal data. Internet connectivity

further enables real-time data collection across multiple locations, allowing sensors to feed directly into models that predict pollution levels, track disparities across neighborhoods, and capture dynamic events.

The combination of commercially available sensors with advancements in machine learning and deep learning models enables us to develop a distributed and decentralized network that reflects the lived realities of exposure. These sensors can be embedded in schools, health clinics, or even individual households, ensuring the vulnerable populations are no longer invisible in surveillance systems. This democratization of monitoring also opens pathways for participatory science, where communities themselves can generate and interpret data to advocate for policy change.

1.6. Challenges in Deploying Technological Solutions in Low-Resource, High-Vulnerability Settings

While low-cost sensors and machine learning techniques offer new opportunities for real-time and decentralized air pollution surveillance, their effectiveness depends on more than technical specifications. Two broad sets of challenges remain unresolved, underscoring the need for further study.

1.6.1. Air pollution as a Context-Specific, Multi-Level Challenge for Surveillance

Air pollution does not manifest as a uniform problem; its drivers, exposures, and consequences vary substantially across social, political, and infrastructural contexts.[40] While global frameworks emphasize household, community, and institutional determinants, the specific configuration of these factors in a given setting determines both how pollution is experienced and how it can be monitored. Understanding this context-specific complexity is therefore essential for designing surveillance systems that are accurate, equitable, and actionable.

At the household level, vulnerability arises not simply from fuel use but from the broader conditions that constrain choices.[41] In low-income urban settlements, households may rely on coal or biomass not out of preference but because cleaner alternatives are unaffordable, inaccessible, or unsupported by infrastructure. In these contexts, exposure to air pollution is inextricably linked to poverty, housing insecurity, and limited access to energy. For monitoring technologies, this means that a "generic" sensor network cannot assume uniform exposure or capacity to act on warnings; instead, surveillance must be designed to capture the lived realities of households whose risks are structurally imposed rather than individually chosen.

At the community level, exposure is shaped by urban inequality, informal settlement patterns, and infrastructure gaps.[42] For example, in contrast to higher-income neighbourhoods, low-income neighbourhoods and informal settlements experience disparities in exposure to proximity to highways, industrial zones, or garbage-burning sites.[43] These differences illustrate that the same pollutants can generate very different risk profiles depending on context. Surveillance systems must therefore move beyond citywide averages to reflect neighbourhood-level dynamics, particularly where risks are most acute yet least measured.

At the institutional and policy level, governance structures, enforcement capacity, and political priorities determine whether surveillance data is generated, trusted, or acted upon. In LMICs, limited budgets and weak institutions often leave large populations without adequate monitoring.[44] At the same time, in high-resource settings, robust monitoring may still fail to protect communities if political resistance to regulation or public distrust undermines action.[45] This demonstrates that barriers to surveillance are not universal but vary according to governance regimes, economic pressures, and histories of public engagement. For monitoring technologies, the implication is

clear: even technically sound systems will fail without alignment to the institutional realities in which they operate.

These dynamics suggest that the development of real-time monitoring and early warning systems must begin with contextual analysis. Surveillance is not simply a technical exercise of placing sensors; it is embedded in the social, political, and infrastructural conditions that shape exposure and response. By foregrounding these context-specific complexities, this thesis argues that effective monitoring technologies must be designed not as a universal solution but as systems tailored to the environments, institutions, and communities they intend to serve.

1.7. Adoption and Sustainability of New Technologies

In low-resource, high-vulnerability settings, adoption cannot be assumed to follow a linear path from development to implementation. While new technologies promise new opportunities for interventions, whether they are adopted and sustained depends heavily on how they are perceived and experienced by users and institutions.

Adoption is also inherently context-specific.[46] In some settings, new systems may be seen as valuable because they provide timely and actionable information. In contrast, in others, the same systems may be dismissed if they are not viewed as useful or relevant to daily challenges. Ease of integration is equally important. Technologies that require significant effort, new skills, or resources are unlikely to be sustained in environments where capacities are already stretched to the limit. Trust could also shape whether people and institutions engage with public health tools. Communities that have experienced inconsistent communication or neglect may be reluctant to rely on tools regardless of technical accuracy, and institutions may hesitate to act on data they do not fully trust.

These dynamics suggest that adoption must be examined before technologies are widely developed or scaled. Without understanding how people will interpret and interact with these tools, there is a risk of creating technically sophisticated tools that remain underutilized or irrelevant. This is particularly critical in low-resource, high-risk environments, where exposure burdens are greatest but where coping strategies are constrained, and digital access is uneven. Institutional pathways for acting on data are fragile.

Foregrounding these context-specific dimensions of adoption ensures that the design of these technologies goes beyond technical performance alone. By aligning system design with perceptions of usefulness, ease of integration, and conditions of trust, surveillance can be built to respond to the realities of the population it aims to protect rather than assuming universal uptake.

These perspectives underscore that public health tools cannot be separated from the contexts in which they operate. On one hand, exposure is shaped by complex and interdependent social, community, and institutional factors that vary across settings. On the other hand, the adoption and sustainability of new technologies depend on whether they are perceived as useful, easy to integrate, and trustworthy by both communities and institutions. As a result, while some public health tools hold significant promise in theory, their effectiveness depends on grounding development in the lived realities of those most affected. Addressing this gap requires research that integrates technical innovation with social and institutional understanding —a challenge that this thesis seeks to address.

2. Situational Analysis of Air Pollution in Ulaanbaatar, Mongolia

Air pollution in Mongolia represents one of the most severe public health challenges globally, with Ulaanbaatar consistently ranked among the most polluted capitals in the world. Its unique combination of rapid urbanization, harsh winters, reliance on coal-based heating, and socioeconomic disparities has produced an extreme case of urban air pollution, with profound implications for the health of its residents. This chapter situates the thesis within this context, outlining the scale and nature of Mongolia's air pollution crisis, its health impacts, the institutional and policy responses to date, and the persistent surveillance gaps that constrain effective action. By grounding the discussion in Mongolia, the chapter highlights why this setting provides an important and urgent case for investigating new approaches to air pollution monitoring.

2.1. Air Pollution Related Health Crisis

Air pollution has emerged as one of the leading drivers of mortality and morbidity in Ulaanbaatar, with impacts felt more acutely during the winter season. Epidemiological studies estimate that approximately 10 percent of all deaths in the city can be attributed to air pollution, including nearly a third of cardiopulmonary deaths and 40 percent of lung cancer cases.[47] Earlier analyses suggested around 600 deaths annually were linked to ambient pollution, while more recent reports place the burden even higher, with thousands of excess deaths recorded during severe winter episodes.[47] Another suggests that air pollution is responsible for 1000-1500 premature deaths per year by aggravating respiratory and cardiovascular conditions.[48] Beyond mortality, the disease burden is evident in elevated rates of pneumonia, bronchitis, asthma, and other respiratory infections during winter pollution peaks.[49,50] Residents of the ger area, already disadvantaged by a lack of clean water, sanitation, and basic infrastructure, are disproportionately exposed to household and

ambient pollution. The layering of multiple vulnerabilities compounds their risks, reinforcing social inequities.

2.2. Reasons for Extreme Air Pollution in Ulaanbaatar

Ulaanbaatar's extreme air pollution is the product of interconnected demographic, environmental, and infrastructural dynamics that have intensified over the past three decades. Unlike many other contexts where air pollution is primarily driven by industrialization, Ulaanbaatar's crisis is rooted in the intersection of rapid rural-to-urban migration, energy poverty, and geographic conditions that amplify exposure.

2.2.1. Rural-to-Urban Migration and Informal Settlements

Following the transition from socialism in the 1990s, Mongolia experienced a sharp increase in internal migration, with rural herding households moving to Ulaanbaatar in search of employment, education, and healthcare opportunities.[51–53] The city's population more than doubled, yet infrastructure expansion lagged far behind. Migrants settled in the ger areas, sprawling peri-urban areas characterized by informal housing, limited infrastructure, and lack of access to district heating systems.[54–57] Today, nearly half of Ulaanbaatar's population resides in these districts, where residents rely on coal-burning stoves for cooking and heating.[58]

2.2.2. Dependence on Raw Coal and Solid Fuels

Ulaanbaatar's long and harsh winters, which last up to six months, drive enormous household demand for heating. In the absence of affordable or accessible alternatives, many households in rural areas rely on traditional stoves to burn raw coal, wood, and even waste products.[59,60] These stoves are inefficient and produce large volumes of fine particulate matter (PM2.5, PM10), black

carbon, and other toxic pollutants.[61] Despite efforts to distribute "improved stoves" and subsidize cleaner fuels, economic barriers and inconsistent supply chains persist, making reliance on alternative fuels a persistent issue.

2.2.3. Geographic and Climatic Amplifiers

Ulaanbaatar's geography exacerbated these dynamics. The city is situated in a valley at a high altitude, surrounded by mountains that restrict air circulation.[48] During winter, a thermal inversion occurs —a meteorological condition in which temperature increases with altitude, creating a layer of cool, dense air trapped beneath a layer of warmer, lighter air.[62] This results in emissions being trapped near the ground, preventing dispersion and concentrating pollutants closer to the surface. As a result, localized emissions accumulate across the entire urban basin. These conditions create some of the highest seasonal pollution levels recorded worldwide. Seasonal peaks in burning result in dramatic spikes in ambient pollution, with PM levels regularly exceeding WHO guidelines by 10 to 20 times or more during the winter months.[63]

2.2.4. Air Pollution Monitoring

Air pollution monitoring in Ulaanbaatar relies on a network of reference-grade monitoring stations operated by the National Agency for Meteorology and Environmental Monitoring (NAMEM) in coordination with municipal authorities. The system has gradually expanded from a few sensors in the early 2000s to 19 today,[†] forming part of a wider national network of around 40 sites.[65]

[†] In 2025, the U.S. State Department discontinued sharing air quality data from more than 80 embassies and consulates globally, citing budgetary constraints. Embassies were instructed to keep monitors running, with plans to explore “secure and reliable” data transmission methods if funding is restored.[64]

These stations record hourly concentrations of major pollutants, including particulate matter ($PM_{2.5}$ and PM_{10}), Sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon Monoxide (CO), and Ozone (O_3). Although not every station measures the full suite of pollutants, all stations record hourly concentrations of at least one of these pollutants.[65] Sites are distributed across different parts of the city, central districts, roadside areas, industrial zones, and ger areas, to capture diverse exposure conditions. Data generated by these stations are evaluated against Mongolia's national air quality standards and feed into public reporting systems, academic research, and policy assessments. Reference-grade stations remain the official and primary source of air quality data for Ulaanbaatar, underpinning evaluations of health risks and interventions.

2.3. Institutional and Policy Response

Mongolia's response to air pollution has involved multiple stakeholders, including government officials, development partners, and civil society organizations. These initiatives reflect recognition of the crisis and experimentation with solutions, but they remain fragmented in scope and sustainability.

2.3.1. Government Initiatives

The Mongolian government has implemented a range of initiatives aimed at reducing energy consumption, improving public health, and enhancing urban planning. The National Programme on Reducing Air and Environment Pollution (NPRAEP) provides an overarching framework intended to integrate environmental policy with coordinated implementation across ministries.[66] In practice, government actions have focused on household-level measures and seasonal subsidies. Examples include the provision of free nighttime electricity to ger households, the distribution of fuel-efficient stoves, air purifiers, and masks, and the ban on raw coal introduced in 2019.[66–68]

Health-oriented policies have expanded pneumococcal vaccination pilots to all newborns in Ulaanbaatar and provide medicine subsidies and allowances for parents during child illness to reduce wintertime hospital crowding.[69] Efforts at the urban planning level, including building "service centers" in ger areas and the suspension of rural-to-urban migration registrations to manage infrastructure pressures.[70,71] These interventions underscore the government's acknowledgment of air pollution as both an energy and a health issue, although many remain short-term, subsidy-based, or subject to limited enforcement.

2.3.2. Development Partner Engagement

Development partners have played a critical role in supplementing government efforts with financing, technical expertise, and advocacy. The Asian Development Bank (ADB) has provided policy-based loans and technical assistance through the Ulaanbaatar Air Quality Improvement Program, strengthening regulatory frameworks and integrating air quality into urban and energy planning.[72] The Japan International Cooperation Agency (JICA) has emphasized technical capacity building, supporting the development of emission inventories, air quality evaluation, and stack gas measurement.[73] UNICEF Mongolia has been particularly influential in reframing air pollution as a child health emergency through evidence generation, community engagement, and targeted interventions. Among these is the Cooking, Heating, and Insulation Package (CHIP) program, which deploys integrated household solutions, such as electric stoves, insulation, and ventilation, for low-income households.[74] By 2024, nearly 2,000 CHIP units had been deployed in Ulaanbaatar and provincial centers, with further expansion underway. Civil society NGOs such as the Czech-based People in Need (PIN) have contributed through the Right to Breathe project (2018-2020), which installed monitoring stations and promoted public transparency of air quality data.[75] These examples demonstrate how external partners have expanded Mongolia's surveillance

capacity, reframed air pollution through a public health lens, and piloted innovative interventions, though often on a donor-dependent basis.

2.3.3. Civil Society and Global Frameworks

Beyond state and donor initiatives, civil society and global frameworks have become increasingly important in shaping Mongolia's air pollution agenda. Grassroots movements, such as Breathe Mongolia and its Agaar Neg platform (https://agaarneg.mn/), have amplified youth voices, enhanced transparency, and created a digital platform for civic engagement. At the policy level, Mongolia has joined international efforts to integrate air quality and climate agendas. Through the Climate and Clean Air Coalition's Short-Lived Climate Pollutant (SLCP) SNAP Initiative, the country has incorporated pollutants such as black carbon and tropospheric ozone into national inventories, aligning air quality management with climate and health priorities. Similarly, Mongolia's Investment Case for Air Pollution Reduction, developed with the support of UNDP and the EU, quantified the economic and health costs of pollution and catalyzed the National Multi-Sectoral Action Plan (MSAP) on Air Pollution and Health, a step in cross-ministerial planning.[76] Global commitments also include a pledge to align national standards with WHO guidance, embed air pollution in non-communicable disease strategies, and enhance data transparency for public accountability.

These initiatives underscore that Mongolia’s air pollution crisis is widely recognized and has prompted responses at multiple levels. The multi-layered landscape reflects both the diversity of actors engaged and the persistence of critical gaps. Despite these efforts, the continuing severity of health impacts, alongside widespread perceptions that progress has been insufficient, indicated that current responses remain fragmented, limited in scale, and not fully aligned with the lived realities of vulnerable populations.

2.4. Conceptual Definitions and Use of Terms

Throughout this thesis, terms such as low- and middle-income country (LMIC), vulnerable, resource-limited, high pollution, high risk, and underserved are used with deliberate analytic intent grounded in public and environmental health frameworks. These terms are not employed as generalized descriptors of populations, but as a shorthand for structural and institutional conditions that shape exposure, capacity for protection, and health system response.

Mongolia's classification within global income categories warrants brief clarification. While the World Bank currently designates Mongolia as an upper-middle-income country (UMIC) based on gross national income per capita, income classification alone does not adequately capture health system and governance capacities that shape environmental risk management.[77,78] In environmental and public health research, countries with similar income classifications may nonetheless face persistent constraints in surveillance coverage, regulatory reach, and the translation of exposure data into timely and effective action.

In this thesis, the term low- and middle-income country is therefore used not as a strict economic label, but as a descriptor of constrained health system capacity. The use of LMIC as an analytic category aligns with common practice in global health research and funding, where it often serves not only as an economic classification but as a proxy for differences in health research capacity and health system performance and governance that are salient for study design and interpretation.[79–81] Accordingly, the emphasis throughout this thesis is placed on structural conditions, institutional constraints, and health system responsiveness, rather than on income classification per se.

Vulnerability is conceptualized as a public health construct that reflects the interaction of exposure, susceptibility, and capacity for mitigation.[82] Rather than being treated as an inherent attribute of individuals or communities, vulnerability is understood as arising from social, economic, infrastructural, and governance conditions that influence who is exposed to air pollution, what protective options are available, and how effectively health and environmental systems respond. This framing aligns with population health approaches that emphasize social determinants of health, environmental context, and system-level drivers of inequity.

The term resource-limited is used to describe limitations in public health systems and environmental governance systems, including gaps in monitoring coverage, delays in data integration, constrained enforcement mechanisms, and limited cross-sectoral response. These conditions may be present in LMICs, UMICs, or marginalized regions within high-income settings.

Reference to high pollution denotes sustained or recurrent population-level exposure to ambient air pollution concentrations that exceed health-based guidelines or locally defined standards, rather than isolated or episodic events. The term high-risk is used to describe the increased likelihood of adverse health outcomes arising from interaction of elevated exposure, limited capacity to reduce or avoid exposure, and delayed or inadequate institutional response. Risk is treated as a dynamic, system-mediated construct rather than a function of exposure alone.

The term underserved is used to describe populations or geographic areas that experience disproportionate exposure or health burden while remaining inadequately represented in monitoring networks, health surveillance systems, or policy responses.[83] In this context, being underserved reflects gaps in environmental health protection and institutional attention that constrain the translation of community agency into effective protective action.

3. Research Aim, Objectives and Questions

Air pollution remains one of the most pervasive environmental threats to human health, with disproportionate effects in low-resource and high-vulnerability settings. Epidemiological evidence demonstrates its association with respiratory and cardiovascular disease, adverse pregnancy outcomes, and developmental harms. Yet, despite this evidence, surveillance systems remain inadequate, with sparse monitoring networks, limited spatial coverage, and insufficient capacity to generate timely or actionable data. This gap prevents public health authorities and communities from protecting themselves during acute exposure events, while also undermining long-term strategies for prevention and adaptation.

The overarching aim of this thesis is to advance the development of real-time monitoring and early warning systems (RTM-EWS) for air pollution that are technically robust, socially responsive, and context-specific, particularly in low-resource, high-vulnerability settings. Achieving this aim requires addressing not only the technical barriers to surveillance but also the social, political, and institutional dynamics that determine whether new technologies can be trusted, adopted, and sustained.

The central research question guides this aim:

How can real-time air pollution monitoring and early warning systems be designed and implemented in a manner that is both technically robust and socially responsive, with a focus on context-specific needs, particularly in low-resource, high-vulnerability settings?

To answer this question, the thesis is structured around three interrelated objectives, each paired with a guiding research question. Together, these objectives build a holistic understanding that spans lived experience, technical innovation, and adoption dynamics.

3.1. Objective 1: Understanding Lived Experiences of Air Pollution

The first objective is to examine how individuals and communities perceive, experience, and respond to air pollution in their daily lives, with a particular focus on disadvantaged and underrepresented populations where health systems are strained and resources are limited. Guided by the Social-Ecological Model, this work considers not only individual-level perceptions of health risks but also the coping strategies people employ and the broader social, structural, and policy contexts that shape these behaviours. In contexts such as Ulaanbaatar, Mongolia, where reliance on coal and biomass fuels is widespread and wintertime pollution reaches extreme levels, it is critical to understand how households navigate exposure, how communities mobilize around risk, and how institutions support or constrain protective action.

Research Question 1: *How do individuals and communities in high-exposure, resource-constrained settings perceive the health risks of air pollution, and what coping strategies do they adopt in response?*

3.2. Objective 2: Investigating the Adoption and Sustainability of Monitoring Technologies

The second objective recognizes that the success of any surveillance system depends not only on its technical capabilities but also on whether it is adopted, trusted, and sustained by both communities and institutions. In low-resource and high-vulnerability contexts, adoption is shaped

by perceptions of usefulness, ease of integration into everyday practices, and trust in both the data produced and the institutions disseminating it. Without this foundation, even the most sophisticated technologies risk being underutilized or dismissed. This objective, therefore, focuses on identifying the behavioural, social, and institutional factors that drive or hinder engagement with RTM-EWS, ensuring that systems are not only built but also adopted and practiced.

Research Question 2: *What social, behavioural, and institutional factors shape the adoption, trust, and sustained use of real-time monitoring and early warning systems in low-resource, high-vulnerability settings?*

3.3. Objective 3: Developing a Real-Time Monitoring and Early Warning System

The third objective addresses the technical limitations of conventional monitoring systems by designing and developing a scalable RTM-EWS. This work develops a system that integrates low-cost IoT sensors, an automated ETL pipeline for data collection and storage, and a Transformer-based deep learning model to predict air quality index (AQI) values in real-time. The aim is to enhance spatiotemporal coverage and predictive accuracy while ensuring that insights are delivered at the speed and resolution needed for actionable decision-making. By bridging the gap between costly regulatory networks and the realities of resource-constrained settings, this objective demonstrates how technical innovation can be harnessed to produce high-resolution surveillance that supports public health interventions.

Research Question 3: *How can low-cost sensors and predictive modelling techniques be leveraged to design a real-time monitoring and early warning system that provides accurate, high-resolution, and context-sensitive air pollution data?*

These three objectives and corresponding research questions operationalize the overarching aim of the thesis. Objective 1 provides the necessary understanding of lived experiences and contextual vulnerabilities. Objective 2 provides a framework for adoption, trust, and sustainability in practice. Objective 3 develops the technical systems necessary to address existing surveillance gaps. While each objective aligns with a distinct strand of research, they are interdependent: social insights inform system design, adoption analysis ensures that these possibilities translate into meaningful public health action, and technical innovation generates new possibilities. Collectively, they advance the development of a real-time and early warning system that are not only technically rigorous but also socially responsive and context-specific, offering a pathway to more equitable and effective air pollution surveillance.

3.4. Consideration and Statement of Positionality

This section outlines the positionality, epistemological orientation, and reflexive commitments that shape the research presented in this thesis. These considerations are foundational to the program of work as a whole, informing the framing of research questions, the design and interpretation of qualitative inquiry, and the technical decisions embedded in the development of surveillance systems. Given the interdisciplinary and partnership-based nature of this research, making these assumptions and commitments explicit is necessary for transparency, accountability, and interpretive clarity.[84–86]

3.4.1. Researcher Positionality and Context

This research is grounded in being from Pakistan, a context where air pollution and climate-related health challenges are embedded in everyday life rather than experienced as exceptional events. In such settings, exposure is rarely a matter of individual choice. It is structured by infrastructure,

affordability, housing conditions, and governance. Decisions about avoiding polluted air are constrained by what systems provide, what households can afford, and what institutions are able or willing to enforce. This context shapes how environmental risk, responsibility, and protection are understood.

That grounding informs the orientation of this thesis. Rather than approaching air pollution surveillance as a problem of optimizing measurement under ideal conditions, this work focuses on what surveillance needs to look like when options are limited and institutional support is uneven. The emphasis is not on designing systems for high-capacity environments, but on understanding what kinds of information are meaningful, actionable, and trustworthy in settings where exposure is persistent, and agency is constrained. This perspective shaped both the research questions and the prioritization of usability, interpretability, and institutional feasibility throughout the work.

I conducted this research as an external researcher affiliated with a Canadian academic institution, working in close partnership with Mongolian organizations, communities, and international development partners. While I share experience with living in a context where air pollution is a persistent public health concern, I do not share the cultural, linguistic, or political realities of living in Ulaanbaatar. This positionality required deliberate attention to power, interpretation, and representation throughout the research process.

3.4.2. Epistemological Orientation

The qualitative components of this thesis are informed by constructivist and pragmatist epistemological orientations. From a constructivist perspective, the research recognizes that perceptions of air pollution, health risk, and responsibility are socially produced and situated within specific historical, cultural, and institutional contexts. Participant accounts are treated as

meaningful interpretations that shape behaviour, trust, and expectations of institutions, rather than as objective measures of exposure.[87,88]

From a pragmatic perspective, the value of knowledge lies in its capacity to inform and shape action within specific contexts.[89,90] This orientation prioritizes insights that clarify how information is interpreted, negotiated, or disregarded in practice. Knowledge is not evaluated solely on explanatory power, but on how interpretations enable or constrain decision-making, protection, and feasibility within real-world systems, and how their consequences inform ongoing inquiry.

Together, these epistemological orientations shaped the analytic focus of this thesis. They emphasized the lived experience, interpretability, and the practical consequences of surveillance design, while also guiding decisions about which claims could be made and which forms of generalization were appropriate.

3.4.3. Reflexivity and Knowledge Production

Reflexivity was a guiding principle throughout the research process. Given my position as an external researcher and the interdisciplinary nature of this work, ongoing attention was paid to how assumptions, training, and institutional affiliation shaped the production and interpretation of knowledge. Interview guides were refined iteratively through early field engagement and feedback from local partners.

Analytic decisions were revisited as understanding of the study context deepened, particularly in moments where technical interpretations risked obscuring social or institutional realities described by participants. Accordingly, translation and interpretation were treated as analytic moments rather than neutral procedural steps, with attention to how meaning, emphasis, and cultural framing

influenced the data. Throughout analysis and writing, care was taken to avoid overgeneralization, deficit framing, or the imposition of external assumptions onto participants' experiences.

Reflexivity in this thesis does not assume that power asymmetries can be eliminated through awareness alone. Rather, it is treated as an ongoing practice aimed at making interpretive choices visible and open to scrutiny.[91]

3.4.4. Partnership, Power, and Interpretation

Partnership played a central role in shaping this research. Access to participants, data, and institutional contexts was made possible through collaboration with local organizations, translators, and development partners. These partnerships extended beyond logistics. They influenced the framing of research questions, the interpretation of findings, and assessments of what constituted plausible, relevant, and useful conclusions.

Local collaborators provided critical contextual knowledge that shaped analytic decisions and helped situate participant accounts within broader social, institutional, and policy landscapes. Their involvement functioned as an epistemic contribution, grounding the research in lived and institutional realities that could not be accessed through technical expertise alone. Thus, attention to partnership also required ongoing negotiation of power, authorship, and representation, particularly in balancing academic objectives with community priorities and institutional constraints.[92]

3.4.5. Implications for Study Design and Interpretation

The positionality and epistemological orientation outlined in this chapter shaped how the research engaged with existing monitoring infrastructure and interpreted data generated within it. Rather than seeking to replicate or replace regulatory monitoring systems, the objective was to explore

what forms of surveillance might support protective action in contexts where formal systems are sparse, delayed, or inaccessible.

This stance required balancing technical rigour with contextual realism and making tradeoffs explicit rather than treating them as limitations to be concealed. In turn, it also shaped how findings are interpreted, emphasizing analytic generalization over claims of representativeness and situating technical performance within institutional and social constraints.

Finally, this thesis recognizes that choices about what is measured, how information is communicated, and whose knowledge is prioritized carry ethical and political implications. By foregrounding positionality, epistemology, reflexivity, and partnership in a dedicated chapter, this work aims to make such choices visible and accountable, and to situate its contributions within the realities of the people and institutions it seeks to serve.

Bridging Foreword to Manuscript 1

The first manuscript marks the entry point into the broader program of work that underpins this thesis. It is positioned here because everything that follows is grounded in the lived realities, constraints, and forms of expertise shared by residents of Ulaanbaatar. Rather than treating air pollution as an abstract exposure, this study traces how people come to understand it as a threat, weigh immediate needs against long-term risks, and navigate limited, uneven, and sometimes conflicting institutional responses. These narratives surfaced daily calculations about work, warmth, care for children and elders, and the tradeoffs imposed by housing, income, and policy decisions.

The decision to publish these findings as a stand-alone manuscript reflects a deliberate commitment: any technical or digital infrastructure proposed later in this thesis must remain accountable to the people who experience the greatest burdens and have the least margin for error. By organizing the analysis through a social-ecological lens, this paper offers more than context. It provides the ethical and conceptual anchor for the subsequent manuscripts, specifying the kinds of vulnerabilities, power dynamics, and institutional gaps that any monitoring or early warning system must take seriously if it is to be meaningful and justifiable in settings like Ulaanbaatar.

4. *"This Will Be the Cause of Our Death"*: Examining Perceptions, Inequities, and Policy Gaps in Addressing Air Pollution in Ulaanbaatar, Mongolia

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Overview

Air pollution in Ulaanbaatar, Mongolia, represents a critical environmental and public health crisis, disproportionately impacting residents in the low-income "ger" area who face heightened exposure and limited resources to mitigate its effects. This study examines the perceptions, behaviours, and systemic challenges associated with air pollution through the lens of the Social-Ecological Model (SEM), addressing individual, interpersonal, community, organizational, and policy factors. Semi-structured interviews with 25 participants from Ulaanbaatar were audio-recorded, transcribed, and thematically analyzed using a hybrid inductive-deductive approach. Deductive coding was guided by SEM, which considers how multiple levels of influence shape health-related behaviours.

Participants described vivid physical symptoms, emotional stress, and the normalization of hazardous conditions, reflecting the pervasive impacts of prolonged exposure. Broader structural forces deeply shaped these individual and household-level experiences. The findings highlight systemic inequities, inadequate healthcare infrastructure, and widespread mistrust in government policies driven by poorly implemented initiatives and unintended consequences. Coping strategies were constrained by financial limitations and insufficient access to reliable information, underscoring the urgent need for evidence-based, transparent, and community-driven interventions. Improved health literacy and targeted education efforts emerged as essential for empowering communities to mitigate exposure and foster resilience.

This research positions air pollution as a wicked problem characterized by complexity, competing stakeholder priorities, and dynamic challenges. Addressing this requires interdisciplinary and participatory approaches that integrate community engagement, urban planning, public health, and policy reforms to ensure effective and equitable solutions. While context-specific, this study offers

insights into the lived experience of air pollution in Ulaanbaatar and highlights potential considerations for policy and practice in similar urban environments.

Keywords

Air pollution, Social Ecological Model (SEM), lived experience, public health

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Disclosure statement

The funders had no role in the design of the study, data collection, analysis, interpretation of the findings, or writing of the manuscript.

4.1. Introduction

Air pollution is recognized by the World Health Organization (WHO) as the most significant environmental health risk.[93,94] It poses a major global public health challenge, causing substantial health and developmental harm by emitting toxic particles and gases.[95,96] Additionally, air pollution serves as a critical driver of climate change.[97] According to the 2019 Global Burden of Disease (GBD) report, air pollution was responsible for approximately 6.7 million deaths in 2019.[98] Addressing air pollution aligns with many of the United Nations' Sustainable Development Goals (SDGs) for 2030, where it is explicitly mentioned in two targets aimed at improving global health and sustainability.[99]

The challenges associated with air pollution are particularly acute in many low- and middle-income countries (LMICs). Rapid urbanization, economic growth, weak environmental regulations, and inadequate monitoring systems frequently lead to air pollution exceeding permissible standards.[100–102] Communities in low-resource settings frequently face disproportionate exposure to air pollution due to substandard housing, proximity to pollution sources, and reliance on solid fuels for cooking and heating.[103] These inequities exacerbate the public health burden in these regions, with Mongolia serving as a stark example of this crisis.

Mongolia faces severe air pollution challenges, particularly in its capital city, Ulaanbaatar, among the most polluted cities globally.[104] The annual average concentration of PM2.5 in Ulaanbaatar is measured at 75 μg/m³, seven times higher than the WHO's PM2.5 air quality guidelines, and escalates to 148 μg/m³ during the winter months.[105] The PM2.5 mean concentration has been recorded at 250 μg/m³ in the low-income "ger" district areas.[105] According to Allen et al., approximately 29% of cardiopulmonary deaths and 40% of lung cancer deaths in Ulaanbaatar are attributed to outdoor air pollution, accounting for nearly 10% of the city's total mortality.[105]

In response, the government of Mongolia and international development partners have implemented various policies and strategies to mitigate air pollution. In March 2017, the government adopted the National Programme on Reducing Air and Environmental Pollution (NPRAEP) with a target of reducing air pollution by 80% by 2025.[106] Specific initiatives under this program include providing free electricity to low-income households in the ger areas during winter, distributing clean stoves and face masks to low-income households, and supplying air purifiers to schools and hospitals.[107] Additional measures aimed at reducing the health impacts of air pollution include providing subsidies for parent caregivers to help manage child illnesses and ease hospital overcrowding, piloting pneumococcal vaccines in high-risk districts, and ensuring access to essential medicines during the winter months.[107] In May 2019, the government enacted a ban on the domestic use of raw coal in six of Ulaanbaatar's nine districts (Bayangol, Bayanzurkh, Chingeltei, Khan-Uul, Songinokhairkhan, and Sukhbaatar).[108] To support this policy, refined coal briquettes, compressed blocks made from coal dust and binding agents designed to burn more efficiently and cleanly than raw coal,[109] were introduced as an alternative at subsidized prices, with significant investment in their production and distribution.[68]

Air pollution in Ulaanbaatar exemplifies a 'wicked problem,' a deeply entrenched systemic issue shaped by the intersection of economic, political, social, cultural, and environmental factors. Its complexity stems from a combination of rapid urbanization, reliance on coal-based heating, insufficient infrastructure, and systemic policy challenges, all of which contribute to persistent pollution despite ongoing interventions. Wicked problems, like air pollution in Ulaanbaatar, resist straightforward solutions due to their dynamic and interdependent nature, where addressing one factor (such as banning raw coal) can lead to unintended consequences (such as increased reliance on alternative fuels or rising household costs). These challenges are inherently scale-sensitive,

involving interactions across different levels, from individual households making daily survival decisions to city-wide policies, international environmental agreements, and energy geopolitics.[110] The problem is further complicated by historical policy decisions, governance structures, and public perceptions, which shape the current crisis and the feasibility of future solutions. Thus, addressing air pollution in Ulaanbaatar requires a multi-sectoral, adaptive approach that accounts for these interconnected challenges and unintended policy effects.[110,111]

This study examines how individuals and communities in Ulaanbaatar perceive and experience air pollution as a public health and environmental issue, with a focus on underrepresented communities in vulnerable settings where health systems are strained and resources are limited.[112–115] Guided by the Social-Ecological Model, the study addresses three objectives: (i) to examine how individuals perceive the health risks of air pollution in their daily lives; (ii) to explore the coping strategies and behaviours they adopt in response; and (iii) to understand how broader social norms, policy responses, and structural constraints shape these experiences. This focus on public perspectives is especially critical in marginalized settings where the urgency of the problem leaves little room for trial and error, and where community-informed interventions are essential for equitable and effective solutions.

4.2. Methods

4.2.1. Study Context

To explore how residents experience and respond to air pollution across these contexts, semi-structured in-depth interviews were conducted with individuals living in Ulaanbaatar. The city consists of Bayangol, Bayanzurkh, Chingeltei, Sukhbaatar, Songinokhairkhan, Khan-Uul, Nalaikh, Bagakhangai, and Baganuur districts. Ger areas, residential zones primarily composed of

traditional portable dwellings known as gers, are present in all nine districts,[116] with particular concentration in Sukhbaatar, Chingeltei, Songinokhairkhan, and Bayanzurkh districts.[117]

4.2.2. Interview Guide and Design

The interview guide was developed in collaboration with a local community partner and the grassroots air quality advocacy organization Breathe Mongolia – Clean Air Coalition (BM) to ensure that the questions were culturally and contextually appropriate. The guide was designed to explore topics that enabled participants to share their experiences across individual, interpersonal, organizational, community, and policy perspectives. Ethics approval for the study was obtained from the University of Waterloo Office of Research Ethics (ORE Project ID #45755).

4.2.3. Participant Recruitment

Participants were recruited from across the nine districts of Ulaanbaatar and one ger area to achieve diversity in age, income, education, gender, occupation, geographic representation, housing quality, environmental setting, household income, household size, number of children, and length of residence in Ulaanbaatar. Recruitment was conducted through two approaches: in urban areas, participants were recruited online via social media channels managed by UNICEF and BM, while in the ger area, recruitment was facilitated through UNICEF's Early Childhood Development Center in the Bayanzurkh district, which provided direct access to community members.[‡] To

[‡] Ger districts are administratively and geographically part of Ulaanbaatar. However, policy and planning discourse have often framed them as peripheral or separate, contributing to inequitable access and service delivery.[118] In this study, this distinction between "ger" and "non-ger" districts is used solely to clarify recruitment strategies, while recognizing that both are integral to the urban fabric of the city.

ensure representativeness, the recruitment strategy accounted for gender balance and included variation in age, education, income level, and residential districts to capture a broad range of perspectives and experiences.

4.2.4. Data Collection

Data collection took place between January 2024 and February 2024 using semi-structured interviews to examine how individuals interact with and perceive their exposure to air pollution. The interview guide used open ended prompts to explore three domains: interaction with air pollution in the physical environment, including knowledge and awareness; responses to air pollution, including health concerns and strategies to manage exposure; and institutional interactions, focusing on perceptions of societal and political institutions in the context of air pollution. The same interviews also included questions related to technology use and perceptions of monitoring systems, which were analyzed separately in Study 2.

The interviews were conducted at the UNICEF Mongolia and People in Need (PIN) country offices, as well as the UNICEF Early Childhood Development Center, for participants residing in the ger area of Bayanzurkh. Interviews were conducted by a team comprising English-speaking interviewers and a bilingual translator. Questions were posed in English and translated into Mongolian, and responses were recorded in English or Mongolian. Translators provided real-time back-translations into English during the interviews to ensure accuracy and coherence.[119,120] All interviews were audio-recorded, transcribed using Otter.ai®, and subsequently uploaded to NVivo 15 (Lumivero LLC, Denver, CO, United States) for analysis.

4.2.5. Data Analysis

The data was analyzed using a hybrid inductive-deductive approach to represent participants' voices and experiences accurately.[121] The analysis began with a thorough reading and re-reading of the interview transcripts to gain an in-depth understanding of participants' perceptions and experiences. Recurring ideas, experiences, and beliefs were identified and assigned codes during this process. To enhance the rigour of the analysis, coding was conducted collaboratively and iteratively. Team members regularly discussed coding decisions to refine themes and resolve discrepancies, thereby supporting cross-validation of interpretations.[122] Through this iterative process, initial themes emerged, grounded in the data rather than a preconceived theoretical framework.

Subsequently, a deductive approach was employed to map the emergent themes onto the SEM framework. This involved examining how each inductively derived theme aligned with the existing SEM categories (e.g., individual, interpersonal, organizational, community, and policy). Incorporating the SEM lens provided a structured approach to interpreting the findings holistically, offering deeper insights into how perceptions operate across multiple levels of influence and facilitating connections between the themes and established theoretical constructs. The definitions of each SEM category are provided in Table 1 for reference.

Table 1: Definitions of the five levels of the Social-Ecological Model (SEM) used in this study.

SEM Aspect	Definition
Individual	Focuses on personal behaviours, attitudes, and health impacts related to air pollution, emphasizing the direct experiences of individuals.
Interpersonal	Examines social interactions and relationships, particularly within families or among peers, highlighting the influence of these dynamics on exposure and coping strategies.
Organizational	Explores the role of institutions, such as healthcare and education systems, in shaping individual and community responses to air pollution exposure.
Community	Investigates the collective context of air pollution, including regional disparities, shared challenges, and the role of community-level interventions.
Policy	Analyzes the broader systemic and governmental structures, including regulations, implementation challenges, and public trust in addressing air pollution.

4.3. Results

Participants (n = 25) represented six districts of Ulaanbaatar, with a near equal split between urban (n = 13) and ger area (n = 12). Most participants lived with family members (n = 21), including children (n = 17). Housing arrangements varied across gers, houses, and shared compounds. This sample size was selected based on existing recommendations for achieving thematic saturation in qualitative research, which suggests that 20-30 participants are sufficient for capturing diverse perspectives in heterogeneous populations.[123] Detailed participant descriptions are provided in Appendix 1. To supplement the thematic findings presented in the Results section, an Appendix has been included with representative quotations for each theme (see Appendix B).

4.3.1. Individual

4.3.1.1. Air Pollution as a Persistent Presence in Daily Life

Participants described air pollution as an inescapable concern that permeates their daily routines and long-term decisions. One participant emphasized the constant nature of this worry, stating,

"Every day, minute, second. It is killing my future. Maybe I can go to another country but that is [a] very hard decision. This environment is affecting my everything… health, future, etcetera" [P10].

Another described the physical and sensory burden of pollution, particularly the smell, and its mental toll.

"When I walk after work, usually around 8pm… 7 to 8pm. That's when the air quality drops and becomes difficult to walk outside. It's just difficult for my head to manage the smell. [P11]

Participants described physical symptoms associated with air pollution, such as difficulty breathing and throat irritation, with one respondent likening the city's air to a *"smoking room"* [P7]. Other reported sensory experiences, such as a strong sulphur odour in certain areas [P5], are exacerbated by the introduction of coal briquettes and dust accumulation from construction materials that worsen the air quality year-round [P8]. The long-term health risks were a particular source of anxiety. As one participant shared:

"The most immediate concern that I have would be the possibility of catching future diseases, especially lung related. I see a lot of my immediate circle talking about them catching possible lung cancer in the future, just because they're exposed to all the pollution all the time" [P1].

Another participant echoed this growing concern,

Well, I used to [not] think about it. But lately people around me started getting cancer [and] I started thinking what is the cause of this? Is it the air pollution? [P7].

4.3.1.2. Health Concerns Attributed to Air Pollution

Participants described a wide range of health concerns associated with air pollution, focusing on both immediate effects and long-term implications. The discussions highlight the pervasiveness of health issues and the emotional and psychological toll of living in polluted conditions. Participants reported flu and flu-like symptoms, including common colds [P2, P4, P5, P8, P9, P10, P15, P17, P18, P21, P24], fever [P4, P5, P24], dizziness [P6, P11, P14], frequent headaches [P10, P11, P14, P15, P17, P19], and allergies [P12, P22]. Several participants identified chronic health conditions they attributed to prolonged exposure to air pollution. Among these, respiratory issues were most mentioned, including wheezing [P23], asthma [P15, P21], and undiagnosed lung problems severe enough to require hospitalization [P16]. Participants also described experiencing fluctuating blood pressure [P19], seizures [P14], and the presence of heavy metals, such as lead, in their blood [P11], all of which they believed were consequences of ongoing exposure to air pollution.

4.3.1.3. The Emotional and Psychological Toll

For many participants, prolonged exposure to pollution was strongly associated with fears of developing severe health conditions. Concerns about future illnesses such as lung cancer [P1, P7, P25] and chronic respiratory diseases [P1, P2, P10, P12, P22] were common. Some participants also highlighted concerns about air pollution's impact on reproductive health, believing it could contribute to infertility [P4, P19] or, in women, result in miscarriages [P4]. These fears reflect the broader apprehension about how air pollution affects the body in profound and long-term ways.

Several participants described the psychological toll of air pollution, including feelings of stress [P1, P17, P21], sadness [P22], and frustration [P9, P20]. One participant reflected on the contrast between their childhood and present-day life in the city, stating:

"Well, we used to breathe fresh air in the countryside. [Now], the pollution goes throughout the body. I feel sad thinking about the impact [on] our future generation's organs like lungs, heart" [P22]

Others shared frustration over the unknown health conditions stemming from pollution exposure, with one participant noting that they had once overcome colds and flu without medication but now relied on medicine *"like food,"* highlighting weakened immune systems [P9]. Another participant voiced helplessness, expressing confusion about how to protect themselves or whom to turn to for guidance:

"When the air pollution is bad, I think not only [about] myself, but [also about] people and small children who reside around me. I [get] concerned about how these children will live and how will their health be. I [get] sad. What should we do...can't do anything about it… whom should I talk to? [P20].

Finally, some participants conveyed resignation, acknowledging pollution as a poisonous force that would inevitably lead to health problems [P13] and death [P3, P10, P19]. One participant lamented that air pollution would result in widespread chronic organ diseases, predicting a significant loss of life [P10]. Another described the inescapable dilemma of burning coal to stay warm, contributing to air pollution and health risks, versus freezing to death without it. As they explained:

"How [do I] protect myself? If I don't burn briquette coal, I will freeze to death. If I burn it, I am poisoned to death. There is no other choice than death. No other choice." [P19]

These circumstances left them feeling trapped in a situation where every choice posed a threat to their health and survival.

4.3.1.4. Coping and Adaptation

4.3.1.4.1. Individual-Level Actions

Participants described various measures they employed to protect themselves and their families from air pollution. Participants frequently mentioned wearing masks to mitigate exposure [P1, P2, P3, P5, P6, P9, P10, P11, P14, P15, P16, P17, P18, P22, P23], although usage varied based on perceived pollution levels and individual comfort. Masks were often worn during peak pollution times, such as mornings or evenings, but some participants [P3, P18] expressed doubts about their effectiveness, citing blackened mucus even when masks were used [P3]. Others opted for scarves as an alternative [P12, P16, P24], particularly when masks were unavailable or uncomfortable [P11].

In addition to physical barriers, some participants adopted health practices to minimize the impact of air pollution. These included drinking fluids believed to *"cleanse lungs,"* such as milk, tea, or beverages rich in antioxidants, including Vitamin C, sea buckthorn, and red huckleberry [P5, P6, P13, P18, P20]. For some, these measures were routine, while others used them sporadically based on symptom severity. Participants did not adopt these preventive measures based on Western scientific evidence but drew upon local knowledge and practices passed down through generations. Many described learning these approaches from their parents or grandparents [P12, P13, P18, P20]. For instance, one participant shared,

"I try to boost [my immune system with] vitamins, sea buckthorn and boiling curd drink. Even when we were little, we used to boil sea buckthorn, curd, etc.… saying that it would support good immunity against colds. We got it from our parents" [P12].

Another emphasizing that these practices were rooted in their Mongolian identity,

"Since I am a Mongolian, I make soup with garlic and boil curd. When someone is coughing, we give them curd and soup which makes it better" [P16].

4.3.1.4.2. Household Measures

Household measures were a common line of defence. Many participants used air purifiers to improve indoor air quality, although their usage varied [P1, P3, P5, P8, P25]. Some used purifiers for only a few hours daily due to concerns about electricity costs [P8], while others diligently replaced filters to maintain efficiency [P5]. Participants also employed sealing windows and doors to prevent smoke infiltration [P1], boiling water to humidify the air, and using vaporizers [P18, P22]. Ventilation practices were adapted to pollution conditions. Participants opened windows during less polluted times, such as windy days, to allow for fresh air circulation but kept them closed during peak pollution periods [P1, P8]. One participant adapted their heating practices from burning coal to using an electric heater [P14].

4.3.1.4.3. Behavioural and Lifestyle Adaptations

Participants frequently adopted behavioural adaptations to minimize exposure to air pollution, with many emphasizing the stark contrast in health outcomes between life in the countryside and the city. Several participants shared that they rarely fell ill while living in rural areas [P2, P4, P21, P22], and some attributed their stronger immune systems to growing up in the countryside, which they believed provided a natural resilience against illnesses [P2, P21, P25]. For those living in urban areas, recovery from illnesses often took significantly longer, with some cases even necessitating hospitalization [P2, P4, P21, P25]. One participant described this disparity by comparing her firstborn child, raised in the countryside, with her younger children born in the city:

“There is a difference. My oldest child doesn’t catch cold when we all have it. Even if she does, it’s mild and she barely takes medicine to recover. Even if she catches a cold, it is mild, and [she] recovers without coughing. The other ones [took] more than 14 days and some of them almost got pneumonia. It is difficult for them to recover” [P21].

To alleviate the health impacts of Ulaanbaatar's air pollution, many participants sought temporary relief by taking weekend or seasonal retreats to the countryside [P1, P3, P4, P7, P11, P12, P13, P17, P18, P21]. Some families purchased summer homes in cleaner regions, while others regularly sent their children to stay with relatives in less polluted areas [P4, P7]. These measures illustrate the lengths families go to protect themselves and their children from the harmful effects of air pollution, even if only temporarily.

4.3.1.4.4. Public Awareness and Attitude Toward Air Pollution

Participants highlighted significant gaps in public knowledge and understanding about air pollution and its associated risks. A recurring theme was the lack of awareness about protective measures or strategies to mitigate exposure. Many participants acknowledged that they and others in their community did not know how to effectively protect themselves or their families from air pollution [P2, P3, P5, P7, P9, P10, P14, P17]. One participant explained that many of their efforts to mitigate air pollution's effects rely on speculation, stating,

"We [guess] that air pollution negatively impacts human health. We assume it has [adverse] effects on the mind and memory" [P7].

Similarly, another shared,

"If there is something to protect us from air pollution, we would like to protect ourselves…but I do not know what else there is except [wearing] the mask" [P2].

These reflections highlight a broader sense of uncertainty and disempowerment that arises from prolonged exposure. Despite their desire to protect themselves, participants often lacked access to reliable information, which contributed to a reliance on speculation and incomplete strategies.

4.3.2. Interpersonal

4.3.2.1. Health Concerns About Children and Older Family Members

All participants in this study were adults, and any information related to children reflects perceptions and experiences shared by parents or guardians. Interpersonal dynamics highlight the significant impact of air pollution on families and social relationships, particularly concerning vulnerable groups. Several participants reported adverse health outcomes in their children resulting from exposure to air pollution. These health issues ranged from respiratory problems and infections [P2, P4, P6, P12, P23] to flu-like symptoms [P4, P8, P9, P17, P21, P24] and seasonal allergies [P22]. Two participants highlighted instances where their children required hospitalization due to severe fevers and colds, which they attributed to prolonged exposure to air pollution [P4, P24].

Participants expressed concern for the health of their children and older family members, highlighting the heightened vulnerability of these groups to air pollution. Many expressed that their primary concern was not their health but the well-being of their children and grandchildren [P2, P19, P22], with one participant poignantly stating, *"My happiness is in their well-being"* [P22]. Nearly all participants shared deep concerns about how air pollution affected their children, grandchildren, and other immediate family members. Several participants explicitly mentioned the current health impacts on children, including respiratory issues and compromised immunity [P1, P3, P5, P6, P8, P9, P11, P16, P17, P19, P24, P25].

One participant described the emotional strain of raising a daughter alone amid worsening pollution:

"I am a single father, and it's been just the two of us for 10 years. I'm really worried about her health. Even the snow is dusty. It's the same [in] the children's body. Her body is ashy inside, and I think she can smell and taste it" [P17].

Another participant shared that her daughter was hospitalized four times due to a worsening cold. While some attributed the illness to cold temperatures, she firmly believed air pollution was the underlying cause [P24].

Concerns about children's future health were also prevalent among participants [P2, P4, P12, P13, P15, P20, P22, P23]. One participant noted that children's smaller lungs make them especially vulnerable to air pollution, predicting they will grow up to face even greater health challenges. As he shared:

"I am very worried about my children. They have little lungs, right? This is how their little lungs are growing…If you let them live in a polluted place, they will grow up and become sicker. I have started to think that one day I will leave this place" [P4].

Another participant reflecting on her stage in life,

"I am old person and getting old[er]. I only worry about my children. What kind of diseases will they have in the future because of the air pollution?" [P23].

A few participants also voiced concerns about the effects of air pollution on older family members [P6, P7, P13, P14, P24]. These concerns were often linked to preexisting health conditions that

could be exacerbated by air pollution [P6, P13] or the general vulnerability associated with advanced age [P14, P24].

4.3.2.2. Coping and Adaptation

4.3.2.2.1. Health-Focused Interventions

Some participants also limited their own and their families' outdoor exposure, especially for children [P12, P13, P15]. This was particularly prevalent during the winter months, when pollution levels reached their peak, as one participant explained,

"I try not to go out during winter. I usually stay with my children. [I] can't do anything about my children who go to school, but I stay at home with the younger ones. I [avoid] sending them to the kindergarten" [P15].

4.3.2.2.2. Behavioural and Lifestyle Adaptations

Long-term relocation was an aspiration for some participants, who expressed a desire to move permanently to areas with better air quality. However, they also voiced concerns about the well-being of family members who would remain behind in polluted environments, emphasizing the emotional challenges of such a decision [P8, P21].

4.3.3. Organizational Level

4.3.3.1. Engagement with Healthcare Services

Organizations, including healthcare facilities and educational institutions, played a significant role in shaping participants' experiences and responses to air pollution. Participants occasionally highlighted their interactions with hospitals and the healthcare systems, underscoring the challenges posed by air pollution-induced illnesses [P4, P6, P13, P15, P24, P25]. Hospital care

was frequently required due to severe and ongoing heat-related problems, especially among children [P4, P15, P24]. One participant shared that his youngest child was hospitalized due to a high fever that could not be managed at home. He expressed frustration that despite using medication, the child's condition worsened,

"My youngest child was even hospitalized. They [had] a very bad fever. It was not curable at home. Medication was not helpful at all. So, hospitalization was necessary. I just don't think my kids are getting sick this often because of the cold weather" [P4].

Another shared that she had to spend ten days in the hospital due to contamination of her amniotic fluid and the occurrence of calcification. She attributed these complications to air pollution, noting that the incident occurred during winter [P15].

Participants also emphasized the strain on the healthcare system during winter. They observed that hospitals are often overcrowded, with insufficient resources to accommodate the influx of patients suffering from air pollution-related ailments [P15, P25]. One participant described:

"Hospitals are filled with children; all these terrible viruses and various diseases are spreading [as a] result of air pollution. Even when children get pneumonia and need to be hospitalized, there is no space. They go back home, [meaning] the hospitals are packed" [P15].

This lack of access exacerbated their feelings of vulnerability and helplessness.

Regarding protective care, some participants expressed concerns about the effectiveness of prescribed treatments for conditions related to air pollution. They felt that the healthcare system lacked the necessary tools and expertise to address the root causes of their illnesses [P4, P9]. For instance, one participant shared his disappointment that treatment often involved strong

medication, which he felt was a band-aid solution rather than addressing the larger issue of air pollution [P9].

Healthcare engagement was a recurring ordeal for some families with young children. Some participants detailed routine doctor visits for illnesses attributed to air pollution [P4, P15, P24]. This added an economic burden, as frequent consultations, medications, and hospital stays place a financial strain on families [P4, P6, P24]. One participant, a physician working in an emergency department, illustrated the scale of this crisis:

"Two hundred to three hundred children come to the emergency department a night. More than half of them are coughing because of air pollution…Parents don't have the money to buy medicine or afford [an] air purifier" [P5].

These barriers perpetuate a cycle of illness and vulnerability, particularly for families living in lower-income areas.

Finally, participants expressed an overarching sentiment of frustration and resignation, as their reliance on healthcare services seemed to result from an environmental crisis beyond their control. They highlighted the need for systemic changes to improve air quality and reduce their reliance on healthcare systems [P15, P25]. For many, the healthcare system served as a stopgap rather than a long-term solution, leaving them yearning for broader environmental and public health interventions [P5, P25].

4.3.3.2. Shortcomings of the Education System

Participants noted the absence of clear and accessible information, particularly regarding the health impacts of air pollution and effective interventions [P2, P3, P5, P7, P14, P17]. One participant mentioned the lack of research on the causes of air pollution and its health effects, saying,

"Children are getting poisoned…we do not know anything about this or how to get information [on this]" [P2].

Others pointed out that even when research exists, it is often not communicated effectively to the public, leaving many feeling *"far away from the information"* [P17].

Another prominent theme was the role of education and access to reliable information in shaping awareness and action on air pollution. Participants with professional or academic backgrounds had greater exposure to scientific literature, specialized training, and expert networks, which provided them with a more structured understanding of air pollution and protective measures [P1]. However, access to such resources varied significantly, with many residents in the ger area relying on intergenerational knowledge, practical coping strategies, and informal sources of information such as social media. Some participants from non-ger areas interpreted these differences primarily as a lack of education, attributing responsibility to individuals rather than to structural barriers. As one participant stated,

"They don't know how to protect themselves… their parents are also uneducated, and these children end up like this" [P10].

Such narratives illustrate how blame was directed towards the ger communities, obscuring the systematic inequities that limit access to education, information, and protective resources.

These inequities were further reflected in accounts of the economic and material constraints shaping everyday choices in ger households. A participant who works as a physician in an emergency department highlighted how systemic barriers such as economic hardships and limited access to affordable heating alternatives shaped household decisions in the ger area. She recounted

instances where families, unable to afford wood, burned old tires to stay warm, exposing children to harmful pollutants. As she explained:

"Parents said they didn't have money to buy wood, so they burned old tires…When I say you can't do this to your child, they say, 'No, it's okay.' There is no one to look after my child" [P5].

Her account highlighted both the environmental and health risks associated with these practices and the deeply rooted structural inequities that drive survival-based decision-making. These findings illustrate how systemic and historical constraints shape exposure and force families to make difficult trade-offs between immediate needs and long-term well-being.

Participants suggested that education and awareness could play a role in addressing air pollution [P4, P8, P9]. While not overly optimistic, they highlighted education as a possible avenue for encouraging informed action and changing societal attitudes. Some participants proposed that providing accessible and accurate information about the causes and consequences of air pollution might foster greater public engagement. One participant suggested,

"If people can get the right understanding, they will do the right thing" [P4].

Another participant highlighted the need for collective effort, expressing frustration at feeling *"the only one in the crowd"* and wishing for more widespread mobilization to address the issue [P9].

4.3.4. Community Level

The community level highlighted disparities in the impact of air pollution across different regions in Ulaanbaatar, as well as the collective responses to these challenges. Participants expressed a wide range of concerns related to the persistent and pervasive air pollution in Ulaanbaatar, which they attributed to several sources, including coal burning smoke [P4, P7, P12, P13, P14], car

exhaust [P1, P2, P13] and industrial emissions from nearby factories [P3]. Two participants mentioned the excessive morning and evening smoke, attributing it to neighbouring residents burning wood for heat [P12, P18]. Geographic variations in pollution levels were frequently noted, with districts closer to the ger area experiencing higher pollution than districts farther south [P4]. However, even residents in these comparatively *"cleaner"* areas acknowledged that escaping the overall polluted environment of the city is challenging [P5]. One participant noted that Ulaanbaatar's geographic location in a valley, combined with a lack of wind, prevents the dispersion of air pollution and expressed a sense of resignation toward their fate. [P4].

4.3.4.1.1. Perceptions of Changes in Air Quality Over Time in Ulaanbaatar

Most participants reported a general worsening of air quality in Ulaanbaatar over the past few years [P1, P4, P5, P7, P8, P11, P15, P13, P19, P20, P23, P24, P25]. Several participants noted that introducing briquette coal initially appeared to reduce visible smoke and slightly improve air quality; however, this improvement was temporary [P1, P11].

A few participants observed changes in visibility, describing moments when they could not see nearby buildings due to the dense smoke, which they felt had worsened significantly over the past five years [P5]. Many attributed this decline in air quality to the increasing population [P8], expansion of the ger area [P4], and the number of cars and construction projects [P20].

While some participants noted slight, temporary improvements in air quality, especially in less densely populated areas or during specific times of the year [P14, P18], the overall sentiment was one of frustration and concern. Many expressed unease about the briquette coal's effect on health, noting that inhaling its smoke produced a sour taste in the mouth [P3] and a strong sulphur-like odour [P7, P8], which led some to question whether the processed coal contained additional

harmful chemicals. Many expressed resignation, feeling that despite efforts to improve air quality, the changes were insufficient, with one participant describing the air as *"10-20 times more poisonous"* than when they first arrived in the city [P19].

4.3.4.2. Perceived Variations in Air Quality in Different Parts of Ulaanbaatar

Participants consistently noted significant differences in air quality depending on their location within Ulaanbaatar. The northern, eastern, and the ger areas were repeatedly described as having the worst air pollution [P1, P4, P8, P11, P13, P15, P16, P17, P21, P24, P25]. Several participants referred to these areas as *"disastrous," "grey,"* and *"black"* [P15, P16], with smoke so thick that it feels toxic, obscuring visibility and lingering heavily in the air [P19]. Upon entering these areas, some participants reported immediate physical reactions, such as coughing, throat irritation, and difficulty breathing [P6, P7, P15, P17]. One participant noted that the smell of smoke gets absorbed into their clothes when visiting relatives in these locations [P4].

Conversely, southern districts were often described as having better air quality due to their distance from the ger area and more favourable environmental conditions, such as wind, which disperses pollutants. Participants living on hills or at higher elevations also noted that the air quality was comparatively better than in low-lying valley areas, where smoke accumulates [P3, P7, P19].

In the city center, experiences were mixed. Some participants observed better air quality than the ger area [P5, P6, P13, P17, P21] primarily because less coal is burned [P21]. However, others highlighted the impact of car emissions, particularly in areas with heavy traffic, such as around the central square [P5, P13]. Despite this, participants still described the city center as a polluted environment, with a lingering smell of toxicity in the air [P21].

4.3.4.3. Perceptions of Briquette Coal

A recurring concern among participants was the uncertainty surrounding the composition of the coal [P1, P2, P3, P7, P9, P12, P15, P17, P22], which led to widespread distrust. Many participants noted that while raw coal was also a source of air pollution, they considered it less harmful in some respects. Briquettes were introduced with the intention of improving air quality in the city. However, many participants felt that conditions had not improved and, in some cases, had worsened [P3, P4, P8, P24]. Several participants described the experience of handling briquette coal as unpleasant, highlighting the excessive dust it produces and the difficulty of cleaning up after contact [P3, P9, P12, P13, P20, P22]. Some individuals perceived raw coal smoke as less irritating, describing it as visually smoky but without the *"sour taste"* or pungent smell associated with briquette coal [P3, P7]. They questioned whether briquette coals met the claimed cleanliness standards. They speculated that they might release higher levels of harmful elements such as sulphur or heavy metals, leaving them feeling misled [P1, P7, P22]. This suggests that raw and unprocessed coal was, for some, viewed as a lesser evil compared to the briquette alternative.

The distrust in composition extended to beliefs that briquettes were responsible for various health problems caused by burning them. Many described physical symptoms, such as sore throats, headaches, and respiratory issues, which were attributed to the smoke and particulate matter emitted during combustion [P3, P15, P18, P19]. One participant likened the effects of briquette coal to working in a mining site, explaining,

"The new coal is very sour and bad; it hurts my throat. Even my spit is black when exposed to the smoke" [P3].

Another added that dust and ash from briquettes settled on surfaces, worsening indoor air quality:

“The briquettes produce more dust. And after burning it, when I look at the table, it is already dusty. It wasn't like that when I was burning raw coal” [P12].

4.3.4.4. Perceived Apathy, Skepticism, and Normalization of Air Pollution

A recurring theme was the adaptation to poor air quality, with some respondents indicating that they have redefined *"unhealthy"* levels as acceptable and a new norm due to prolonged exposure [P6]. Another participant illustrated this by stating that air quality labelled as "unhealthy" on their computer often feels healthier compared to what they experience at other times, highlighting how individuals recalibrate their perceptions of risk and normal conditions [P1].

Participants commonly described a widespread lack of care and engagement with air pollution issues among Mongolians, citing societal and systemic barriers that prevent meaningful action [P4, P6, P9, P10, P12, P20, P21, P24]. This perceived apathy, compounded by financial struggles, highlighted the challenges of addressing air pollution individually and collectively [P9, P20]. Many participants observed a general indifference toward air pollution, noting that it has become normalized in daily life [P4, P6, P10, P12, P20, P21]. One participant explained,

"People generally do not care about air pollution… Mongolians especially do not care" [P4].

Another participant remarked on the resignation among individuals, saying,

"They have already accepted the smoke as a part of their life, not a problem" [P10].

This normalization reflects how prolonged exposure to air pollution has desensitized communities, making the issue feel less urgent. Some participants expressed frustration with the attitudes of others toward air pollution [P4, P9, P10, P20]. Some noted a lack of accountability, observing that

people seemed indifferent to their potential role in addressing the issue [P4]. Instead, they tended to focus on complaining and placing blame on society as a whole [P9].

Resistance to new ideas also emerged as a significant obstacle. Participants highlighted how communities are skeptical of innovative solutions, often perceiving them as corrupt or untrustworthy [P6, P20]. One participant explained,

"People think that what those people [with new ideas] are doing is all lies and just trying to [commit] fraud" [P20].

This lack of trust in change further hinders the adoption of effective measures to combat air pollution.

4.3.5. Policy Level

At the policy level, participants expressed deep mistrust in government institutions and skepticism about the effectiveness of policies. Participants highlighted a range of political drivers and challenges contributing to the persistence of air pollution in Ulaanbaatar. Across the narratives, a pervasive distrust of government emerged, rooted in perceptions of inefficacy, corruption, and mismanagement of resources. These sentiments influenced participants' perspectives on the political aspects of air pollution and the obstacles to meaningful change.

4.3.5.1. Financial and Infrastructure Barriers

Economic constraints featured prominently in discussions [P4, P16, P17, P18, P19, P20, P21, P22, P23, P24, P25]. Participants noted that reliance on coal was driven by the high cost of alternatives, such as electric heating systems, compounded by the limited capacity of existing power grids [P13, P16, P18, P21, P23, P24]. One participant explained,

"I wanted to switch to electric heating, but the voltage drops, or power goes out, so it's not feasible" [P18].

Participants called for increased investment in infrastructure, such as additional power plants and improved electricity distribution, to support the transition away from coal.

Participants also discussed the unequal impacts of air pollution policies, noting that the financial burden of transitioning to cleaner technologies fell disproportionately on low-income households. One participant emphasized,

"We need systemic solutions, not just individual fixes. People living in poverty can't afford to stop burning coal" [P24].

This inequity fueled a sense of resignation among some participants, who felt powerless to influence broader policy decisions.

4.3.5.2. Government Inaction and Misdirected Policies

Several participants expressed frustration with the government's failure to address air pollution effectively, citing misaligned priorities and inadequate implementation of policies [P1, P4, P8, P9, P10, P11, P12, P13, P14, P18, P19, P24, P25]. One participant observed that while the government had focused on distributing improved stoves and briquette coal, these measures failed to address the root causes of pollution, such as energy insecurity and inadequate urban planning [P1]. Another participant noted,

"The government is trying to solve the issue by distributing furnaces, but people are still burning coal. Air pollution won't decrease if coal use persists" [P13].

4.3.5.3. Distrust in Government and Institutions

Distrust in the government was a recurring theme, with participants questioning the transparency and accountability of political leaders [P4, P6, P8, P9, P10, P19, P22]. One participant stated,

"It seems like the government is lying and not really trying to help. The smoke problem has been discussed for years, but nothing has changed" [P6].

Another participant described how government officials manipulated information, creating a sense that solutions were superficial or designed to placate public criticism rather than address systemic issues. This erosion of trust was further exacerbated by the perception that government initiatives often excluded citizen input or failed to address the needs of marginalized communities [P22].

Distrust in the government was a recurring theme in discussions about briquette coal, with participants expressing skepticism about its purported benefits compared to raw coal [P4, P7, P8, P19, P22]. Many questioned the government's claims that briquette coal had reduced air pollution, with one participant stating,

"Our politicians said that air pollution has decreased by using improved coal, but that is wrong" [P8].

Concerns about inconsistencies in briquette quality were attributed to a lack of oversight, further undermining public confidence [P22]. The government's handling of the initiative was criticized for its lack of transparency, with some participants speculating about corruption or ulterior motives, as one remarked,

"A lot of people say they are doing it on purpose to kill" [P24].

These statements reflect the deep-seated mistrust among citizens and their frustrations with policy implementation.

Additionally, participants raised health concerns, describing briquette coal as potentially more toxic than raw coal due to its distinctive smell and perceived adverse health effects. For instance, one participant remarked,

"The briquette coal is coming from [Russia] and forcefully given to the citizens" [P19]

Others shared anecdotes of suffocation cases linked to its use [P3, P13]. Such accounts heightened fears about potential chemical contaminants in briquette coal and their long-term health implications. Beyond health and trust issues, participants also noted practical and economic challenges, including the higher cost of briquette coal, which placed an additional financial burden on households [P9]. This combination of financial strain, dissatisfaction with quality, and health concerns further fueled public resentment toward the government and its initiatives.

Frustrations with the physical properties and performance of briquettes compounded these concerns. Many participants described briquette coals as difficult to light, producing excessive fly ash and emitting a strong, unpleasant, and potentially toxic smell. Briquette coals require binding materials to hold them together for transportation, forming, and storage.[108,124] Participants [P19, P22] speculated that the composition of these binders contributed to air pollution and poisoning. One participant [P1] observed that air quality initially improved when the briquette coals were introduced but later worsened, raising suspicions about a decline in briquette quality over time. Such accounts underscore broader anxieties about policy inconsistency, material safety, and the absence of transparent government communication.

4.3.5.4. Urbanization and Decentralization

Urban planning issues, particularly the growth of ger areas, were identified as a significant contributor to air pollution [P1, P10, P16, P18, P19, P22]. Participants criticized the lack of policies to decentralize Ulaanbaatar and reduce population density in the capital. One participant remarked,

"The city was designed for 500,000 people, but now it has 1.5 million, and the infrastructure can't keep up" [P19].

Participants supported efforts to encourage migration to rural areas through improved housing and job opportunities, which they believed could alleviate pressure on the city's resources [P8, P21].

4.3.5.5. Barriers to Engagement

Participants emphasized how financial and social pressures hindered engagement with air pollution, as the immediate priorities of securing food, warmth, and daily survival often took precedence, showing the complex trade-offs residents must navigate [P9, P6]. One participant explained,

"Those who are worried about their everyday meals do not think about air pollution." [P9].

Another participant shared,

"I am too busy to care... if I don't have money today, I don't accept smoke as my [greatest] problem," [P6].

These statements reflect not indifference to air pollution, but the reality of systemic constraints that force individuals to prioritize short-term survival over long-term environmental health.

Additionally, structural barriers and widespread mistrust in governance further complicate efforts to address air pollution. Participants criticized policies that exacerbate poverty and fail to provide viable alternatives, limiting opportunities for collective action. One participant described these systemic constraints as *"a policy not to develop the citizens but try to keep them poor"* [P9], underscoring how economic and political structures reinforce cycles of vulnerability. Such perceptions of policy failure and systemic neglect fostered frustration, resignation, and a sense of powerlessness among affected communities.

These findings are summarized in Figure 1, which illustrates the multi-level determinants of air pollution perception and adaptation, organized according to the SEM.

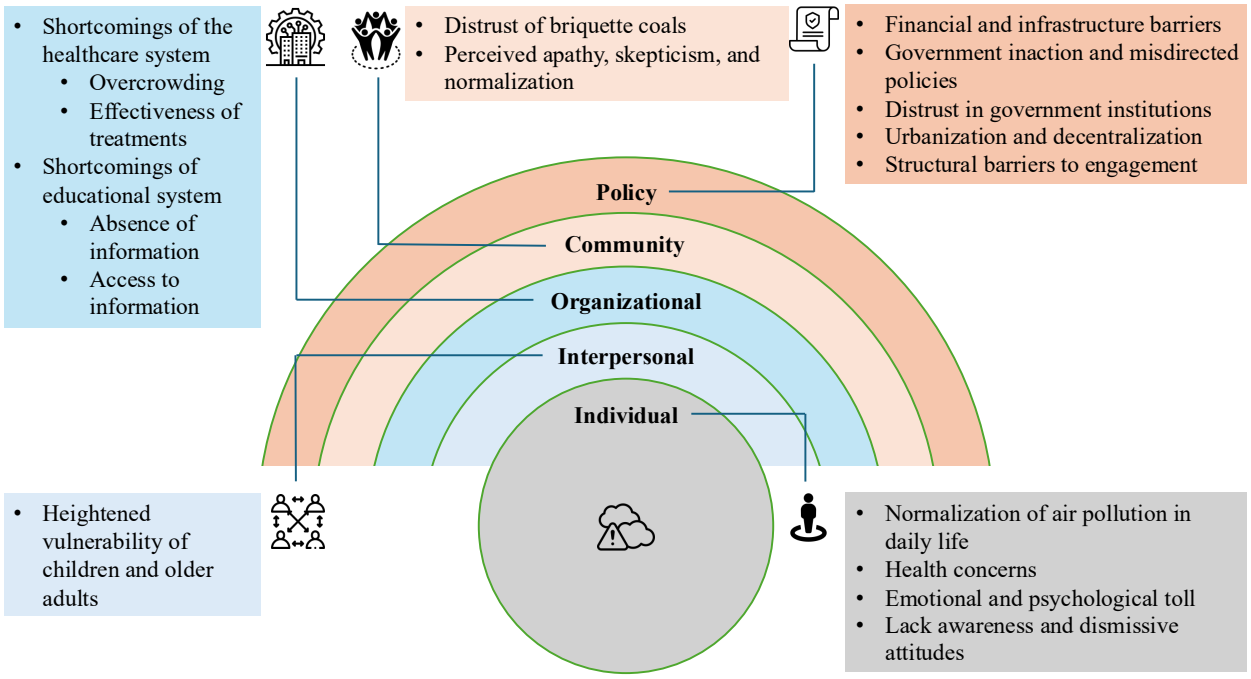


Figure 1. Multi-level determinants of air pollution perception in Ulaanbaatar, organized using the Social Ecological Model. The diagram synthesizes factors identified at the individual, interpersonal, organizational, community, and policy levels.

4.4. Discussion

This study aimed to understand how individuals and communities in Ulaanbaatar experience and respond to air pollution, with particular attention to the social and structural factors that shape health outcomes and coping behaviours. By applying the SEM framework to qualitative data, this research offers a multi-level analysis that foregrounds the lived realities of affected populations and identifies key leverage points for more equitable, health-centred policy interventions.

4.4.1. Health and Emotional Toll of Air Pollution

The individual-level participants reported severe physical symptoms linked to prolonged exposure to air pollution, including coughing, sore throats, respiratory issues, and dizziness. These symptoms align with existing research that quantifies the adverse cardiovascular and pulmonary effects of air pollution.[125–127] However, less visible health impacts, such as hypertension and neurological disorders, may go undetected without medical examination.[104] Additionally, air pollution has been linked to mental health concerns, including anxiety, depression, and personality disorders, which require clinical testing and diagnosis.[128]

Beyond physical health, participants described the emotional burden of living in highly polluted conditions. Feelings of helplessness, anxiety, and uncertainty were common, particularly given the difficulty of understanding long-term health risks. Many participants relied on anecdotal knowledge rather than scientific information, further compounding fears and misinformation about the severity of exposure.

4.4.2. The Normalization of Poor Air Quality

Compounding this sentiment is limited knowledge about the health impacts of pollution and an inadequate understanding of the individual's role in fostering safer environments.[103] Consequently, many participants believed that the effects of environmental harm are inevitable, diminishing their willingness to engage in actions to mitigate the problem. This fatalism is further exacerbated by competing priorities that overshadow environmental concerns. Participants described focusing on immediate and tangible challenges such as housing, poverty alleviation, and access to water, which often relegated air pollution to a secondary concern.[129]

Aligned with findings from research in other low-resource settings, several participants emphasized these competing challenges.[103] For example, some described burning coal to stay warm, prioritizing survival needs such as securing meals or managing financial constraints over concerns about air quality. Air pollution was viewed as less urgent than their pressing daily struggles. This perception that people "don't care" about air pollution is often linked to a tendency to shift blame onto others, as seen in studies identifying a "halo effect."[30] In these cases, individuals attribute pollution to external factors or perceive their areas as less polluted, thereby shifting responsibility away from themselves or their communities.

4.4.3. Attributing Responsibility: The 'Halo Effect' and Shifting Blame

In this study, a notable pattern emerged in how participants attributed responsibility for air pollution. Residents of the ger areas acknowledged that much of the pollution stemmed from coal burning within their communities. This form of self-recognition aligns with findings from research on other informal settlements, where pollution sources are often perceived as stemming from immediate, local activities.[103] In contrast, some participants from urban districts recognized the presence of pollution in their areas but deflected blame, attributing it primarily to the behaviours

of those living in the ger areas. These perceptions failed to account for the structural constraints and survival imperatives that shaped practices in ger communities. This tendency to minimize one's own community's contribution while emphasizing the shortcomings of others reflects a partial application of the halo effect, a social bias in which individuals perceive their group or setting more favourably, shaping judgment about responsibility and blame in ways that obscure structural realities.

This confluence of factors—fatalism, competing priorities, and shifting blame—contributes to the perception that people are indifferent to air pollution. Several participants mentioned that they or others had resigned to living with smoke and pollution, seeing it as an inescapable part of their reality. However, this perceived indifference is better understood as the result of complex social and structural barriers that prioritize air pollution as a less urgent issue.

4.4.4. Coping Strategies and Systemic Barriers

The normalization of air pollution highlights the broader systemic challenges faced by individuals. Participants relied on coping strategies such as mask-wearing and traditional remedies, which, while offering some protection, reflect the lack of accessible and sustainable interventions. These individual responses are shaped and constrained by systemic barriers, including financial limitations and a lack of clear, reliable information about air pollution and its mitigation. This disconnect between personal agency and structural support highlights the complexity of addressing air pollution on an individual level. While individual actions remain important, the findings underscore the importance of systems-level interventions. Effective strategies must address the root causes of air pollution and provide equitable solutions, bridging the gap between individual efforts and the systemic challenges that limit their feasibility. These findings are consistent with

research from other LMIC countries, particularly South Asia, where populations face comparable levels of chronic air pollution alongside limited infrastructure, economic hardships, and low health literacy.

At the interpersonal level, family and community networks emerged as both sources of support and contributors to emotional strain. Participants expressed deep intergenerational concerns about the long-term impacts of air pollution, emphasizing their responsibility to protect children and younger generations. The psychological burden on parents underscores the emotional toll of air pollution, which extends far beyond its physical effects. These findings align with studies indicating that families disproportionately bear the mental and emotional strain associated with environmental crises.[131]

Several factors contribute to this strain. Parents often feel inadequate in preparing their children for an uncertain future, particularly given the intangible nature of air pollution, where exposure and its damage are difficult to measure.[131] Without access to reliable information or expertise, risks can feel vague and invisible, intensifying feelings of helplessness and anxiety. Many parents rely on common beliefs or "common sense" rather than scientific evidence to assess the impact of air pollution, struggling to gauge how much pollution their children are exposed to or its immediate effects. The inability to see, measure, or avoid air pollution makes the issue feel overwhelming and insurmountable.[132] This uncertainty, coupled with the prevalence of misinformation, exacerbates a pervasive sense of dread.

The absence of accessible knowledge about mitigation strategies within familial and community networks further underscores a critical gap in public health interventions. Without clear guidance, many families feel unequipped to address exposure risks for their children, leaving them

vulnerable to both the immediate and long-term impacts of air pollution. Participants emphasized the urgent need for targeted, community-based education and outreach programs to bridge these gaps and provide households with practical and actionable solutions.

Critical gaps exist in healthcare and education systems at the organizational level. Participants describe overcrowded hospitals, limited expertise in treating pollution-related illnesses, and the economic burdens of healthcare access, highlighting systemic inadequacies. These challenges are particularly acute in low-income areas, where financial constraints exacerbate disparities in healthcare access.[115] The reliance on temporary solutions, such as air purifiers and masks, underscores the urgent need for sustainable interventions that address root causes rather than symptoms.

Addressing these healthcare challenges requires targeted efforts to improve health literacy, which is pivotal in equipping individuals with the knowledge and agency to navigate exposure risks. Improving health literacy has been shown to enhance health outcomes by empowering individuals better to understand the impact of air pollution on their health.[133,134] Higher health literacy enables individuals to navigate the healthcare system more effectively, comprehend treatment options, and communicate confidently with healthcare providers. This improves patient outcomes and eases the burden on the healthcare system by encouraging prevention and early intervention.[135] Additionally, improving health literacy can help mitigate helplessness and anxiety, fostering a sense of control and resilience among affected populations.

However, the effectiveness of health literacy initiatives depends on addressing significant disparities in education and information dissemination. Participants, particularly in ger areas, relied on informal sources, traditional practices, or what made sense. This educational gap limits

informed decision-making and reinforced systemic inequities, leaving vulnerable populations with fewer resources to mitigate exposure risks. These findings align with existing literature, highlighting the role of education in facilitating collective action and the need for targeted interventions to address knowledge gaps in the public.[136,137]

Improving access to reliable information and addressing educational disparities are essential in tackling the organizational-level challenges of air pollution. Community-based education and outreach programs can equip individuals with the knowledge and tools to make informed decisions and proactively protect their health. Additionally, leveraging technology for public health monitoring and education initiatives will foster greater accountability in monitoring individual exposure and reducing contributions to air pollution. These efforts must be accompanied by structural reforms in healthcare and education systems to ensure sustainable and equitable solutions that address the root causes of air pollution and its far-reaching impacts.

At the community level, the findings highlight the interplay between socioeconomic inequities and public skepticism. Most participants reported relying on visual cues rather than technological or scientific measurements to assess air pollution levels. Participants' accounts of worsening air quality in areas near ger areas underscore Ulaanbaatar's unequal distribution of environmental burdens.

Two specific policies were of particular concern. The first was the 2019 raw coal ban, which prohibited the use of raw coal in most areas of Ulaanbaatar. The general perception among participants was that it had not improved air quality, as many relied on visual cues and reported no observable changes. The second component of this policy was the introduction of briquette coals, which were subsidized to make them comparable in price to raw coal.[138] While most households

transitioned to briquette coals for heating and cooking, some participants admitted to continued use of raw coal, and instances of tire burning were mentioned second-hand. However, these cases were reportedly minimal.

Research on briquette coals shows mixed results. While they are associated with increased efficiency and reductions in emissions and fly ash, they have also been linked to increased PM10 emissions and heightened risks of carbon monoxide poisoning.[108,124] This perceived ineffectiveness extends beyond air quality improvements to public health outcomes, with participants noting a rise in carbon monoxide poisoning within their communities. Research supports these observations, showing an increase in carbon monoxide poisoning rates from 7.2 and 6.4 per 100,000 person-years in the two 12-month periods before the coal ban to 38.9, 42.0, and 40.1 per 100,000 in the three 12-month periods after its implementation.[108]

Perceptions of the briquette policy were mixed. Many expressed doubts about its effectiveness and safety over time. Concerns about the content and quality of the briquettes, including speculation about possible health effects, reflected a broader climate of uncertainty and mistrust. Together, these findings highlight a disconnect between policy goals and public perceptions. The government must address public concerns about the source and chemical composition of briquette coals. Clear and targeted education programs are essential, focusing on proper usage and ventilation techniques to mitigate risks like carbon monoxide poisoning.[108] Furthermore, future initiatives should transition from coal-dependent programs toward innovative community-based technological solutions, such as the CHIP program, which has shown promise.[74]

The success of the raw coal ban will depend on the efficacy and efficiency of its implementation, as well as the availability, accessibility, and trust in alternative solutions such as briquette coals,

and the socio-cultural acceptance of these alternatives. Additionally, unintended negative consequences must be carefully considered, including health risks associated with improper use and the loss of economic opportunities.[68] To address these challenges, the government must prioritize transparency and actively involve communities in decision-making.

At the policy level, significant shortcomings persist in addressing air pollution as a systemic challenge. Participants expressed widespread mistrust in government initiatives, often citing corruption, mismanagement, and a disconnect between policy objectives and public needs. A common concern was the government's failure to address the financial and social pressures driving the expansion of the ger areas, which significantly contribute to air pollution. This underscores the interconnected nature of environmental and socioeconomic challenges, highlighting the need for comprehensive, systemic solutions.

Participants highlighted issues such as briquette coal, insufficient public education, inadequate healthcare systems, and the lack of viable alternatives. These concerns illustrate how narrowly targeted interventions can generate unintended consequences. For example, while briquette coal aimed to reduce visible smoke, participants noted new issues, including health risks and financial burdens, which deepened public mistrust and reduced engagement. These findings underscore the urgent need for community-based participatory approaches that prioritize transparency, equity, and local input at every stage of policy design and implementation.

Policy efforts must focus on rebuilding public trust and fostering interdisciplinary and multi-sectoral collaboration. Transparency and accountability are essential to restoring trust, requiring policymakers to communicate decisions, address practical concerns, and integrate community feedback throughout the policy process. Adopting an "open data" approach,[139] where data driving

policy decisions is publicly accessible, can further enhance transparency, build public confidence, and ensure accountability. At the same time, effective policies demand collaboration among local communities, academics, NGOs, and grassroots organizations to address the interconnected social, economic, and environmental dimensions of air pollution. By incorporating diverse perspectives and leveraging expertise across disciplines, policies can deliver equitable, sustainable, and inclusive solutions that meet the needs of all stakeholders while fostering a culture of cooperation and shared responsibility.

4.4.5. Air pollution is a Wicked Problem in Ulaanbaatar

Air pollution in Ulaanbaatar exemplifies a wicked problem due to its multi-dimensional complexity, stakeholders' diverse and often conflicting priorities, and the inherent uncertainty surrounding effective solutions. Wicked problems resist straightforward resolutions because they involve interconnected factors that span environmental, social, economic, and political domains. These factors interact in ways that create feedback loops, trade-offs, and unintended consequences, making it nearly impossible to address one aspect without exacerbating another.[140,141]

The systemic nature of Ulaanbaatar's air pollution is compounded by the city's geographic, economic, political, and social context. Its valley location amplifies pollution retention while expanding ger areas, which are driven by socioeconomic inequities and rural-to-urban migration, adding complexity to the problem. Stakeholders, from residents in the ger areas to policymakers and international organizations, often operate with conflicting priorities: survival needs versus long-term environmental sustainability and economic accessibility versus health outcomes. This misalignment contributes to mistrust and undermines collective action.

Efforts to mitigate air pollution are further hindered by uncertainty surrounding the root causes and the effectiveness of potential solutions. Policies such as the coal ban demonstrate how addressing one element of the problem can lead to unintended consequences, including economic burdens on vulnerable populations and heightened risk of carbon monoxide poisoning associated with briquette use. These trade-offs reflect the dynamic and evolving nature of wicked problems, where solutions must constantly adapt to changing circumstances and emerging challenges.[142,143]

Addressing air pollution in Ulaanbaatar requires more than technical fixes; it demands a collaborative, interdisciplinary approach that incorporates diverse perspectives and navigates the intricate web of interconnected factors. The problem cannot be isolated from broader systemic issues such as urban planning deficiencies, governance challenges, and socioeconomic disparities. As such, air pollution in Ulaanbaatar epitomizes the defining characteristics of a wicked problem—complex, multifaceted, and resistant to resolution through linear, one-dimensional solutions.

4.4.6. Air Pollution as a Shared Transboundary Challenge

The challenges documented in Ulaanbaatar reflect broader patterns observed in LMICs, particularly in South Asia, where urban centers face similarly high levels of chronic air pollution. These contexts share key structural characteristics: rapid urbanization, deep-rooted socioeconomic inequities, and limited public trust in institutions. In cities such as Delhi, Dhaka, and Lahore, these dynamics contribute to persistent air pollution, as well as how communities experience and respond to its impacts. These structural similarities suggest that although air pollution is experienced within specific local contexts, it is driven by shared systemic challenges that transcend national borders.

These similarities are reflected in how individuals and communities adapt and cope with air pollution across different settings. In India, Chhabra et al. (2024) found that caregivers adopted coping measures, such as limiting outdoor exposure and encouraging mask use, to protect children from the health impacts of air pollution. These behaviours closely parallel those reported by participants in Ulaanbaatar.[144] In both contexts, participants emphasized not only the limitations of individual actions but also the need for broader systemic change. As part of their accounts, caregivers identified the need for increased public awareness, integration of environmental health into medical education, and stronger leadership from the health sector in addressing air pollution. In the short term, these findings highlight the need to enhance the capacity of health systems to address pollution-related health concerns, particularly among vulnerable populations. Over the long term, participants' calls for systemic reforms suggest a shared understanding that sustainable solutions will require institutional leadership and reorientation of policy to place health at the center of environmental governance.

Emotional and psychological coping also emerged as key themes across contexts. In Lahore, Rahim (2024) reported that participants exposed to persistent smog experienced increased anxiety, irritability and mood swings, social isolation, fear of long-term effects, and disrupted daily lives.[145] These experiences closely mirror the mental health impacts described by Ulaanbaatar residents, many of whom expressed feelings of helplessness, frustration, and emotional exhaustion. Across both settings, the psychological impacts of pollution were deeply felt yet often overlooked in public health and policy responses, underscoring the need for integrated approaches that address both physical and emotional dimensions of environmental stress.

In both contexts, structural barriers to protection have also been documented across LMIC contexts. In Dhaka, Hashem et al. (2024) examined air pollution knowledge, attitudes, and practices among traffic police officers. They found that awareness and uptake of protective behaviours were closely tied to education and income levels.[146] This finding resonates with the experiences of participants in Ulaanbaatar, who described socioeconomic disparities in access to clean fuels, air quality information, and protective resources. Both contexts emphasize the importance of targeted public health communication and equitable access to preventive tools to mitigate the impact of air pollution.

These findings highlight air pollution as a complex public health issue shaped by shared structural challenges across diverse low-resource contexts. The study contributes to the current understanding by centring on lived experiences and drawing attention to parallels in coping strategies, emotional burdens, and systemic gaps across LMIC settings. This perspective strengthens the case for cross-regional collaboration, policy learning, and integrated community-informed approaches that prioritize health equity and long-term resilience.

4.4.7. Study Limitations

This study has several limitations that should be taken into account when interpreting its findings. The research included residents from several districts in Ulaanbaatar; however, participants from some districts were underrepresented. This may limit the ability to capture diverse experiences and perspectives across the city fully. Although ger areas are distributed across various districts in Ulaanbaatar, this study specifically included participants from the Bayanzurkh district due to accessibility. Consequently, while perceptions are likely similar across districts, experiences in other areas may differ.

Mongolia has experienced significant protests in recent years. Since 2022, Ulaanbaatar has been the site of numerous rallies and demonstrations against allegations of corruption, rising costs, and government mismanagement.[147] Given that this study relied on self-reported data, participants' responses may have been influenced by recall bias,[148] social desirability bias,[149] or personal perceptions shaped by media coverage of these events. Additionally, interviews were conducted in English and Mongolian, with bilingual translators facilitating communication. Despite efforts to ensure accuracy through real-time back-translation, subtle nuances or meanings may have been lost or altered during the translation process.[150]

4.5. Conclusion

This study sheds light on the complex and multifaceted challenges of air pollution in Ulaanbaatar, Mongolia, highlighting its profound impacts on individuals, households, and communities, as well as the systemic barriers that hinder effective mitigation efforts. By leveraging the Social-Ecological Model, the findings highlight how air pollution intersects with socioeconomic inequities, urban planning deficiencies, healthcare inadequacies, and governance failures, underscoring its complexity as a complex and multifaceted problem.

Participants' narratives highlight that air pollution is not merely an environmental issue, but a pervasive concern for public health and social justice. The study underscores the urgent need for evidence-based, transparent, and community-driven policies, ensuring that interventions address the lived realities of those most affected. Structural reforms must address systemic inequities, improve healthcare access, and rebuild public trust in governance. Collaborative and interdisciplinary approaches that actively engage communities, academics, and other stakeholders are essential to designing equitable, sustainable, and inclusive solutions. Empowering residents

with accessible information, resources, and platforms for participation can foster collective action and resilience at the grassroots level.

Future studies should incorporate a broader range of stakeholders, including policymakers, healthcare providers, and industry representatives, to gain a deeper understanding of the systemic factors driving air pollution and its associated impacts. While this study focused on Ulaanbaatar, similar or even more severe pollution challenges are present in other provinces, underscoring the importance of nationwide research.

Addressing air pollution in Ulaanbaatar requires a holistic, multi-level approach recognizing its interconnected challenges and evolving dynamics. Collaborative efforts that prioritize health, equity, and resilience are essential for developing sustainable solutions that meet the needs of all stakeholders.

Bridging Foreword to Manuscript 2

The second manuscript is situated at a critical bridge in this thesis. Having foregrounded lived experience and structural inequities in Paper 1, the work here asks: under those conditions, what would it actually take for real-time monitoring and early warning tools to be welcomed, trusted, and sustained, rather than ignored or abandoned. This paper draws on the same participant cohort to bring together perspectives from community members and interrogate assumptions often embedded in technology-driven interventions, including ideas about access, literacy, responsibility, and trust.

This paper performs two functions for the integrated thesis. First, it translated the qualitative insights and tensions from Paper 1 into concrete requirements for system design, communication, and governance in high-risk, low-resource settings. Second, it reframes technology acceptance as a relational and political question rather than a purely individual attitude or a set of usability outcomes. By doing so, this manuscript provides an explicit framework for assessing which technical choices in the final paper are defensible, which tradeoffs are acceptable, and how future systems should be evaluated. It prepared the reader to see the implementation work that follows not as a neutral technical exercise, but as a response to clearly articulated expectations and constraints.

5. Beyond Acceptance: Rethinking Real-Time and Early Warning System Design in High-Risk, Low-Resource Settings — A Case Study from Ulaanbaatar, Mongolia

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Overview

Real-time monitoring and machine learning-based early warning systems (RTM-EWS) are increasingly used to support public health adaptation to climate change, particularly in environments with severe air pollution. However, little is known about how such systems are perceived and adopted in low-resource, high-risk settings, especially among socially and technologically diverse populations. This study examines the perceived acceptability and intended use of a proposed RTM-EWS that was under development at the University of Waterloo at the time of the interviews, by residents of Ulaanbaatar, Mongolia, using an adapted Technology Acceptance Model (TAM).

We conducted 25 semi-structured interviews with adult residents across diverse demographic groups in Ulaanbaatar. Participants were presented with a prototype of the system and asked to reflect on its perceived usefulness, ease of use, and trustworthiness. A deductive thematic analysis approach was used, guided by the TAM constructs, and transcripts were organized to support comparative analysis across participants.

Perceived usefulness and ease of use were important, but deeper contextual factors also conditioned them. Trust emerged as a central filter shaping how other constructs were interpreted, contingent on both institutional legitimacy and data clarity. Health concerns often amplified motivation to engage, while digital comfort, education, and infrastructural constraints shaped how systems were evaluated. User archetypes suggested intersecting pathways to adoption, ranging from digitally fluent caregivers to those with structural constraints.

Technology acceptance in high-vulnerability environments is shaped by dynamic interactions between emotional urgency, social norms, and structural agency, rather than individual traits or interface design. Public health technologies must account for digital plurality, credibility, and contextual vulnerability to ensure equitable access and meaningful engagement.

Keywords

Air pollution, technology acceptance, high-risk low-resource settings, user-centred design, public health surveillance.

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5.1. Introduction

Ambient air pollution is the leading environmental cause of morbidity and mortality globally. According to the Global Burden of Disease report, air pollution is among the top risk factors contributing to disease burden, accounting for 4.2% of all disability-adjusted life years (DALYs) and 7.2 million deaths.[151] It is associated with both short and long-term health effects, including chronic respiratory diseases,[152] cardiovascular conditions,[153] and increased mortality.[99] In infants and children, early exposure can lead to perinatal complications and developmental delays with lifelong health consequences.[154,155]

The burden of air pollution is disproportionately higher in low- and middle-income countries (LMICs), where limited infrastructure, rapid urbanization, and social inequities exacerbate exposure risks.[156] An estimated 90% of pollution-related deaths occur in LMICs, highlighting significant environmental health disparities.[98] In many low-income communities, access to real-time pollution data is limited, hindering efforts to mitigate exposure or advocate for policy interventions.[157] As seen in Study 1 of this thesis, this often leads to a perception that air pollution is an insurmountable issue, fostering feelings of helplessness, especially when families are directly affected.

Ulaanbaatar, Mongolia, presents a striking case of extreme air pollution, particularly during the winter season. The city's valley location traps cold air and pollutants, a problem intensified by widespread use of solid fuels like coal and briquettes for heating and cooking.[59,105] Rapid rural-to-urban migration has led to the growth of ger areas, traditional nomadic dwellings and houses built on the city's outskirts, where residents often lack access to cleaner energy alternatives.[116,158] As a

result, winter pollution levels in Ulaanbaatar can exceed World Health Organization (WHO) guidelines by up to 80 times.[63]

Recent technological advances have enabled the development of real-time monitoring and machine learning-based early warning systems (RTM-EWS) to help individuals track and respond to their personal exposure to air pollution. These systems hold particular promise in settings like Ulaanbaatar, where pollution patterns can vary dramatically over short timescales, and where behavioural responses such as limiting outdoor activity or temporarily relocating to the countryside could mitigate short-term exposure. However, beyond technical capabilities, uptake of such systems is likely shaped by user perceptions, digital access, and trust in both data and the institutions behind them. These factors remain insufficiently understood in low-resource, high-risk environments. This study investigates these behavioural and perceptual dimensions to explore what drives or hinders engagement with RTM-EWS in such contexts.

5.1.1. Proposed AI-Based Air Quality Monitoring System

Traditional air quality monitoring relies on expensive, stationary sensors that, while accurate, are limited in number due to high acquisition and maintenance costs.[38,39] These limitations leave significant spatial and temporal gaps in coverage, especially in LMICs. To address these limitations, the proposed RTM-EWS uses a network of low-cost Internet of Things (IoT) sensors to deliver hyperlocal, real-time air quality data. Integrated with machine learning, the system includes three components (Study 3 of this thesis): (i) real-time monitoring of personal exposure through a distributed sensor network; (ii) a deep-learning model that estimates air quality in areas without sensor coverage (together comprising the RTM); and (iii) a forecasting module that

predicts short-term pollution trends (comprising the EWS). Together, these elements aim to equip residents with timely, actionable information that supports health-protective behaviours.

5.1.2. Conceptual Framework and Analytical Assumptions

Technology adoption is often conceptualized as a sequential process in which awareness shapes attitudes, which in turn inform intentions and behaviours. This process underpins theoretical models that explain how users evaluate and adopt new technologies.[159] Although digital health research in LMICs is growing, most of it remains focused on institutional or provider-facing tools. While mobile health applications have been explored, especially in maternal health, COVID-19 response,[160–164] and chronic disease management,[165] there is limited research on technologies that deliver time-sensitive forecasts and require intermittent, context-specific response. This highlights a gap in research on user engagement with self-directed, preventive technologies in LMICs, particularly those addressing environmental health risks, such as air pollution.

In this context, we chose the Technology Acceptance Model (TAM) as a parsimonious and minimally presumptive lens.[166,167] TAM's core relations have been empirically validated primarily in quantitative research, whereas in qualitative research it functions as a conceptual lens and set of sensitizing constructs that guide design and interpretation.[168–170] TAM foregrounds perceived usefulness and perceived ease of use, which map directly onto questions of access, design, and everyday feasibility in low resource high vulnerability settings. Compared with broader frameworks such as the Unified Theory of Acceptance and Use of Technology (UTAUT), Theory of Planned Behaviour (TPB), Health Belief Model (HBM) or Protection Motivation Theory (PMT) that may be too complicated and resource-intensive for real-world implementation despite their theoretical strengths, TAM provided enough structure to organize interview design deductive

coding, and interpretation without constraining theme development.[171–176] We use TAM as a conceptual lens, treating its constructs as sensitizing concepts rather than fixed categories. Because TAM does not foreground structural constrains, we situate it within a broader sociotechnical perspective attentive to infrastructural fit, social norms, and constrained agency, and include trust and health concerns as context specific extensions.[171]

At its core, TAM posits that two beliefs, perceived usefulness and perceived ease of use, shape users' attitudes toward technology, which in turn influence their intention to use it. Perceived ease of use also influences perceived usefulness, since systems perceived as easier to use are often seen as more beneficial.[177] Drawing on this framework, we set out the following assumptions:

A1: Attitude toward use positively affects the intention to use an air quality monitoring system.

A2: Perceived usefulness has a positive effect on attitude towards using the system.

A3: Perceived usefulness positively affects intention to use the system.

A4: Perceived ease of use positively affects attitude towards using the system.

A5: Perceived ease of use positively affects perceived usefulness of the system.

Trust is a critical determinant of technology adoption, encompassing beliefs about system accuracy, ethical design, institutional safeguards, and the credibility of the source.[178–182] These dimensions are especially important in novel systems like RTM-EWS, where users often cannot independently verify outputs and must rely on the credibility of the system and its providers. In low-resource, high-vulnerability settings, trust is further shaped by broader concerns about institutional reliability, governance failures, and systemic inaction.

This study adapts the TAM to reflect these contextual realities. While TAM traditionally emphasized perceived usefulness and ease of use as primary drivers of technology adoption, we position trust as a central construct that both influences and is influenced by perceived usefulness. Users are more likely to find a system useful if they trust its data and the institutional backing behind it. At the same time, systems that are seen as beneficial and aligned with user needs may reinforce trust.

A6: Trust has a positive effect on the perceived usefulness of the system.

Transparency in how systems present information is crucial for building user trust, particularly when handling complex data.[183] When users can easily navigate and interpret the system, they are more likely to view it as credible.[184–187] Perceived ease of use can reduce cognitive burden while enhancing trust by making the system appear transparent and user-centred. This is particularly relevant for users with low digital comfort, for whom intuitive design helps reduce anxiety and builds confidence.[188,189]

A7: Perceived ease of use positively affects trust.

Motivation to adopt RTM-EWS may be stronger among individuals with heightened health concerns or caregiving responsibilities. These individuals may be more responsive to tools that promise protection or risk reduction.[190,191] In such cases, the influence of perceived usefulness, trust, and attitude on adoption may be amplified.

A8: Among individuals with high concern about the health impacts of air pollution, the links from perceived usefulness, attitude toward use, and trust to intention to use are stronger. Here moderation is conceptual and does not denote a statistical interaction.

Figure 1 presents the conceptual framework underpinning this study.

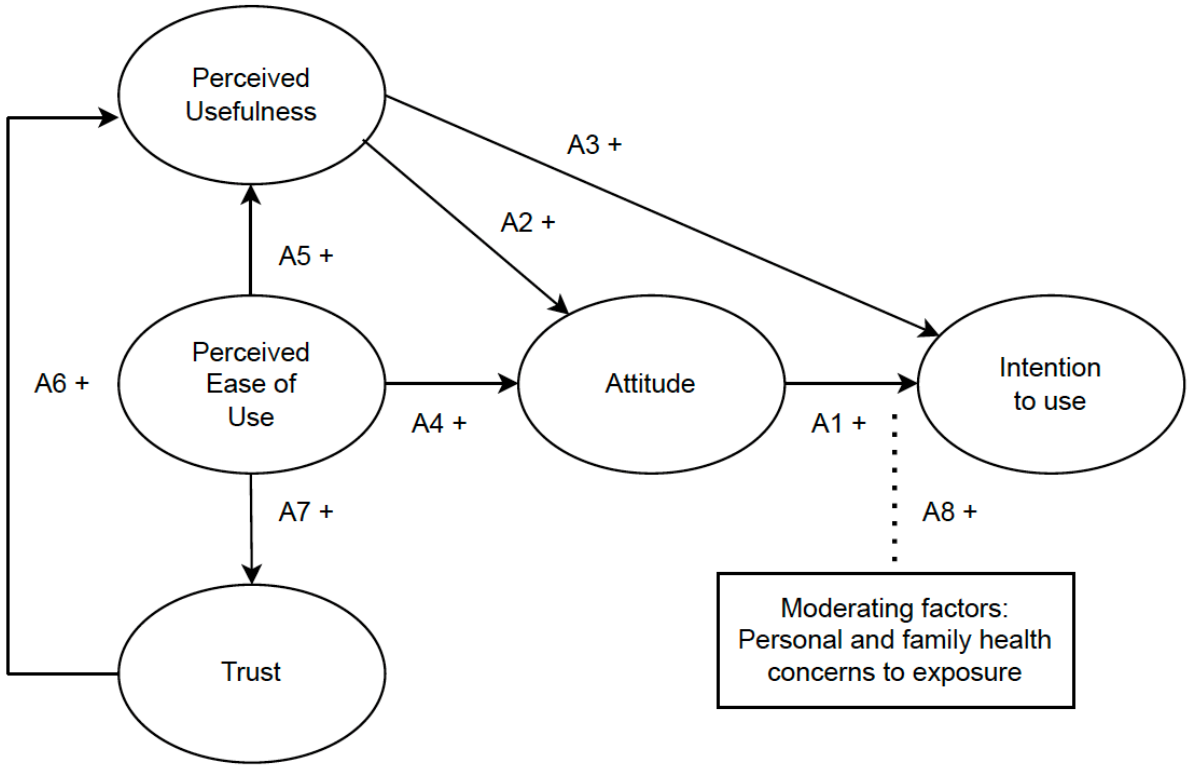


Figure 2. Adapted conceptual framework based on the Technology Acceptance Model (TAM), illustrating assumed predictors of intention to use a proposed air quality real-time monitoring and early warning system (RTM EWS). Dotted lines indicate a moderating influence on the paths to intention. These moderators are conceptual and were not statistically tested.

5.2. Methods

5.2.1. Interview Guide and Design

This study draws on qualitative data collected as part of a broader project examining perceptions, behaviours, and systemic challenges related to air pollution exposure in Ulaanbaatar, Mongolia (Study 1). The interview guide, developed in collaboration with local community partners Breathe Mongolia – Clean Air Coalition (BM), included a subset of questions specifically focused on

technology use and perceptions. These questions were tailored to reflect the local context and participants' levels of digital comfort. Ethics approval was granted by the University of Waterloo Research Ethics (ORE Project ID #45755).

5.2.2. Participant Recruitment

Participants were recruited from across all nine districts of Ulaanbaatar and one ger area to ensure diversity in age, gender, education, occupation, income level, environmental settings, household size, and number of children. Two recruitment strategies were used: in urban areas, participants were recruited online through social media platforms managed by UNICEF and BM; in the ger area, recruitment was conducted in person via UNICEF's Early Childhood Development Center in Bayanzurkh, which provided direct access to community members.[§] To ensure representativeness, the recruitment strategy accounted for gender balance and included variation in age, education, income level, and residential districts to capture a broad range of perspectives and experiences.

5.2.3. Data Collection and Analysis

This study draws on the same set of interviews described in Study 1. All interviews were conducted as integrated conversations that included both experiential questions related to air pollution and questions focused on the use, interpretation, and trust of monitoring technologies. Data collection

[§] Ger districts are administratively and geographically part of Ulaanbaatar. However, policy and planning discourse have often framed them as peripheral or separate, contributing to inequitable access and service delivery.[118] In this study, this distinction between "ger" and "non-ger" districts is used solely to clarify recruitment strategies, while recognizing that both are integral to the urban fabric of the city.

took place between January and February 2024 using semi-structured, in-depth interviews. Open-ended questions were structured to elicit insights aligned with core constructs from the adapted TAM. Table 1 summarizes each construct and its corresponding interview focus.

Table 2. Interview constructs aligned with the adapted TAM and their operational focus

Construct	**Interview focus**
Perceived usefulness	How participants perceived the usefulness of real-time and temporally forecasted air quality information in informing daily behaviours, health-related decisions, and environmental awareness.
Perceived ease of use	Preference for system design, delivery platforms, and integration with existing technologies to enhance ease of use and accessibility.
Trust	Determinants of trust in the system, including perceived credibility of data sources, transparency in communication, and institutional affiliation
Attitude towards use	General feelings towards using such a system, including enthusiasm, skepticism, and emotional response related to perceived value or limitations.
Moderating factors	Personal and contextual variables (e.g., presence of young children, caregiving responsibilities, chronic health conditions, digital comfort, or income level) that might influence how individuals interpret and respond to air quality information.

Interviews were conducted at the UNICEF Mongolia and People in Need (PIN) country offices, as well as the UNICEF Early Childhood Development Center in the Bayanzurkh ger district. The interview team consisted of English-speaking researchers supported by a bilingual Mongolian translator. Questions were posed in English and translated into Mongolian; participants' responses

were recorded in either language, with live back-translation provided to ensure clarity and mutual understanding.[119,120] All interviews were audio-recorded and transcribed using Otter.ai®. The transcripts were reviewed for accuracy and uploaded to NVivo 15 (Lumivero LLC, Denver, CO, United States) for thematic coding and analysis.

A deductive thematic analysis approach was used to structure interpretation around the TAM framework.[192] Coding categories were developed *a priori* based on TAM constructs, and transcripts were then thematically organized to enable comparative analysis across participants. Analytical rigour was supported through iterative engagement with the data, whereby preliminary codes and emerging themes were revisited and refined to ensure consistency and relevance. Findings were grounded in participant narratives and aligned with established constructs to enhance interpretive clarity and conceptual coherence.

5.3. Results

A total of 25 participants (64% female; n = 16) were included in the study. Ages ranged from 24 to 64 years (mean = 40.7; SD = 11.6). Educational attainment varied widely, with the most commonly reported levels being high school (20%, n = 5), bachelor's degree (16%, n = 4), college diploma (16%, n = 4), and master's degree (15%, n = 4). Additional qualifications included an MBA (n = 1), post-residency medical training (n = 1), and various forms of technical or incomplete post-secondary education (n = 6). One participant reported having completed up to Grade 3.

Monthly household income also varied considerably. Most participants reported earning between 1 and 2 million MNT (36%, n = 9), while 24% (n = 6) earned less than 1 million MNT. Smaller subsets reported incomes of 2 and 3 million MNT (n = 2), 3 and 4 million MNT (n = 2), 4-5 million MNT (n = 1), and more than 5 million MNT (n = 1). One participant declined to report income.

This sample size was selected based on existing recommendations for achieving thematic saturation in qualitative research, which suggests that 20 to 30 participants are sufficient for capturing diverse perspectives in heterogeneous populations.[123] Detailed participants' information is provided in Appendix 1.

5.3.1. Current Practices in Technology Use for Air Quality Monitoring

Participants reported varying levels of engagement with technology to track exposure to air pollution. Some participants relied on visual cues, such as haze, smell, or visibility, rather than digital tools to assess air quality [P13, P17, P19]. Among those who used technology, some participants reported using online tools but were unsure of the specific tools they used [P7, P24]. Several reported relying on generic search engine-based services (e.g., Google, Bing, or Outlook) that display air quality indices for multiple global cities [P1, P8, P10]. Others relied on systems built by local public and non-profit agencies [P4, P5, P11].

A significant portion of participants had never engaged with digital tools to track air pollution or were unaware such resources existed [P2, P3, P6, P7, P9, P12, P13, P15, P18, P19, P21, P22, P23, P25], while some from these participants did not access these tools themselves but relied on family members to relay updates on local environmental conditions, often without knowing which tools were being used [P14, P20]. Many of these participants relied on second-hand transmission of information related to air pollution through television [P15, P16, P17, P21, P22, P23] and social media, almost exclusively Facebook [P17, P21]. These varied sources reflect both infrastructural constraints and the role of social intermediaries in shaping access to environmental information, particularly in low-resource environments.

5.3.2. Perceived Usefulness of Real-Time Monitoring

Participants' perceptions of the usefulness of the real-time air pollution monitoring system varied, depending on how such a system intersected with their daily decision-making, health priorities, and access to reliable information. The following four themes capture how real-time monitoring was perceived as useful, not useful, or conditionally useful across different contexts.

5.3.2.1. Guiding Daily Behavioural Decisions

Participants frequently cited the potential of real-time monitoring systems to inform everyday decisions, especially those related to exposure avoidance. These included opening or closing windows [P1], letting children play outside [P13, P15] using masks [P6, P7, P8, P23] or changing commuting patterns [P8, P13, P17, P24, P25]. The utility of the data was directly tied to its ability to support immediate and practical actions that could be embedded into routines. Several participants acknowledged that while avoiding polluted environments was not always feasible due to employment demands, housing limitations, or caring responsibilities, access to accurate air quality information enabled them to make more informed decisions. These participants saw real-time monitoring as empowering, not because it eliminated the risk, but because it offered a sense of control in an otherwise uncontrollable environment. As one participant explained,

"I [won't] go to the polluted area[s] as much. If [I] know that the air around [my] home is free of pollution, my child will be fine to go outside and breathe the air." [P13].

Another added,

"It would most likely help me decide whether I should drive if the pollution is really bad, or whether I need to use my smoke masks [or] to open the windows or not" [P1].

This suggests a high perceived usefulness when data was timely, localized, and actionable, even among participants who lacked structural power to effect long-term environmental changes.

5.3.2.2. Understanding Health Risks

Participants consistently emphasized that the usefulness of the real-time data depended on its ability to explain tangible health impacts, particularly respiratory symptoms, cancer-related concerns, and long-term developmental impacts on children. Many indicated that its value would be enhanced if paired with actionable recommendations for minimizing harm [P5, P6, P7, P8, P9, P10, P15, P17, P18, P19, P20, P21, P23, P25]. As such, real-time data was often not viewed as a catalyst for major behavioural or structural change, but rather as a tool for validating health experiences and supporting long-term planning.

"Will I change my daily life? That is quite difficult. I think I want to know about how air pollution is affecting my and my children's health such as which organ system is affected by it. And in order to prevent it what measures should I take? Of course, I will try to avoid and try not to go places with more air pollution" [P21].

Another participant added that information for the sake of providing information is not helpful.

"Any information about the toxins air pollution, the type of chemicals, I will take. Because I need to know toxic substances and need to know how to protect myself. But is there any need to give information [if] the citizens can't be protected? There is no need to give information [of it] poisoning us" [P19]

Others similarly expressed a desire for data that could bridge scientific evidence with their lived realities. One participant explained:

"There is a lot of dust and construction materials polluting the air and [we] don't know how it affects human health. If it is proven by research that the air pollution [from] building materials actually affects human health, then we will change the place where we live" [P8].

In this way, perceived usefulness was closely tied to the process of meaning-making. Participants did not merely want numbers; they wanted to understand what those numbers meant for their health and well-being. Many linked real-time data, which has the potential to improve health literacy and facilitate proactive planning. As one expressed:

"[In other tools] there were numbers here and there, and the most polluted area was indicated in red or something. I don't know what to do now, how can we protect ourselves?... Don't exactly know what to do." [P7].

This theme highlights the informational utility of real-time monitoring as a means of bridging scientific knowledge with both immediate and long-term health decision-making.

5.3.2.3. Contextual and Actionable Usefulness

For several participants, the usefulness of the system hinged not only on what data was presented, but where and how it was generated. Participants emphasized the need for hyperlocal information that aligned with their actual exposure rather than relying on generalized, averaged, or distant monitoring stations [P4, P10, P11, P12, P13, P16, P24]. As one participant noted,

"[Current] tools are just based on monitoring stations in certain locations…it's not actually representative of the real air quality we are living. The stations are far from roads or serious pollution sources. I don't rely on it" [P11].

This disconnect between lived experience and system output highlighted participants' desire for future tools that provide more precise, location-specific data aligned with their daily exposure patterns. Participants also envisioned monitoring systems that could help identify the sources of pollution and serve as tools for broader accountability and transparency.

"I want to know what exactly is [in] the smoke, why it's there, and who is causing it… and how to take action against those people" [P10].

In this framing, real-time data systems were imagined not only as health resources but also as instruments for advocacy and structural change. Together, these perspectives reflect a future-oriented understanding of usefulness that prioritizes spatial precision, interpretability, and potential to influence both personal decision-making and broader policy responses.

5.3.2.4. Limitations of Usefulness in Low-Agency Contexts

A significant number of participants described feeling powerless or uncertain about how to use air quality information. Even when they trusted the accuracy of the data, many questioned its utility in the absence of clear alternatives [P4, P6, P9, P12, P16, P17, P19, P20, P24]. For some, the information reinforced a sense of resignation. As one participant put it,

"Even if there is air pollution, life goes on…There is very little I can do to reduce this pollution" [P4].

Several participants echoed this sense of limited control.

"There is no point in getting this information because the environment is already like this… people will just blame the politicians and nothing else" [P9].

"Even though the air pollution is terrible here, I won't be able to move away… I'll just know that it is terrible in this area" [P16].

In these accounts, real-time data confirmed the scale of the problem but offered no meaningful pathway for response. Some also reflected on the emotional toll of receiving such information [P17, P20]. One participant shared, *"I'll be really sad and think about what to do, who can help [me]?* [P20], highlighting the psychological burden of knowing the risks without having the means to act. In this sense, real-time monitoring was perceived as informative but not transformative. Participants acknowledged its awareness-raising potential, but in the absence of structural reforms, public services, or access to cleaner environments, many felt unable to translate that knowledge into action. For some, the cognitive dissonance of knowing the air was harmful while remaining exposed led to a complete disengagement. These insights highlight a core limitation of perceived usefulness in low-agency environments, where information may exist, but structural or social barriers prevent people from acting upon it.

5.3.3. Perceived Usefulness of Forecasting Systems

In contrast to real-time monitoring, forecasting tools were viewed through the lens of anticipatory planning and long-term coping. While most participants recognized their theoretical value, perceived usefulness varied depending on individual agency, caregiving roles, and emotional response. These insights differed from views on real-time systems, reflecting a shift from immediate decision-making to proactive preparation and psychological readiness.

5.3.3.1. Planning and Proactive Action

Several participants found forecasting systems potentially useful, especially for proactive planning. Forecasts were viewed as beneficial for those with caregiving responsibilities or flexible routines, offering an opportunity to take preventive actions, such as rescheduling plans or temporarily relocating vulnerable family members [P1, P3, P4, P7, P8, P10, P13, P17, P19, P21, P23, P24, P25]. As one participant noted:

"If I know that [pollution] will be really bad, I may choose to send [my wife] to the countryside" [P1].

Others echoed similar sentiments, such as taking protective measures to protect their children [P23] or adapting spousal work schedules to avoid peak pollution periods [P21]. These responses suggest that forecasts were not merely information but rather seen as tools to regain agency. Participants appreciated the opportunity to act proactively, rather than reactively, after exposure had already occurred.

5.3.3.2. Symbolic Usefulness and Structural Inflexibility

For some participants, the capacity to act on forecast information was limited. Inflexible work schedules, immovable housing situations, and financial limitations curtailed their ability to respond [P1, P5, P6, P10, P12, P16]. While they see the logic in forecasting, they experienced it more as symbolic knowledge than as a tool for change. As they explained,

"Even if I know [that] the air pollution will be really bad a month from now, I wouldn't be able to move outside the city anyway" [P1].

"Since I can't move away, there is nothing much to do. I will just hear about it and that is it" [P16].

These accounts suggest that while forecasting systems offer temporal foresight, their usefulness remains conditionally dependent not only on data availability but also on people's structural capacity to act on the data.

5.3.3.3. Emotional Weight of Anticipated Risk

In contrast to real-time systems, which participants often framed as validating or informative, forecasts introduced emotional complexity. Knowing poor air quality lay ahead prompted feelings of sadness, helplessness, or anticipatory stress [P9, P19, P20, P22].

"There won't be any changes, one participant remarked. *"All [it will] do is upset [me]… such negative information is not necessary"* [P9].

Others described feelings of pressure and emotional burden:

"I will stock up on food… be under pressure… just by knowing" [P19].

For some, forecasting data triggered not action but worry, reinforcing a sense of vulnerability and limited control [P20]. While real-time systems were often perceived as pragmatic tools for day-to-day coping, forecasting tools were more likely to heighten emotional distress by drawing attention to future risks participants felt powerless to avoid. This distinction highlights the temporal dimension of perceived usefulness: real-time data helped respond, whereas forecast data forced them to anticipate without necessarily being able to act, shifting the emotional weight from validation to foreboding.

This theme illustrated that more information is not always welcomed. In contexts where few mitigation options exist, predictive systems may unintentionally deepen emotional strain, highlighting a key limitation of perceived usefulness in constrained settings.

5.3.4. Perceived Ease of Use

This section explored participants' perceptions of the ease or difficulty of engaging with the RTM-EWS, including both real-time monitoring and forecast tools. Ease of use was shaped not only by interface design but also by integration into daily routines, accessibility across diverse platforms, and the format of the information.

5.3.4.1. Integration with Existing Digital Routines and Equitable Access

Participants emphasized that an effective system should not rely solely on one platform. Instead, they should disseminate alerts and updates across multiple digital channels to reach a broader and more diverse user base. They also expressed a preference for platforms already embedded in their digital routines, particularly through social media (almost exclusively Facebook) [P1, P5, P7, P8, P9, P10, P11, P12, P13, P15, P16, P17, P19, P20, P24, P25], SMS [P10, P12, P23], and weather or dedicated applications [P3, P4, P11]. These channels were described as intuitive, familiar, and requiring minimal effort to access or understand. Many noted that air quality information should be delivered through applications they already use, thereby avoiding the burden of learning or remembering a new platform.

"It's like when we check the weather to decide how to dress or when to go out. If air quality could be displayed in real-time with the forecast, it would be useful in the same way. If I have to go to a different application or website to check, [or] it is complicated, [I will] not [use] that" [P11].

Participants noted that if accessing data involved too many steps or unfamiliar platforms, they were unlikely to engage. They preferred systems that pushed information to them rather than requiring them to seek it out, suggesting that ease of use was tied to both accessibility and automation.

Ease of use was also discussed in terms of accessibility and inclusivity. Participants highlighted the importance of leveraging existing non-digital tools, such as television broadcasts [P5, P8, P9, P13, P14, P15, P17, P19, P21, P22, P24] and large digital billboards already installed across the city [P1, P4, P5], and non-digital public posters [P5, P10]. This was especially critical for older adults, people with inconsistent internet access, or those less engaged with mobile technology. In this way, participants framed usability not only as an interface issue, but also as a question of equitable access across various digital environments.

5.3.4.2. Importance of Visual Simplicity and Digestibility

Ease of use was also closely tied to how information would be presented. Participants emphasized that a future air pollution monitoring system should prioritize intuitive, visual formats such as clear symbols, colour coding, or simple graphics or language to make information easily understandable at a glance [P8, P11, P17]. These formats were seen as especially important for individuals with limited time, technical literacy, or familiarity with environmental data. Participants frequently referenced familiar tools, such as weather applications, as design models, suggesting that new systems would be more engaging if they mirrored interfaces that users already trust and understand.

5.3.4.3. Role of Trust in Design and Deployment of Future Systems

Trust emerged as a critical factor in influencing participants' willingness to engage with the RTM-EWS. Participants consistently emphasized that the source of the information, their credibility, and whether actions matched words all shaped their trust and, in turn, their likelihood of using the system.

5.3.4.4. Trust in Professional Expertise Over Institutional Labels

Participants emphasized that trust is earned by expertise, not affiliation. Whether information came from the government, NGOs, universities, or international researchers mattered less than whether the people behind the data were seen as genuine, professional, and scientifically grounded. Participants expressed skepticism towards institutions without demonstrable technical credibility.

Mistrust of government actors was a recurrent theme. Participants described how empty promises, a lack of action, inconsistent communication, and the absence of visible results, despite promises, had eroded faith in official institutions. Thus, people expressed doubt in sanctioned interventions or data [P6, P10, P11]. Some participants also referenced information overload and confusion, exacerbated by social media, which made it difficult to distinguish truth from misinformation.

Participants favoured NGOs, researchers, scientists, and health professionals who are experts in the field [P2, P6, P7, P11, P15, P19, P21, P25]. This emphasis on non-state actors suggests a strong desire for apolitical, evidence-based communication, free from domestic political entanglements [P13, P15, P17], while also focusing on explaining the origin, methodology, and implications of the statistics. They also value clear explanations of data origin, methodology, and implications, as well as visible and consistent actions that align with reported information.

5.3.5. Attitude Towards Use

Individual assessments of system features did not solely determine attitudes toward system use but were often co-constructed through participants' social environments. Several participants reflected on how their willingness to engage with digital tools was shaped by the behaviours, priorities, and reactions of those around them. [P6, P9, P21, P24]. For example, one participant explained,

"If I receive [alerts] 7 days earlier, and others don't care about it, I don't care either." [P6]

This suggested that intention to use was not formed in isolation but was embedded in shared norms and perceptions of collective urgency. When environmental tools or warnings were socially dismissed or deprioritized, their relevance could diminish even among individuals who might otherwise be affected.

Similarly, some participants reflected on their engagement with air quality information as a form of shared social responsibility, emphasizing collective exposure and mutual accountability:

"It is not only me, [but also] everyone in the city. So, we all have to fight, don't we?" [P9]

"When I hear the conversation of people from the city. [They] seem to be really stressed." [P21]

These reflections highlight that the perceived value of digital tools was amplified when framed as part of a broader communal effort rather than an individual burden. In such cases, motivation was derived not only from system attributes but also from a recognition of shared struggle and interdependence. These accounts suggest that attitudes towards technology adoption were not only rooted in rational cost-benefit appraisal, but also in emotion resonance, social reinforcement, and communal framing. Future system design could leverage community norms, shared language, and peer-based diffusion strategies to foster collective buy-in.

5.3.6. Moderating Factors

Participants' preferences for system design and delivery reflected not just individual traits such as age, comfort, or education in isolation, but composite digital engagement profiles shaped by their intersection. Rather than treating these as discrete variables, our findings suggest they converge to form user archetypes, each with distinct needs, expectations, and thresholds for trust and usability.

Health concerns emerged as a cross-cutting moderator that shaped participants' overall engagement with the system. Participants who expressed heightened anxiety about air pollution, especially caregivers of young children, older adults, or those with preexisting chronic health conditions, viewed air quality information as essential rather than optional. As participants with children explained,

"If I get proper information about the air pollution, I can protect myself and my children as well. It is much better to know what to do to protect myself and my children when we go outside. I will do my best to protect ourselves." [P15]

"By knowing, [I] will think about what steps I [could] take in the future right? Get [an] idea on how to protect my child from toxic exposure in [the] quickest way." [P17]

"I want to know about how the air pollution is affecting my and my children's health [like] which organs [are] affected by it? And in order to prevent it, what measures should I take?" [P21]

These reflections illustrate that health risk perceptions amplified participants' willingness to engage with unfamiliar technologies and lowered their threshold for perceived usefulness. In these

cases, even participants with limited digital familiarity indicated that they would take proactive steps to access and act on air quality alerts if it could help protect their families.

Beyond health, technology adoption was also shaped by a blend of age, education, and digital comfort. Some younger participants with higher education and high digital comfort preferred integrated platforms that offered real-time, hyperlocal data with references or links to source material. For these participants, ease of use included automation, multi-platform compatibility, and transparent methodology. Digital comfort and trust calibration also interacted with education. Participants with university-level education were more likely to request technical clarity and express interest in system design, suggesting trust was contingent on perceived scientific legitimacy:

"I'm just curious about how reliable the forecast would be. Would it be based on enough data? If the team who has developed that technology could explain what [forecasts] are based on. Then I will consider [using] it." [P11]

In contrast, those with lower formal education emphasized clarity, familiarity, and whether someone they trusted could explain the information. For these participants, communicative accessibility serves as a key pathway to establishing epistemic transparency, highlighting that trust could be rooted as much in clear and relatable communication as in technical detail.

Discomfort with digital tools was not confined to older adults. While some older participants emphasized the value of television or SMS as accessible and familiar formats, many, including those over 50 years of age, also reported regular use of Facebook for news and communication.

Their preference for a streamlined, low-interaction format was often less about digital literacy and more about information fatigue, network bandwidth, or a desire for passive consumption.

These findings suggest that technology acceptance in this context is shaped less by isolated demographic traits and more by dynamic intersections of health urgency, digital fluency, and social embeddedness. Health concerns often served as a catalytic force, intensifying digital engagement even among those with limited familiarity. At the same time, trust was calibrated through different channels; some participants emphasized scientific rigour, while for others, trust was channelled through clarity and relational credibility. These insights underscore the importance of designing for digital plurality, recognizing not just who users are, but how they experience and navigate risk, technology, and social support.

To synthesize these intersecting pathways of digital engagement and health motivation, we developed five user archetypes that reflect recurring patterns in how participants approached trust, usability, and system relevance. These archetypes are not rigid classifications; rather, these are heuristic groupings that illustrate how digital capacity, health urgency, and structural constraints combine in practice to shape technology engagement. The table below summarizes the key traits of each archetype and their corresponding system design needs.

Table 3. Summary of five user types based on digital fluency, health motivation, and trust, with corresponding system design considerations.

User archetype	Characteristics	System Needs
Digitally fluent caregiver	Higher education, higher digital comfort, strong health motivation (e.g., parents, caregivers)	Multi-platform access, hyperlocal and real-time data, actionable alerts, and reference links. Prioritize user control.
Health-motivated but digitally constrained	High health concern, but limited digital comfort or literacy. May rely on routine formats, such as SMS or television. Often older adults or low-income caregivers	Prioritize simple, familiar delivery (TV, SMS), health-relevant alerts, and minimal interaction. Ensure information clarity and trust cues.
Informed skeptic	Higher education and digital comfort. Engages critically and seeks transparency in methodology. Trust contingent on scientific legitimacy.	Provide technical details, source credibility, and forecast logic. Support opt-in exploration for deeper understanding (e.g., link to methodology).
Structurally constrained responder	Trusts the system and understands the risks, but faces barriers such as poor connectivity, financial limitations, or caregiving duties.	Pair alerts with actionable support (e.g., subsidies, community help). Enable low-bandwidth access and offline options.
Low-trust, low-perceived need	Minimal health concern and low trust in institutions. Engagement is often shaped by prior disillusionment or a perceived lack of vulnerability.	Co-design with community intermediaries, emphasize transparency, and promote relevance before frequency. Build trust through demonstration, not assumption.

These archetypes do more than illustrate variation in adoption; they imply how intersecting vulnerabilities, responsibilities, and capacities produce differentiated trajectories of engagement. Such patterns challenge the universalism of traditional acceptance models, suggesting instead that

constructs like usefulness, ease, and trust are contingent and relational. By situating adoption within these archetypal pathways, we see that acceptance is not simply a matter of individual cognition but of social position, relational trust, and structural constraints. Recognizing this complexity has direct implications for design: interventions must be responsive to the protective logics of caregivers, the pragmatic logics of digitally comfortable users, and the relational logics of those who rely on intermediaries, ensuring that technology does not amplify existing inequities but instead mitigates them.

5.4. Discussion

This study examined how residents of Ulaanbaatar interact with digital air quality information systems, suggesting a complex interplay of health concerns, digital practices, and social environments that influence the acceptance of technology. While we applied the Technology Acceptance Model (TAM) as a conceptual starting point, our findings challenge the linear applications of TAM in low-resource, high-vulnerability settings. Instead, they point to a recursive, context-sensitive process in which perceived usefulness, ease of use, and trust are mutually reinforcing and contingent on broader structural and socio-environmental factors.

5.4.1. Reframing Usefulness: Functionality as Situated Value

Across interviews, the perceived usefulness of the proposed RTM-EWS was not defined solely by the system's technical features but by its alignment with users' lived realities, structural constraints, and health priorities. This challenges the notion of usefulness as a fixed property, instead supporting a situated perspective in which utility is dynamic, relational, and contingent. Participants evaluated usefulness not just in terms of what the system could do, but whether it could help them navigate their specific circumstances. For caregivers and individuals with chronic

health conditions, real-time alerts were perceived as providing both practical support and psychological reassurance, enabling informed decisions and fostering a sense of control amid environmental uncertainty. In contrast, participants with fewer structural options or heavy care responsibilities described the alerts as either irrelevant to their constrained realities or only symbolically meaningful.

In addition to shaping perceptions of relevance, the absence of actionable pathways influenced how participants emotionally anticipated interacting with the system. Both real-time alerts and forecasted warnings were described as potentially distressing when not accompanied by clear avenues for response. While some participants hoped real-time alerts could assist with day-to-day planning, others expressed concerns that they might become persistent reminders of risks they could not mitigate. Forecasted warnings similarly raised the possibility of anticipatory anxiety, projecting threat without offering tools for preparation. This anticipated double burden —the cognitive and emotional weight of knowing without being able to act —highlights the risk that information systems may reproduce psychological harm when structural barriers remain unaddressed.[193,194]

These reflections align with the psychological construct of learned helplessness, which describes a state in which repeated exposure to uncontrollable adversity diminishes an individual's sense of agency and capacity to respond.[195] In such contexts, warning systems designed to raise awareness may inadvertently reinforce disengagement, particularly among those already navigating structural exclusion or limited options for protective action. These findings complicate techno-solutionist assumptions that more information inherently leads to better outcomes.[196] Instead, they underscore the need to design for actionability, not just awareness, reimagining usefulness as a relationship to

be cultivated between users, information, and the means to act. Such a shift requires a systems thinking approach that attends to the institutional, infrastructural, and social conditions shaping user agency. Digital tools in low-resource, high vulnerability contexts must be designed with an understanding of the complex (à la *wicked*) environments in which they are deployed, where risks are structural, actions are constrained, and interventions carry potential co-benefits, trade-offs, and unintended consequences that intersect with broader concerns of environmental justice and equity.[197]

5.4.2. Digital Comfort as Socially Situated, Not Individually Determined

Ease of use in this study extended beyond interface simplicity to encompass alignment with participants' existing digital habits, social routines, and infrastructural realities. Rather than correlating clearly with age or education, digital comfort was shaped by platform familiarity, perceived effort, and expectations embedded in participants' communication networks. For example, Facebook was cited across age groups as a preferred channel not because it was technologically advanced, but because it was familiar, low-effort, and already integrated into daily life. In many LMICs, Facebook functions as more than a social platform; it is often synonymous with the Internet itself, serving as the primary interface through which people access information, communicate, and participate online.[198,199] Yet this centrality also illustrates the double-edged nature of platform dependence: while it offers reach, it concentrates information flow within an ecosystem shaped by profit-driven algorithms and vulnerable to mis- and disinformation. These dynamics reinforce that abstract notions of technology literacy do not shape digital comfort, but rather by platform familiarity, local usage patterns, and infrastructural embedding.

Preferences for visual clarity, automation, and cross-platform compatibility reflected more than interface usability. They identified a desire for ambient systems that deliver information passively and unobtrusively, without demanding constant interaction or behaviour change. Participants emphasized the importance of multimodal delivery to accommodate diverse needs, ranging from low-bandwidth users to multilingual households and those with mobile-only access. In this context, technically advanced visualizations or complex interfaces were seen as potentially alienating, especially for users without prior experience interpreting analytical results. Previous work in visual analytics suggests that systems designed for exploration and interactivity may fail to communicate meaningfully to a general audience, prompting the question, *"What does this actually mean?"* when interpretability is sacrificed for sophistication.[200]

While these preferences reflected interface-level concerns, they also pointed to a deeper expectation: that systems should not demand new behaviours, time investments, or technical expertise. Ease of use, in this broader sense, referred to a system's ability to integrate unobtrusively into the rhythms and constraints of everyday life. It was not simply about simplicity but about fit – the extent to which digital tools align with diverse capacities, infrastructures, and routines. This underscored the need to design for digital plurality, especially in LMICs where connectivity, device access, and bandwidth remain uneven.

Beyond convenience, their expectations were about meaningful access in unequal contexts. When digital systems fail to account for contextual fit, ease of use risks becoming unevenly distributed. This reflects the phenomenon of intervention-generated inequality, where well-intentioned interventions disproportionately benefit those who are better resourced, thereby reinforcing exclusion and widening the digital divide.[201,202] These findings suggest that ease of use is a context-

dependent experience, shaped by digital practices, socially shaped expectations, and structural barriers.

5.4.3. Trust as Epistemic Credibility and Relational Familiarity

In parallel with digital comfort, participants emphasized that trust in the information source was equally important to their engagement with RTM-EWS. Trust was not automatically conferred based on institutional affiliation, but rather was earned through perceived competence, transparency, and neutrality. Participants distinguished *who* provides the information and *how* it is communicated, a duality that reflects two interrelated dimensions of trust: epistemic credibility and relational familiarity. Epistemic credibility captured perceptions of technical expertise and rigour, whether the source "*knew what they were talking about."* Relational familiarity, by contrast, reflected whether the information was presented in an accessible, socially resonant, and culturally attuned way. This dynamic aligns with established models of trust in public health messaging, which suggest that people assess trustworthiness and credibility through perceived competence, integrity, and benevolence.[203,204] As a result, trust was not a binary concept but was actively negotiated. Participants expressed skepticism toward government actors, yet concurrently voiced strong trust in researchers, NGOs, and healthcare professionals. Rather than blanket mistrust, this reflected a pragmatic calibration of credibility based on transparency, track record, and alignment with lived realities.

These dynamics underscore the importance of bridging actors, individuals or institutions perceived as both technically credible and socially attuned, particularly in LMICs, where fragmented infrastructures, historical mistrust of state actors, and diverse information ecologies complicate public health communication.[205] Community leaders often serve this role, especially in settings

with limited access to culturally competent care.[206–209] Their influence stems from deep-rooted social ties and their ability to interpret and share health information in ways that resonate with local communities. During public health crises, they have helped counter misinformation and foster trust, not through credentials, but through responsiveness, accessibility, and embedded presence.[206] Research further suggests that bridging actors are most effective when they prioritize connection over authority.[210] Their ability to navigate social and cultural norms allows them to build trust across both epistemic and relational dimensions, making them key conduits for digital tool adoption and sustained community engagement.[204]

5.4.4. Social Influence and Normative Framing

Beyond personal motivations or interface design, participants' engagement with the RTM-EWS was shaped by the attitudes and behaviours circulating within their social environments. Observing how peers, family members, or community members responded to alerts and warnings influenced participants' willingness to engage. When others in their networks dismissed them or questioned their credibility, participants described feeling less compelled to act, suggesting that trust and adoption can diffuse or erode socially. This reflects the power of descriptive norms in shaping technology use, particularly in collectivist or tightly networked settings where social validation influences perceived usefulness.[211–213] Research has shown that descriptive norms, which emphasize positive behaviours (what people are doing), can serve as cognitive shortcuts that nudge individuals towards adoption, especially when the behaviours are visible and modelled by proximal (i.e., socially close) groups.[214] Such findings underscore how community uptake can become self-reinforcing, especially when early adopters are seen adopting protective behaviours. However, normative influence was not reducible to conformity. Some participants described their engagement with the system as a matter of civic responsibility, a way to model protective

behaviour for others and contribute to broader community safety. This reflects the influence of injunctive norms, or shared expectations about what one ought to do, underscoring RTM-EWS's potential role as a platform for collective action.[214,215] These dynamics suggest that risk perception can elevate moral or civic reasoning above conformity pressures, leading individuals to adopt behaviours even when others do not.[216] In this light, participants were actively interpreting their participation as part of a broader contract to protect one another.

These findings suggest that environmental risk communication should not be framed solely in terms of individual risk management. Instead, aligning system design messaging with social norms, both descriptive and injunctive, can enhance uptake and sustainability. Strategies such as increasing the visibility of system use, showcasing community adoption, or framing alerts in terms of mutual protection can embed RTM-EWS within a shared sense of purpose. Framing the system as a collective asset, rather than an individual tool, may foster more durable engagement, particularly in communities with strong social ties or traditions of collective action.

5.4.5. Towards an Expanded Model of Technology Acceptance

Classical applications of the TAM conceptualize technology uptake as a linear function of perceived usefulness and ease of use, culminating in behavioural intention.[217] While this model has proven valuable in many domains, it often assumes stable infrastructures, individualized decision-making, and a relatively unconstrained context. Our analysis suggests that such assumptions may not hold in high-risk, low-resource environments, where systemic constraints, social interdependencies, and limited protective options shape engagement with public health technologies in more recursive and situated ways. In these settings, core TAM constructs do not operate as discrete or static variables, but as relational and dynamic experiences. Usefulness is not

simply assessed in terms of a system's capabilities, but rather in terms of its alignment with users' capacity to act, their sense of agency, and the sociopolitical structures that condition their choices. Ease of use, similarly, must be reframed not as a function of interface simplicity alone, but as a product of infrastructural fit or how well a system integrates into existing habits, bandwidth, and communication ecologies. Trust, often added to TAM as a supplementary variable, emerges here as a foundation: not only in technical accuracy or data transparency, but in relational alignment with familiar actors, social norms, and local authority structures.

To reflect these dynamics, we propose an expansion of the traditional TAM grounded in a sociotechnical understanding of technology use (Figure 2). Rather than modelling adoption as an outcome of individual assessment, we conceptualize it as an emergent process shaped by intersecting domains of vulnerability, access, and social embedding. As such, acceptance becomes less about cognitive evaluation and more about relational navigation, involving the negotiation of limited options, the calibration of information within structural constraints, and the weighing of perceived benefits against psychological or social costs. Technologies are not evaluated in isolation but in dialogue with surrounding systems of care, responsibility, and meaning.

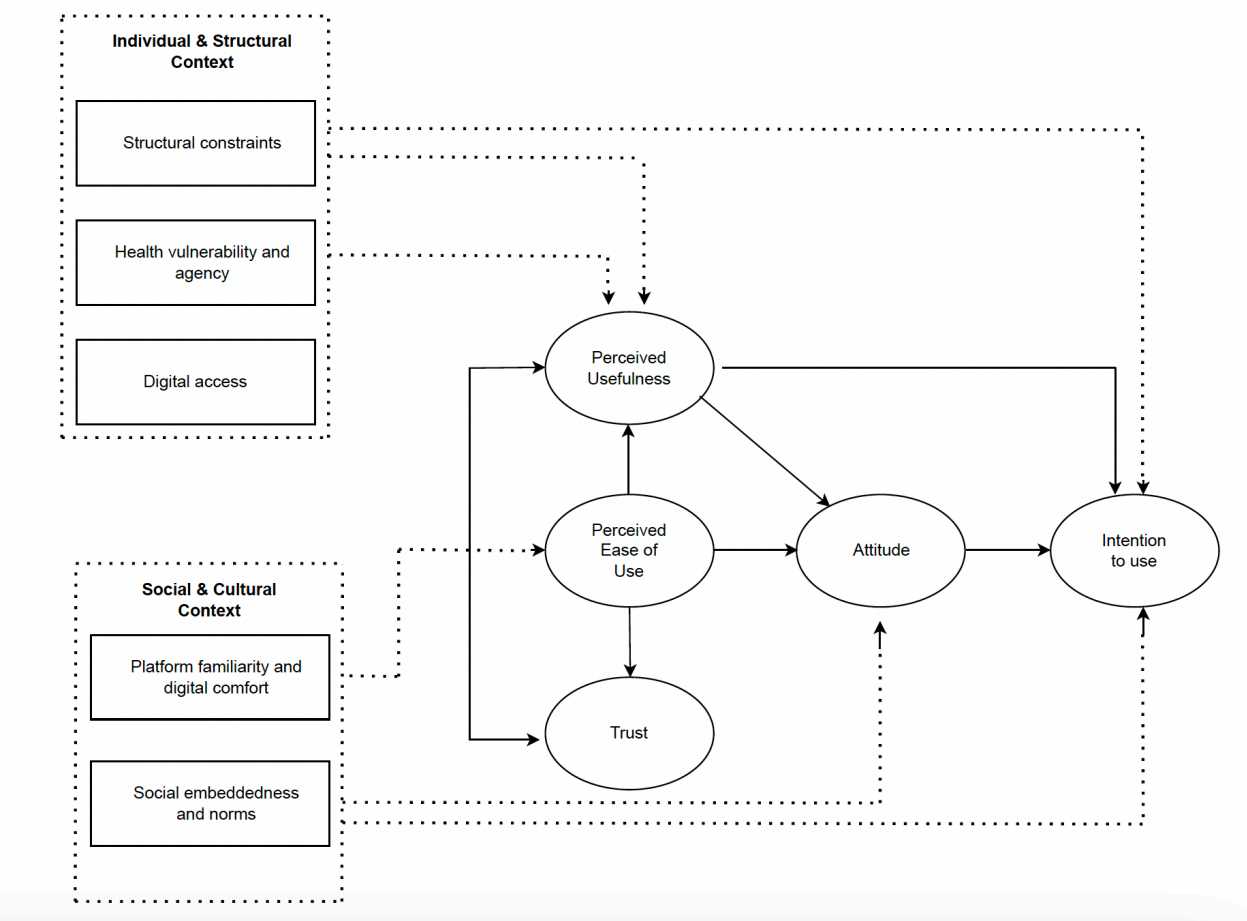


Figure 3. Expanded Technology Acceptance Model (TAM) for low-resource, high-vulnerability settings. Solid arrows indicate direct pathways between TAM constructs; dotted lines represent moderating influences from individual and structural contexts.

This reorientation aligns TAM with critical and participatory frameworks in technology studies that foreground the embeddedness of systems within lived contexts. It also builds on work in environmental justice and health equity that calls for tools to be assessed not only by their functionality but by their fit with community values, capacities, and constraints.[218–222] By situating technology acceptance within broader ecologies of risk, trust, and social obligation, we argue for a model of uptake that recognizes users not as passive recipients of innovation, but as active interpreters navigating uneven landscapes of power, knowledge, and protection. Ultimately,

expanding TAM in this way offers a better fit for understanding digital health tool adoption in low-resource settings, as well as a critical lens for interrogating the assumptions that underpin dominant design paradigms. It encourages designers and implementers to move beyond usability and efficiency toward adaptability, equity, and contextual resonance.

Policy and practice should focus on three levers identified by the expanded Technology Acceptance Model: usefulness, usability, and credibility. In low resource high vulnerability settings, actionable and context specific guidance increases perceived usefulness; low literacy, multimodal, and data light delivery improves ease of use; and transparent data provenance with credible public health messengers strengthen trust. Because health concern amplifies links to intention, early implementation should prioritize caregivers and individuals with chronic conditions through clinics and schools while integrating alerts into routine care pathways. Programs should track indicators tied to these levels, including perceived usefulness, competition of recommended actions, and repeat use as a proxy for trust, and reach among high concern groups.

5.4.6. Study Limitations

This study has several limitations that should be taken into account when interpreting its findings. First, participants were presented with and responded to a proposed prototype, not a fully developed or deployed platform at the time. As a result, their evaluations were based on imagined features and anticipated use rather than real-time interactions. Without the opportunity to directly engage with the tool, it is difficult to fully assess how users would navigate specific design elements, respond to alerts, or sustain usage over time. Second, the findings are grounded in self-reported perceptions and intended behaviours, which may be shaped by recall bias, social desirability bias or uncertainty about how digital systems function in practice.[148,223] While such

perceptions are critical to early-stage design, they may not align with actual adoption patterns when the system is operational. Finally, although the study included participants with diverse levels of education, age, and digital familiarity, it may underrepresent those most structurally excluded from digital and health systems, such as individuals without access to mobile phones, stable housing, or public health infrastructure. These groups likely face unique and compounding barriers to adoption that require further targeted research.

5.5. Conclusion

This study reimagines the traditional TAM model through the lens of lived experience in a high-risk, low-resource setting, advancing a more contextually anchored understanding of digital health tool adoption. Through qualitative engagement with residents of Ulaanbaatar, we explore how traditional TAM constructs are not static but dynamically shaped by social norms, infrastructural limitations, health vulnerability, and emotional readiness. Acceptance emerged not as a linear function of technical design, but as an evolving negotiation between information, context, and the capacity to act.

Our findings highlight the limitations of applying conventional models in settings characterized by systemic constraints and environmental risks. We show that structural barriers, normative influences, and user archetypes co-produce technology engagement in ways that challenge universalist assumptions. By proposing an expanded TAM model that integrated individual and structural moderators, we offer a conceptual framework better suited to understanding adoption in contexts where technology must do more than inform; it must empower, resonate, and enable action under constraint.

As climate-related health challenges accelerate globally, especially in underserved and polluted environments, this work contributes both theoretical refinement and practical insights. It calls for public health systems and technology designers to move beyond interface-level usability and towards models of inclusion that reflect the realities of those most at risk. Along with offering a roadmap for system design, it also reframes technology acceptance through the lens of inequality, emphasizing that adoption cannot be understood apart from the social and structural conditions that shape who can access, trust, and benefit from digital tools.

Bridging Foreword to Manuscript 3

The third manuscript represents the operational stage of the thesis. Building on the lived experience documented in Paper 1 and the design and governance conditions articulated in Paper 2, this paper sets out to develop and evaluate a real-time, low-cost air quality monitoring and forecasting system that can operate within the realities of Ulaanbaatar and similar settings. The work was conducted in partnership with institutional and community stakeholders, and it makes visible the technical and practical decisions when data are sparse, infrastructure is limited, and equity considerations are central rather than peripheral.

As a standalone paper, it contributed to the literature of digital public health surveillance and environmental monitoring. Within the context of this thesis, it has a more specific role: to demonstrate that insights from communities and implementers can be translated into a concrete, functioning architecture, rather than remaining at the level of recommendations. The manuscript allows examiners and readers to evaluate whether the proposed system aligns with the conditions for trust, usefulness, and accessibility established in the earlier papers. Positioned here, it completed the trajectory from understanding the problem, to defining what responsible solutions would require, to testing an approach that begins to meet the responsibility in practice.

6. A Real-Time, Low-Cost Air Quality Monitoring and Forecasting System Using Spatiotemporal Transformer for Low-Resource Settings

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Overview

Air pollution remains one of the most urgent global public health threats, particularly in low- and middle-income countries (LMICs), where reliable exposure data are often unavailable. This paper presents a low-cost, real-time air quality monitoring system designed to operate in data-scarce environments. The system integrates a network of commercial Internet of Things (IoT) sensors with a spatiotemporal Transformer deep learning model and a scalable ETL (Extract, Transform, Load) pipeline for continuous Air Quality Index (AQI) forecasting and visualization. Unlike traditional approaches that rely on fixed-grid or graph-based structures, our model forecasts AQI for future periods and generalizes to unmonitored locations by leveraging spatial and temporal patterns without requiring an explicit grid or graph representation or recurrent sequential architectures. Deployed in Ulaanbaatar, Mongolia, the model attains Validation MSE 12.5939 and RMSE 3.5488; on future periods at known sites, it achieves Temporal Test MSE 7.1111, RMSE 2.6667, and R^2 0.9961; on completely new sites it achieves Spatial Test MSE 3.3849, RMSE 1.8398, and R^2 0.9992. This end-to-end deployment demonstrated the feasibility of AI-enabled environmental surveillance in LMICs and offers a replicable framework for expanding equitable, real-time, public health infrastructure.

Keywords

Air Quality Index forecasting, low-cost sensors, Spatiotemporal transformer, environmental surveillance, digital public health, low- and middle-income countries (LMICs)

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Disclosure statement

The funders had no role in the design of the study, data collection, analysis, interpretation of the findings, or writing of the manuscript.

6.1. Introduction

Air pollution is the leading environmental health risk, contributing to approximately 5.13 million premature deaths annually.[99] Exposure to air pollution is associated with both short and long-term health impacts, including chronic respiratory diseases, cardiovascular disorders, and increased mortality rates.[224] In infants and children, early exposure can result in perinatal and developmental complications, leading to lifelong health consequences.[225,226]

The burden of air pollution exposure is disproportionately high in low- and middle-income countries (LMICs), where limited infrastructure, rapid urbanization, and social barriers exacerbate the risks.[224] Approximately 90% of pollution-related deaths occur in LMICs, highlighting the severe health disparities caused by environmental and economic inequities.[98] Many low-income communities lack access to real-time pollution data and forward looking information, making it difficult to mitigate exposure or advocate for policy interventions. Additionally, reliance on solid fuels for heating and cooking, poor urban planning, and industrial pollution further exacerbate air quality issues.[227]

Beyond its physical health impacts, air pollution also imposes significant psychological and emotional burdens. Salim et al. (2025a) highlight that the lack of reliable exposure data contributes to psychological stress and a diminished sense of agency. As seen in Study 1 of this thesis, without meaningful insights, individuals feel unable to take action to protect themselves or advocate for change. However, research indicates that effectively communicating pollution risks can increase self-efficacy, promote behaviour change, and enhance public advocacy for air quality policies.[228] These findings underscore the critical need for accessible, real-time air pollution monitoring systems that can empower communities with actionable data. However, most existing efforts

remain fragmented, limited to raw sensor outputs without automated preprocessing, predictive modelling, or actionable visualizations.

6.1.1. Limitations of traditional air quality monitoring

Conventional air quality monitoring systems rely on high-cost, stationary sensors that provide accurate measurements but suffer from major limitations. Although government-operated reference stations meet strict accuracy standards, they are expensive to acquire and maintain, requiring regular calibration by trained engineers.[38] Due to these high costs, monitoring stations are sparsely deployed, with many major cities having only a few reference stations to cover vast metropolitan areas.[38,39] The WHO recommends deploying one air quality monitoring station per square kilometre, while the EU Clean Air Directive suggests one station per 200,000 inhabitants.[38] These standards are rarely met in LMICs due to financial and logistical constraints, leaving large populations unmonitored. For example, as seen in Study 1, informal settlements that burn coal for heating during winter often experience localized pollution spikes, but existing monitoring stations fail to capture this granularity.

A notable case study is Ulaanbaatar, Mongolia, home to 1.37 million residents, where winter air pollution levels exceed WHO guidelines by up to 80 times.[229] Nearly 60% of Ulaanbaatar's population resides in ger districts, where dependence on solid fuel combustion leads to extremely high pollution concentrations.[230] Despite these severe conditions, the city relies on a few centralized, government-operated reference stations, which fail to provide hyperlocal pollution data to communities at the highest risk.

The lack of real-time, granular air quality data in LMICs creates significant barriers to pollution mitigation. Without accurate exposure assessments, policymakers struggle to implement targeted

interventions, and individuals lack the information needed to protect themselves from harmful exposure. In response, researchers have begun exploring how low-cost sensing and AI-driven approaches might overcome these gaps, particularly in low-resource regions where traditional systems may not be contextually appropriate or effective.

6.1.2. Related work

6.1.2.1. Emerging Trends in Air Quality Monitoring

A paradigm shift is underway in air quality surveillance, transitioning from centralized, government-operated systems to decentralized, technology-driven approaches.[231,232] Recent advancements in low-cost commercial IoT sensors have enabled more scalable, community-driven air pollution monitoring. Modern low-cost sensors, costing approximately $500 USD, enable denser deployment and improved spatial resolution compared to traditional monitoring stations.[38] Their compact size enables integration into urban infrastructure, ensuring continuous air quality tracking. Additionally, internet-connected IoT sensors enable real-time data collection, facilitating high-frequency monitoring across multiple locations.

Low-cost air quality sensors have been deployed to complement traditional regulatory monitoring, providing increased spatial coverage and real-time tracking of air pollution. These sensors have been integrated into pollution modelling frameworks, such as Land Use Regression (LUR) models, to improve air quality predictions in areas with limited monitoring infrastructure.[233] They have also been used to develop predictive models that estimate pollutant concentrations with greater spatial and temporal resolution.[234] Beyond modelling, low-cost sensors have been leveraged to examine environmental disparities, identifying pollution burdens in disadvantaged communities that regulatory networks may overlook.[235] Additionally, they have played a crucial role in

monitoring extreme pollution events, such as wildfire smoke episodes, by tracking airborne particulate matter and assessing indoor-outdoor exposure dynamics during these events.[236,237]

The increasing adoption of low-cost sensors has enabled a more granular understanding of air pollution patterns, supporting data-driven interventions and expanding air quality monitoring efforts. However, in underserved regions, low-cost sensors alone remain insufficient to address the challenges of air pollution monitoring, as several barriers persist. First, data standardization issues arise because different sensor brands employ varying sensing techniques and collect different pollutants at different time intervals, necessitating a robust processing framework to harmonize the data.[238] Secondly, computation constraints are common in LMICs, which often lack the high-power computing infrastructure needed for large-scale, real-time analysis, making lightweight and scalable processing essential. Third, while sensors collect large volumes of data, they do not inherently produce actionable insights; further transformation is required before they are usable for policymaking or public communication. Finally, sparse sensor deployment remains a limitation; although these sensors are more affordable, it is still often unfeasible to deploy them at the density required for hyperlocal monitoring. As a result, many rural and informal settlements continue to be excluded from real-time surveillance, even in systems that use low-cost technologies.

6.1.2.2. Deep Learning for Spatiotemporal Forecasting

Traditional air quality monitoring relies on stationary reference sensors, which provide highly accurate but spatially sparse data. To address this limitation, machine learning models have been increasingly utilized to estimate air pollution in areas that are not monitored. Convolutional neural networks (CNNs) are widely applied for learning spatial structures and, in air quality applications, for forecasting when paired with temporal modules due to their ability to capture grid-based spatial

features.[239] Studies such as those by Pak et al. (2018, 2020) and Bo et al. (2018) have demonstrated the ability of CNNs to extract spatial features, including pollutant dispersion patterns and meteorological influences.[240–242] While CNNs are effective for modelling structured spatial data, they rely on fixed-grid structures,[239] making them less suitable for air quality monitoring networks, where sensor distributions are irregular and non-uniform.

To overcome CNNs' reliance on structured grids, Graph Convolutional Networks (GCNs) have been introduced for modelling non-Euclidean spatial relationships in air quality prediction, enabling air quality prediction across irregular sensor networks. Qi et al. (2019) used GCNs to predict $PM_{2.5}$ levels in North China, demonstrating their ability to model complex sensor relationships.[243] Despite their flexibility, GCNs rely on static graph structures, which limit their adaptability in dynamic networks, where sensors may be intermittently added or disconnected. Additionally, GCNs are vulnerable to missing data, a common issue in low-resource settings.

Attention-based models enhance adaptability by weighting sensor inputs according to their contextual relevance. Huang et al. (2021) implemented a spatially embedded RNN (LSTM/GRU) for AQI forecasting in Beijing, leveraging attention to capture long-range dependencies in air pollution data.[244] Similarly, Gao et al. (2021) integrated attention mechanisms with Graph Neural Networks (GNNs) to predict $PM_{2.5}$ concentrations in China, allowing for more adaptive spatial feature extraction.[245] While these approaches improve performance, they are typically integrated into hybrid models, inheriting the structural limitations of their base architectures, such as reliance on fixed-grid structures (CNNs), predefined graph relationships (GCNs), or sequential dependencies (RNNs). Collectively, these models rely on structural assumptions, such as grid alignment, fixed graph topology, or sequential dependencies, that limit their adaptability to dynamic, irregular sensor deployments in resource-constrained settings.

Other recent approaches have combined spatial and temporal architectures, for example, by integrating CNNs or GCNs with RNNs or GRUs, to jointly learn location-specific trends over time.[246,247] However, these models often require heavy computational resources and rely on regular time steps, making them difficult to deploy in real-time, low-resource environments.[248,249]

Given the limitations of CNNs, GCNs, and hybrid models, Transformer-based architectures offer a flexible solution for spatiotemporal forecasting in irregular, real time sensor networks. By leveraging self-attention mechanisms, these models weigh inputs dynamically across space and time and can handle spatial inputs without fixed grids or predefined graphs.[248] This flexibility allows them to adapt to irregularly distributed sensor networks, improving accuracy across diverse geographical and climatic conditions. Additionally, Transformers are generally tolerant of missing or noisy data, which is a critical advantage for real-time deployment in resource-constrained settings where sensor failures and connectivity issues are common.[249]

6.2. Study objectives

In collaboration with UNICEF Mongolia, this study aims to develop a real-time, scalable air quality monitoring system for resource-constrained environments. By integrating a network of low-cost IoT sensors, machine learning-based AQI forecasting, and an automated ETL pipeline, the system enhances spatial coverage, predictive accuracy, and enables real-time decision-making, ultimately facilitating high-resolution air quality mapping. Three interconnected objectives guide this study.

First, we aimed to develop a real-time sensor-to-system pipeline using commercially available low-cost sensors. The corresponding research question inquired how these sensors could be integrated into a scalable framework that supports continuous, high-frequency acquisition and

storage of air quality data. This work involved building a reliable infrastructure for real-time monitoring, including automated ETL processes and structured data storage in Elasticsearch.

Second, we aimed to design and train a Transformer-based deep learning model for forecasting AQI. Here, the guiding question was whether the Transformer architecture could accurately and efficiently predict future AQI values using recent history and spatial context by leveraging feature engineering, and whether rigorous evaluation using standard regression metrics could assess its predictive performance under spatial and temporal holdouts.

Third, we focused on integrating the trained Transformer model into the monitoring system to deliver real-time, actionable AQI forecasts. The key question was how such a model could be deployed within the pipeline to provide enriched insights and visualization through Kibana dashboards with automated alerts.

By achieving these objectives, the study bridges the gap between traditional regulatory air quality monitoring systems and low-cost alternatives, providing real-time, high-resolution insights that can support policymakers, public health officials, and communities in managing exposure. Ethics approval for the study was obtained from the University of Waterloo Office of Research Ethics (ORE Project ID #44356)

6.3. Methods

6.3.1. Objective 1: Sensor to Elastic Pipeline

6.3.1.1. System Architecture and Data Ecosystem

The system integrated multiple technologies to create a scalable and efficient data ecosystem. Azure Blob Storage stored large volumes of unstructured data, including ETL scripts and raw

sensor data from APIs. To enable real-time sensor data acquisition, two Azure Virtual Machines (VMs) provided on-demand, scalable computing resources, eliminating the need for physical hardware maintenance. The processing engine, developed in Python, utilized Pandas and NumPy for data manipulation and analysis. For data storage and processing, Elasticsearch managed numerical, textual, and geographic sensor data, enabling real-time analysis and retrieval.

6.3.1.1.1. Data Ecosystem and Pipeline

6.3.1.1.1.1. Server-Side Data Transformation and Loading Framework

Sensor placement reflected existing deployments operated by partner organizations and was concentrated in high exposure residential areas, including ger districts across Ulaanbaatar. Acquiring data from these indoor IoT sensors involved three steps: fetching data from the API, processing it, and storing it. During data acquisition, the virtual machine (VM) collected metadata, including sensor type, manufacturer, location (latitude/longitude), and key air quality variables. Table 1 provides an overview of the sensor brands used and the specific variables collected from each sensor brand. Azure Blob Storage securely stored this raw data while ensuring efficient access control.

Table 4. Breakdown of low-cost IoT sensors, the variables they collected, and their data collection intervals.

Sensor Brand	#	Type	Data Collected	Data Collection Granularity
Purple Air	33	Commercial	$PM_{0.3}$, $PM_{0.5}$, PM_1, $PM_{1.5}$, PM_5, PM_{10}	80-120 seconds
			Humidity, pressure, temperature	
			Latitude, longitude, altitude	
OpenAQ network	4	Aggregate data from reference-grade monitors	CO, O_3, NO_2, SO_2, PM_1, $PM_{2.5}$, PM_{10}	Hourly
			Latitude, longitude	
IQ Air	51	Commercial	AQI value, CO, PM_1, $PM_{2.5}$, PM_{10}	10 minutes
			Humidity, temperature	
			Latitude, longitude	

For newly added sensors, the VM retrieved metadata via a private API key and updated a configuration file with sensor details. It then connected to sensor APIs, pulling historical data into 24-hour bracketed JSON files. For existing sensors, the VM automatically updated data. Once processed, JSON files were uploaded to Azure Blob Storage, and local copies were deleted to optimize storage.

To enhance long-term data accessibility and modularity, sensor data was continuously written to Azure Blob Storage in universally compatible JSON format. This allowed raw data to be preserved independently of Elasticsearch, enabling future research use even if the dashboard deployment is paused. Decoupling storage from Elasticsearch also eliminated dependencies between VM1 and VM2, allowing for independent scaling, system resilience, and simpler redeployment.

6.3.1.1.1.2. Client-Side Data Management

The ETL framework on VM2 managed sensor configurations and retrieved new JSON files from Azure Blob Storage when updates were detected. During data processing, VM2 standardized the data structure, removed inconsistencies, and ensured completeness. It retrieved updated data files and converted timestamps to UTC, ensuring temporal consistency across records. The data was structured into a DataFrame, which ensured flexibility in data manipulation. Before being loaded into Elasticsearch, the structured data was converted from standard JSON to newline-delimited (NDJSON) format to ensure compatibility with bulk indexing operations.

6.3.1.1.1.3. Data Storage and Error Handling

Processed data was securely stored via Elastic Cloud deployment, ensuring efficient access and retrieval. Azure Blob Storage served as a backup repository for data recovery, should it be needed. If loading failed, VM2 resumed from the last saved checkpoint. To maintain data integrity, a duplicate removal script eliminated redundant entries by using a hash key based on identifying attributes. After storage, NDJSON files were deleted from VM2 to prevent unnecessary data accumulation.

6.3.1.1.1.4. User Interface and Data Visualization

Elastic Cloud, powered by the Elastic Stack, integrated Elasticsearch for indexing and Kibana for visualization. Kibana provided various visualization tools, including Maps, Time Series Visual Builder (TSVB), Charts, Metrics, Data Tables, and Vega, enabling comprehensive data analysis. Kibana dashboards enable public health officials to monitor air pollution exposure in real-time. Users can construct visualizations from single Elasticsearch queries or multiple data sources for comprehensive air quality analysis. As new data became available, dashboards automatically updated, providing timely insights for risk mitigation and policy decisions.

6.3.1.1.1.5. Data Security and Privacy

To ensure data confidentiality and integrity, role-based access controls were implemented to restrict cloud storage access to authorized users. Microsoft Azure Storage complied with the United States National Institute of Standards and Technology (NIST) security standards, reinforcing data protection and regulatory adherence. A unified authentication mechanism mitigated data transmission vulnerabilities across diverse sensor types. Users provided explicit consent for the collection and processing of their data, ensuring compliance with relevant privacy regulations. To protect personal information, NIST-compliant guidelines ensured the anonymization of data. A centralized data governance framework maintained compliance and accountability and quickly identified and addressed any data misuse or security breaches.

6.3.2. Objective 2: Model Development and Training

6.3.2.1. Deep Learning Integration

6.3.2.1.1. Data Extraction and Storage

Air quality data was extracted from Elasticsearch indices, where timestamped sensor readings, pollutant concentrations (CO, $PM_{2.5}$, PM_{10}, NO_2, SO_2), and environmental metadata such as temperature, humidity, and pressure were stored. Each reading was associated with sensor identifiers, including device ID, brand, and type, as well as geographic coordinates (latitude and longitude) for spatial analysis.

To maintain data integrity and enable scalable, real-time processing, an automated ETL pipeline continuously retrieved, preprocessed, and prepared sensor data for modelling. The system ensured that raw data was stored in Elasticsearch for long-term access while maintaining a fault-tolerant and efficient high-frequency data streaming process. For troubleshooting and local analysis, raw

data was temporarily stored in CSV files, though Elasticsearch remained the primary repository for large-scale processing.

6.3.2.1.2. Data Preprocessing and Feature Engineering

To create a consistent time series, data were resampled into six-hour intervals. This interval was chosen to balance the need to capture meaningful short-term fluctuations while minimizing the noise and the data sparsity introduced by the low-cost sensor variability. Shorter intervals (e.g., hourly) resulted in unstable readings due to data gaps, while longer intervals (e.g., daily) risked obscuring diurnal pollution patterns. During resampling, the average value of each feature (e.g., AQI, $PM_{2.5}$, PM_{10}, temperature, humidity) was computed within each six-hour window. While EPA AQI breakpoints are formally defined using longer averaging periods for certain pollutants (e.g., 24-hour $PM_{2.5}$), the six-hour aggregation used here reflects an operational compromise common in real-time and early warning systems. This choice prioritizes temporal responsiveness and risk signalling over regulatory compliance, aligning the aggregation window with the system's intended use for timely exposure awareness rather than formal standard setting.

The AQI values were calculated using a piecewise linear interpolation method, ensuring standardization across pollutants. The AQI for a given pollutant was computed using the following equation:[250]

$$I_P = \frac{I_{HI} - I_{LO}}{BP_{HI} - BP_{LO}}(C_P - BP_{LO}) + I_{LO}$$

Where I_P is the AQI for the pollutant P, C_P is the pollutant concentration, BP_{HI} and BP_{LO} are breakpoint concentrations, and I_{HI} and I_{LO} are the corresponding AQI values.

For each six-hour window, AQI was computed separately for each available pollutant, and the maximum sub-index value was retained as the overall AQI, consistent with standard AQI reporting practice. AQI values were computed using the U.S. EPA breakpoint framework, which provides a widely used, health-based mapping between pollutant concentrations and risk, and supports comparability across studies.[251] Its use also reflects prior qualitative findings indicating limited trust in domestic air quality reporting and its native implementation across sever low-cost sensor platform, reducing interpretive inconsistency. AQI is therefore used here as a communicative early-warning metric rather than a claim of regulatory equivalence.

To handle missing data, pollutant readings with absent values were replaced with zeros to prevent disruptions in the modelling process. To reduce bias, binary availability flags such as CO_available and NO_2_unavailable were incorporated, allowing the model to distinguish between true zero values and missing data. Outliers in the dataset were detected and removed using the Isolation Forest algorithm, ensuring that the model is trained on representative and accurate data.

Feature engineering was applied to enhance the model's predictive capabilities. Temporal features, such as the hour of the day, day of the week, and seasonal indicators, were derived from timestamps to capture daily, weekly, and seasonal trends in air pollution. Rolling statistics, including a seven-day rolling mean and median, were calculated to highlight long-term trends, while rolling standard deviations quantified variability in AQI levels over time. An Exponentially Weighted Moving Average (EWMA) was applied to assign greater weight to recent data points, making the model more responsive to sudden fluctuations in pollution due to weather changes or traffic emissions. Additionally, lagged AQI values from previous time steps were included as features to help the model recognize historical patterns, enabling more accurate forecasts. For comparison, a baseline

multivariate linear regression model was trained on the same standardized features, serving as a reference for evaluating the model's predictive performance.

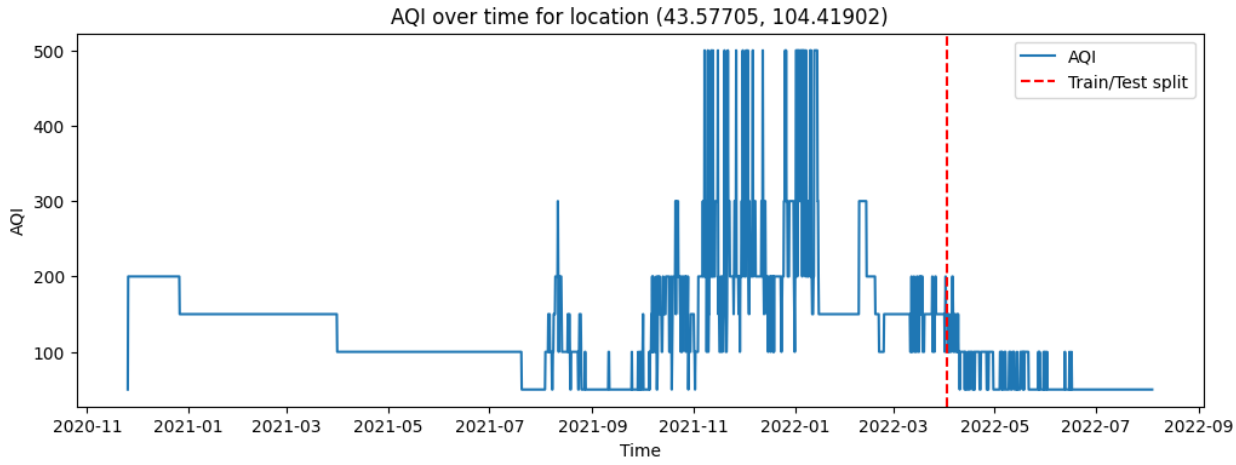


Figure 4. Time series of Air Quality Index (AQI) at one sensor location. The vertical red line marks the temporal split used to define training and test sets.

6.3.2.1.2.1. Evaluation and Data Splitting

To assess generalization across space and time, we used a nested split, where 20 percent of sensor locations were held out completely for spatial test. On the remaining locations, time was split in order so that the first 70 percent formed training, the next 15 percent formed validation, and the last 15 percent formed a temporal test.

Each model input corresponded to a single location and comprised of 28 consecutive six-hour steps, providing a seven-day window that captured diurnal cycles and weekly structure while matching the operational cadence. Latitude and longitude were projected to coordinate embeddings and broadcast across all steps so that geographic context conditions temporal pattern learning throughout the sequence. Only the validation split was used for hyperparameter tuning

and stopping criteria; temporal and spatial test data were accessed after training was finalized to prevent leakage and yield credible estimated of performance on future periods and new sites.

6.3.2.1.2.2. Model Development and Training

The pipeline incorporated a Spatio-Temporal Transformer architecture to forecast AQI values one step ahead at the same six-hour resolution. This architecture was designed to capture complex relationships between pollutant levels, temporal patterns, and lagged data points, making it particularly effective for time-series forecasting. The core of the Transformer model is the self-attention mechanism, which allows the model to selectively focus on relevant features from different time steps and spatial locations. This is defined as:[252]

$$Attention(Q, K, V) = softmax\left(\frac{QK^T}{\sqrt{d_k}}\right)V$$

In the context of air quality modelling, this mechanism enabled the model to dynamically weigh sensor data across various spatial locations, identifying which historical readings were most relevant based on pollutant spread, wind, and proximity, rather than relying on fixed grids or time sequences.

To capture multiple such patterns in parallel, the model uses multi-head attention, where attention is applied across multiple subspaces and the results are linked:

$$MultiHead(Q, K, V) = Concat(head_1, \dots, head_h)W^O$$

Each attention head is calculated as:

$$head_i = Attention(QW_i^Q, KW_i^K, VW_i^V)$$

These heads enabled the model to learn distinct spatial relationships in parallel, for example, short-range pollution dynamics from traffic-dense corridors versus broader pollution plumes originating from coal-burning stoves in the ger area during the cold months (November to February).

The output of each attention layer was passed through a position-wise feedforward neural network:

$$FNN(x) = \max\left(0,\ {}_xW_1 + b_1\right) W_2 + b_2$$

This step further refined the representation of feature interactions, such as how humidity or wind speed may modulate the effect of $PM_{2.5}$, regardless of spatial order.

While temporal features such as lags, rolling averages, and time-of-day encodings were introduced earlier, this stage of the architecture enabled them to inform the prediction by capturing short-term and seasonal context. The task here was single-step forecasting; these engineered inputs enabled temporal dynamics without relying on sequential architectures, such as RNNs.

Before training, the dataset underwent standardization using a StandardScaler to ensure all features were on a uniform scale, preventing a single variable from dominating the optimization process. The input data was then reshaped into three-dimensional tensors to align with the model's requirements. The model was trained using the Adam optimizer with a learning rate of 0.001, chosen for its adaptive properties and balance between convergence speed and stability.[253] Mean squared error (MSE) was used as the loss function, given its suitability for continuous regression tasks such as AQI prediction. Training was conducted for up to 100 epochs with a batch size of 32 resampled sequences, each corresponding to a 6-hour interval. Early stopping with a patience of 10 was implemented to prevent overfitting, and the model converged well before reaching the epoch limit. The batch size was selected through empirical tuning to strike a balance between

convergence stability and GPU memory usage, in line with best practices for Transformer-based time series forecasting.

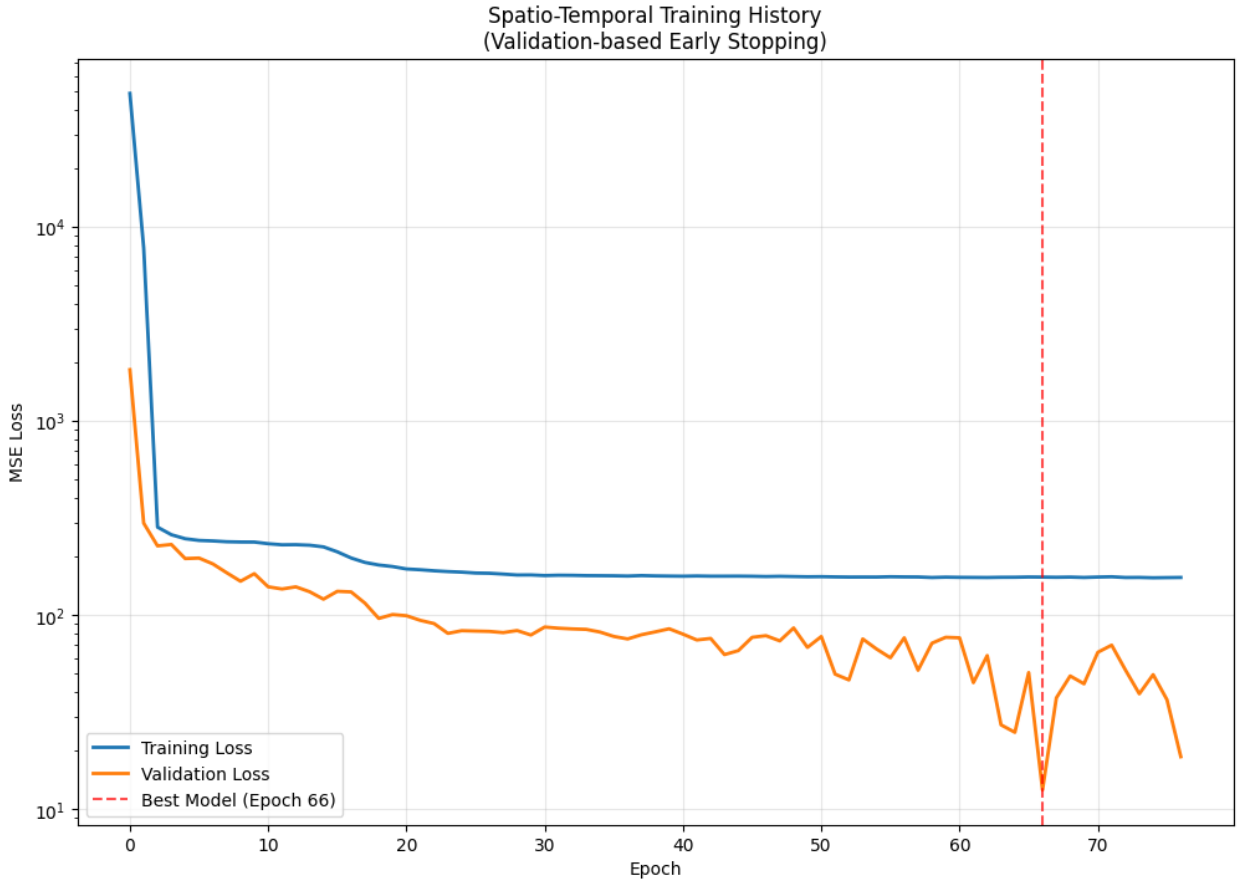


Figure 5. Training history for the spatio-temporal model with validation-based early stopping. Mean squared error is plotted on a logarithmic scale for training and validation sets across epochs.

The model presented a single AQI value corresponding to the forecasted pollution level for the next six-hour step at the given location, generated through dense regression layer that ensured the value is continuous and interpretable as an AQI index. Predictions are aligned with the six-hour resampling and ingestion schedule.

6.3.3. Objective 3: Integration of the Transformer Model

To maintain clarity in systems operations, the architecture included two distinct pipelines. The first was the monitoring pipeline, which acquired raw data from IoT sensors, transformed it, and stored it in Elasticsearch. The second was the prediction pipeline, which retrieved structures sensor data from Elasticsearch, applied the trained Transformer model, and presented the AQI forecast back to a dedicated Elasticsearch index. This separation ensured scalability, simplified maintenance, and improved traceability between sensor data and model output.

After training, the model was exported in TensorFlow's SavedModel format and deployed on VM2, where it processed structures sensor data in real time. As new data arrived from the IoT sensors, it was preprocessed using the same standardization and formatting procedures outlines in Section 4.2. Once preprocessed, the data was fed into the Transformed model, which generated the AQI forecast on a rolling basis. Each forecast was enriched the relevant metadata, as outlines in Section 4.1, to support traceability and contextual relevance. These enriched results were indexed into a dedicated Elasticsearch repository configured specifically for model outputs.

Real-time visualizations were supported through Elastic Stack. As described in Section 4.1, Kibana dashboards were configured to dynamically display forecasts, enabling users to monitor AQI levels across time and location. These dashboards offered detailed views, including maps, time series, charts, and tabular summaries, facilitating rapid interpretation of trends. In addition to visualization, the system triggered automated alerts when forecasted AQI values ≥101, corresponding to the 'Unhealthy for Sensitive Groups' category under the U.S. EPA classification.[251] Alerts were delivered via the dashboard interface, providing stakeholders with timely and actionable insights for public health interventions.

By integrating the trained model into the full ETL pipeline, the system delivered continuous, real-time AQI forecasts that were contextually enriched and visually presented to stakeholders. It enables proactive exposure management in low-resource environments.

6.4. Results

6.4.1. Objective 1: Sensor to Elastic Pipeline Performance

The end-to-end pipeline successfully acquired, transformed, and stored data from over 30 low-cost air quality sensors deployed across Ulaanbaatar. The automated ETL pipeline extracted timestamped readings and metadata from Elasticsearch indices with minimal downtime, supporting continuous real-time data availability. Resampling the data within in each sensor location into six-hour intervals ensured temporal uniformity, and the preprocessing framework reliably handled missing values by interpolating them using the median value or next or previous value as appropriate, and removed outliers using the Isolation Forest algorithm.

Feature engineering steps, including temporal attributes, rolling statistics, lag features, and exponentially weighted moving averages, further enhanced data quality and predictive value. The pipeline demonstrated scalability by maintaining low latency despite increasing data volumes from geographically distributed sources, validating its robustness in low-resource settings where traditional systems are not feasible.

6.4.2. Objective 2: Transformer-Based AQI Model Performance

The spatio-temporal transformer model demonstrated strong single-step forecasting performance at a six-hour horizon. We evaluated performance using standard regression metrics on two test regimes. Table 2 summarizes single-step forecasting under the nested spatio-temporal split. The

model maintains low error and high explained variance on the temporal test, and achieves the strongest fit on the spatial holdout, indicating that learned spatial representations transfer well to unseen locations. These results support both temporal generalization at known sites and spatial generalization to new areas.

The model captured temporal dependencies, seasonality, and sudden changes in pollution within the weekly context window, indicating an ability to learn patterns from pollutant histories and environmental covariates under the nested spatio-temporal evaluation.

Table 5. Single-step (6-hour) Air Quality Index (AQI) forecasting performance under nested spatio-temporal evaluations.

Split	**MSE**	**RMSE**	**MAE**	**R^2**
Training	1.7355	1.3174	0.9980	0.9999
Validation	12.5939	3.5488	1.0227	0.9980
Temporal test (future periods at locations seen in training)	7.1111	2.6667	1.2712	0.9961
Spatial test (all periods at locations held out during training)	3.3849	1.8398	0.9357	0.9992

6.4.3. Objective 3: Real-time Integration and System Monitoring

The trained Transformer model was successfully integrated into the existing ETL pipeline, enabling continuous AQI forecasting for locations across the deployment area, including those without direct sensor coverage. Following deployment, forecasts were generated with each data update and enriched with metadata before being indexed in Elasticsearch.

The system performed reliably under real-time conditions, with model inference integrated into the standard preprocessing pipeline. Prediction values were dynamically visualized through Kibana dashboards, which updated seamlessly as new data arrived. Stakeholders were able to monitor regional air quality trends and receive automated alerts when AQI thresholds were exceeded. These results confirm the system's full end-to-end operability, bridging data collection, model inference, and visualization in a low-resource setting.

6.5. Discussion

This study addresses a core challenge in low-resource settings: how to enable real-time air pollution monitoring in environments where traditional systems are unaffordable, fragmented, or nonexistent. We developed an end-to-end pipeline that integrated low-cost IoT sensors, an automated sensor-to-Elastic data pipeline, and a Transformer-based deep learning model to deliver continuous AQI forecasts. The results suggest that beyond demonstrating technical feasibility, the system is also accurate, resilient, and adaptable to the constraints of LMIC environments.

Previous studies have demonstrated the utility of low-cost sensor networks in expanding urban air quality monitoring.[254–256] Numerous machine learning models have been applied to air quality forecasting, including CNN and recurrent models such as LSTMs.[257–261] These approaches have improved predictive accuracy but often face challenges when deployed in sparse networks with missing or noisy inputs.[262] Our Spatio-Temporal Transformer differs by leveraging self-attention mechanisms that capture spatiotemporal patterns across resampled sequences, improving robustness in settings with sparse coverage and variable data quality. Additionally, the deployment of the model enabled continuous AQI forecasting and stakeholder-facing outputs through real-time visualizations and alerts. By embedding inference in a broader ETL pipeline and integrating with visualization tools, the system ensured that data were collected and transformed into actionable

information. Similar integration of sensing and visualization has been attempted in other urban settings, but few systems have combined automated pipelines with advanced AI architectures in low-resource settings.[263–267] Our results suggest that high-resolution, real-time environmental monitoring and short-horizon forecasting is achievable under these conditions, extending the growing literature on spatiotemporal deep learning in environmental applications.[268–270]

6.5.1. Model Sustainability and Maintenance

While the Spatio-Temporal Transformer handled incomplete inputs during deployment, attention models remain sensitive to data drift and concept drift. In practice, model performance can degrade when the input distribution shifts due to seasonal changes, sensor repositioning, or calibration adjustments.[271,272] To support sustainability, the system should include lightweight monitoring of input data quality and downstream errors, for example: (i) rates of missingness and out-of-range values, (ii) rolling validation loss or RMSE on a fixed hold-out set; and (iii) alerting when error exceeds a predefined threshold. The model does not require daily training; rather, periodic retraining should be triggered by detecting drift or scheduled (at seasonal boundaries, for example) using the same standardized preprocessing. These safeguards maintain the model's robustness without requiring continuous retraining.

6.5.2. Broader Implications

This study demonstrated how advanced ML models and low-cost technologies can be integrated into practical, deployable systems that serve public health needs in underserved environments. The system bridges the gaps between centralized regulatory monitoring and disconnected community-level efforts by offering a scalable, interpretable, and locally adaptable alternative. Its design supports real-time surveillance as well as informed decision-making, including public health

planning, community response, and environmental regulation. By linking technical outputs with actionable thresholds, the system also contributes to efforts to translate air quality surveillance into public health interventions.[273,274]

Including indoor air quality measurement extends surveillance from ambient environmental monitoring towards exposure-relevant public health intelligence. While outdoor monitoring primarily supports population-level assessments and regulatory response, indoor measurements capture the microenvironments where exposure is sustained, and health effects are most directly experienced. Integrating indoor and outdoor perspectives therefore strengthen early warning capacity by aligning surveillance with lived exposure conditions, particularly in informal settlements contexts where housing structure and fuel use blur conventional indoor-outdoor boundaries.

Beyond supporting public awareness, the integration of alert systems and real-time dashboards also presents opportunities for policy translation and implementation. For example, AQI thresholds could trigger targeted municipal responses such as issuing pollution advisories, adjusting school schedules, or guiding emergency preparedness plans. Recent studies have emphasized the importance of ensuring that monitoring systems both inform and empower communities.[275–278] Our results suggest that coupling real-time sensing with predictive modelling can extend these benefits, providing anticipatory intelligence rather than reactive information.

Finally, in regions where environmental injustices have historically left marginalized communities unmonitored or unprotected, this system offers a pathway towards more equitable surveillance. Prior research has demonstrated how low-cost sensing can highlight disparities in exposure to pollutants across disadvantaged populations.[279–281] By enabling granular air quality forecasting in

low-resourced or politically neglected areas, the approach demonstrated in this paper moves beyond describing disparities to support proactive mitigation strategies.

6.5.3. Limitations and Ethical Considerations

While the system performed well across technical dimensions, several limitations remain. EPA AQI categories are derived primarily from epidemiological evidence linking outdoor ambient air pollution to pollution-level health outcomes. In informal settlement context, including ger districts, this indoor-outdoor distinction is often not well defined. Dwellings are semi-permeable, solid fuel combustion frequently occurs within living spaces, and residents experience sustained exposure that reflects a combination of household emissions and surrounding ambient conditions. In this context, measurements from indoor sensors may function as a practical proxy for local ambient exposure, particularly where ambient monitoring may be limited. Accordingly, AQI thresholds in this study were used to structure risk communication and early warning rather than to imply direct equivalence with regulatory outdoor exposure assessments. Future work should investigate exposure-specific calibration strategies and locally grounded thresholds that better reflect the hybrid exposure dynamics characteristic of informal settlements.

The sensor network was concentrated in high vulnerability settings. While this limits generalizability to well-resources urban neighbourhoods or formal housing contexts, it strengthens the systems' relevance for informal or peri-urban settings where conventional monitoring is least available, and health risks are greatest. Findings should therefore be interpreted as applicable to high exposure, resource-constrained contexts.

Low-cost IoT sensors are prone to calibration drift over time due to environmental stress, such as temperature fluctuations and long-term exposure to pollutants. This is especially relevant in

settings like Ulaanbaatar, where winter temperatures frequently drop below -20°C, which can potentially affect sensor reliability. Though the ETL pipeline handled outliers and missing data, the system does not yet incorporate drift correction algorithms or calibration baselines, which are essential for long-term reliability.

Network reliability and sensor uptime also present operational challenges. Many low-cost devices lack buffering capabilities, which means that outages due to power loss, poor connectivity, or physical disruption can result in data gaps. While the current system handles these gracefully during preprocessing, persistent downtime could reduce its effectiveness in real-time surveillance.

The model used in this study performs single-step forecasting at a six-hour horizon; it does not yet produce multi-step forecasts or uncertainty estimates. Moreover, the system has been evaluated to date in only a single geographic region. Broader validation across cities with different climates, topographies, and pollution profiles is necessary to assess its generalizability. A further limitation is related to model upkeep. Although the encoder was resilient to missing or noisy readings at inference, its performance is ultimately limited by the quality of the input data and the persistence of learned relationships. Sustained accuracy in new conditions requires a modest operation later: routine checks on sensor uptime and calibration status, automated data-validation rules before inference, and retaining when monitored errors drift beyond threshold. These needs imply the need for designated personnel with basic data engineering and model operations skills to review alerts, initiate retraining, and document model updates within a pipeline.

The sustainability of the cloud infrastructure must also be considered. While Elasticsearch and Kibana offer free community tiers, and Azure Blob Storage provides limited free usage, these services typically transition to paid tiers as data volumes or user numbers increase. Long-term sustainability requires either securing dedicated institutional or project funding or migrating to

open-source alternatives. Such contingency planning is essential to ensure that the system remains functional and accessible if commercial service tiers change or become cost-prohibitive.

Finally, as the system scales, ethical considerations around data governance and local control must be addressed. The interpretability of results, accessibility of dashboards, and the inclusion of local institutions in shaping how data is used will be key to ensuring meaningful and sustained impact.

6.5.4. Future Work

Future work will extend from single-step to multi-step AQI forecasting, add calibrated uncertainty estimates, and evaluate transfer across additional cities to assess generalizability. Deployments in new cities will help assess the pipeline's flexibility and the model's transferability across contexts. Further integration with public health datasets such as hospital admissions or respiratory illness records could enable the creation of predictive health risk scores or syndromic surveillance systems.

Opportunities also exist to adapt this framework to other environmental domains, such as extreme health monitoring, water quality surveillance, or disease risk mapping. These extensions would broaden the platform's impact and contribute to a more comprehensive, AI-supported public health infrastructure.

6.6. Conclusion

This study presents a deployable, low-cost system for real-time air quality monitoring in low-resource settings, integrating commercially available low-cost IoT sensors, a scalable data pipeline, and a Spatio-Temporal Transformer model capable of producing accurate AQI forecasts in sensor-scarce environments. The system moves beyond proof-of-concept by demonstrating robust, real-time performance in a live setting, while remaining adaptable to future needs.

By bridging gaps in infrastructure, equity, and technical capacity, the platform provides a new model for environmental surveillance, one that is modular, interpretable, and ready for integration with public health. While challenges like sensor calibration, data outages, and generalizability remain, this work lays the foundation for anticipatory, community-relevant monitoring systems. As the platform evolves, it opens the door to broader applications, from temporal forecasting to health risk prediction, strengthening environmental resilience through accessible, AI-enabled public health infrastructure.

7. Discussion

From Measurement to Governance: Reframing Digital Surveillance as a Fragile Public Good in Low-Resource High-Vulnerability Settings: A Viewpoint

This thesis explored how real-time air pollution surveillance can be designed and adopted to be contextually appropriate, equitable, and sustainable in resource-constrained, high-vulnerability settings. Mongolia, specifically Ulaanbaatar, one of the world's most polluted capitals, was selected because its combination of extreme exposure, rapid social change and fragile governance deepens dilemmas faced across many LMICs. The value of the case is not in its uniqueness but in its ability to reveal dynamics of surveillance that are obscured in settings with stronger institutions or denser infrastructure.[282,283]

Although the health harms of air pollution are well established, much research and practice still frame monitoring as a technical race to measure more cheaply, precisely, or frequently. The findings of our work suggest that this framing is inadequate. Surveillance is not only a measurement task; it is a social and political process that decides whose realities are counted, whose data are trusted, and which kinds of evidence can trigger action. Understanding surveillance in Mongolia and in comparable settings, therefore, requires tracing how measurement becomes entangled with governance, inequity, and trust. The case that follows motivates an integrated account of surveillance that considers social realities, institutional routines, and technical capabilities together.

7.1. Ulaanbaatar as an Analytic Case

While this thesis is empirically situated in Ulaanbaatar, the intent is not to claim representativeness across settings. Rather, Ulaanbaatar is treated as an analytically informative case through which

broader dynamics of air pollution exposure, information use, and surveillance under constraint can be examined. The value of the case lies not in its uniqueness, but in how it foregrounds structural conditions that shape how air pollution is experienced, interpreted, and acted upon in contexts of persistent exposure and limited institutional responsiveness.

Certain features of the Mongolian context are distinctive, including the dominance of coal-based residential heating, the prevalence of ger housing, and extreme seasonal variation in pollution levels. These characteristics shape exposure in specific ways for Ulaanbaatar. However, the analytic insights developed in this thesis do not rely on these particulars alone. Instead, they arise from conditions that are common across many LMICs and marginalized urban settings: chronic exposure to environmental hazards, limited individual capacity to reduce risk, delays or gaps in official monitoring, and a persistent disconnect between formal data systems and lived experience.[284,285] In this sense, Ulaanbaatar serves as a lens through which the operation of surveillance under constraint can be examined, rather than as a case to be generalized statistically.

Ulaanbaatar's wintertime exposure, energy poverty, and spatial inequities make the stakes of surveillance unusually visible. What appears to be household fuel choices is the surface expression of deeper systems – housing precarity, uneven service coverage, and urban exclusion – that shape, expose, and constrain the feasibility of protective action. At the same time, low-cost sensing and machine learning can render air quality visible at hyperlocal scales and in real time, making hazards legible in ways that legacy networks do not. The new visibility is not neutral. It obliges institutions to absorb, interpret, and respond within shortened decision windows and under persistent constraints in capacity and trust. These conditions invite a synthesis across lenses rather than a single-track account of technology or behaviours.

These strands converge on a simple mechanism for protection. Surveillance protects when a chain holds: measurement creates visibility; visibility is recognized as legitimate; legitimacy is absorbed into rules that bind threshold to actions; and those actions are delivered in time through channels people already use and trust. Breaks at any link dissipate value—context without innovation yields partial visibility that does not change decisions. Innovation without institutional absorption or legitimacy produces data that circulates but fails to transform practice. Adoption without equity and trust widens the gap between those who can act on information and those who cannot.

7.2. Surveillance Within a Wicked Problem

The interdependencies above make the problem wicked not only because causes are entangled, but because evidence and authority are continually negotiated. In Mongolia, pollution is framed at once as regulatory compliance, infrastructural transition, and household survival. No single framing secures durable legitimacy, so institutions and communities operate in a state of persistent contestation. Strategies that emphasize energy transition can appear inattentive to the daily calculus of warmth and affordability; residents' survival accounts are, in turn, dismissed as obstacles to modernization. The way data are collected and represented concedes authority to some framing while marginalizing others, an epistemic politics in which deciding what is measured is also deciding what can be governed.

These dynamics are recursive. Gaps in energy provision drive reliance on coal; those gaps are then rationalized by statistics that individualize responsibility. Interventions generate feedback loops: a coal ban reduces certain emissions while intensifying economic strain; strain fuels resistance that weakens enforcement. Expanding sensor networks increases visibility while simultaneously exposing divides in digital access and institutional credibility. Divergences between official

statistics and lived experience destabilize authority and become instruments of political contestation. In such settings, measurement itself becomes an intervention that reshapes the problem. This logic extends beyond air pollution to other climate risks in low-resource, high-vulnerability contexts.

Wickedness, in this sense, is not only a tangle of causes or the absence of definitive solutions; it is the instability of the problem's very terms. Competing constituencies mobilize different kinds of evidence (regulatory thresholds, exposure maps, household accounts) to advance incompatible priorities. No single dataset can close the argument. Under these conditions, surveillance does not end disagreement; at best, it makes disagreement governable by clarifying what is being claimed, by whom, and with what consequences for those most exposed.

This has operational implications. When evidence and authority are contested, the credibility of surveillance depends on how contention is handled. Open calibration notes that explain methods and uncertainties, side-by-side reporting that shows where community measures and official data diverge, and clear reasoning about why numbers differ help convert conflict into a legible choice rather than mistrust. When interventions impose costs on already precarious households, decision rules should acknowledge trade-offs, and where possible, couple restrictions with visible forms of support. Legitimacy is sustained when residents can see what the data say and how data are used to reconcile competing claims in ways that are predictable and revisable.

Because interventions alter the conditions they seek to improve, design must anticipate second-order effects and be prepared to adjust. Policies that shift fuel use will also shift income, time, and care burdens; communication that heightens risk salience may also produce fatigue or fatalism if not accompanied by feasible options. The task is to act within short decision windows while

maintaining the capacity to revisit thresholds, messages, and responsibilities as unintended effects become visible. In a wicked setting, success is measured less by settling the debate than by maintaining enough legitimacy to keep acting while learning.

The lessons of Ulaanbaatar can be applied in other settings. Air pollution behaves as a wicked problem, not because it resists analysis, but because analysis alone cannot stabilize the terms on which action is judged fair. Surveillance must therefore be designed and governed with this instability in view. It needs to generate visibility that is credible across constituencies, to anchor rules that connect thresholds to action in ways people can anticipate, and to leave room for course correction as feedback loops unfold.

7.3. Reframing Surveillance as a Fragile Public Good

Digital surveillance plays a pivotal role in governance because it generates the visibility on which both community awareness and institutional action depend. Monitoring data are the basis for acknowledging exposure, prioritizing risks, and justifying interventions. In principle, this function allows households, policymakers, and international actors to work from a shared reference point. In practice, however, the value of surveillance is shaped more by the conditions under which data are produced and used than by the precision of its measurements. Who is represented in the monitoring networks, whether the information is trusted, and how results are legitimized all determine whether surveillance functions as a protective resource or becomes a site of contestation.

Representation is the first point of tension. Monitoring networks rarely capture all populations evenly, and the exclusion of marginalized groups from data perpetuates the same exclusion in governance. In Ulaanbaatar, for example, central districts have historically been more visible in official datasets than the ger areas where exposure is most acute. This disparity is not just a

distortion of accuracy but a political choice about whose realities are counted. The consequences of invisibility are both practical and symbolic: areas that remain underrepresented in data risk being overlooked in interventions.

Trust also shapes the effectiveness of surveillance. Data, no matter how precise, cannot protect unless they are seen as credible by those expected to act on it. Residents who view statistics as politicized or unreliable are unlikely to adjust their behaviour in response to warnings, while institutions that double community monitoring may dismiss results that challenge official accounts. Conversely, even modestly accurate systems can shape outcomes if they are transparent in their methods and participatory in their communication. Trust is not a prerequisite external to surveillance but an outcome of how it is organized and enacted.

Legitimacy adds a further layer of complexity. Conflicting results between data, predictive modelling, and community and personal lived experiences are not simply technical errors, but moments in which authority is negotiated. Whether data is reconciled or dismissed reflects the broader struggles over who has the right to define environmental reality. Mechanisms for open calibration, side-by-side reporting, or transparent explanation of divergence can convert contestation into credibility. Without them, surveillance risks eroding the very legitimacy upon which it depends.

These dynamics suggest that surveillance operates as a chain of capabilities. Data first creates visibility, but visibility must be recognized as legitimate to shape priorities; priorities must be institutionally absorbed to inform policy; and policies must be communicated in accessible ways if they are to support protective behaviour. Weakness in any part of this chain dissipates the value

of the whole. This is why technically sophisticated systems often fail to deliver meaningful protection: they generate data without legitimacy, or legitimacy without institutional uptake.

For this reason, surveillance should be understood as a fragile public good. Its fragility lies not only in limited resources or infrastructure, but also in the political and social conditions that determine who is represented, which institutions are trusted, and what constitutes credible evidence. When these conditions align, surveillance enables coordination across communities and institutions, turning pollution and other climate-related hazards from invisible into actionable concerns. When they do not, surveillance risks reinforcing invisibility and mistrust, leaving both policy and public behaviour unchanged.

7.4. Policy and Global Implications

The implications extend well beyond Mongolia. Surveillance, as the findings suggest, is not simply a neutral diagnostic tool but rather forms a governance lever. When trusted and embedded, it created new capacities for action by aligning communities, institutions, and global frameworks. When fragmented or politicized, it reinforces invisibility and mistrust, deepening the very inequities it is meant to reduce. Understanding surveillance in this way enables us to reconsider what constitutes success in national, regional, and international policy.

In Mongolia, the question is not whether additional data streams can be generated, but whether surveillance can reconfigure the relationships between measurement and decision-making. Surveillance that remains siloed within technical agencies contributes little; surveillance that triggers routines across health, housing, and energy reconstitutes governance. Its role as leverage depends not on precision but on whether it can alter how systems learn and adapt over time.

For LMICs more broadly, the lesson is that innovation cannot be evaluated solely by coverage or accuracy. Low-cost sensors and predictive models expand what can be seen, but their contribution hinges on institutional capacities and community adoption. Context matters because trust and access vary, producing different adoption ecologies. Equity matters because those most exposed are often least represented, and invisibility in data sustains invisibility in policy. The measure of a successful system is therefore not the density of monitoring but the degree to which it redistributes visibility and authority toward those most affected.

At the global scale, the paradox is sharper. International frameworks, such as the Sustainable Development Goals (SDGs), WHO guidelines, and the UNFCCC, rely on surveillance for accountability; yet, the systems most capable of producing globally legible data are concentrated in high-income contexts. Populations most affected by pollution and other adverse impacts of climate change are thus least represented in global governance, while standards are often invoked without regard for local feasibility. This misalignment erodes both local legitimacy and global accountability. Addressing it requires a shift from expecting LMICs to conform to external benchmarks to investing in systems that are interoperable, transparent, and locally embedded. Global surveillance must be conceived not as the extraction of data from peripheries but as the co-construction of infrastructures that are legitimate at both local and international levels.

7.5. Methodological Reflections

7.5.1. Participant Heterogeneity and Differential Capacity for Action

The interpretive claims advanced in this thesis are shaped by the heterogeneity of participants across housing conditions, caregiving roles, and geographic locations within Ulaanbaatar. Rather than enabling subgroup comparison or representational claims, this variation functioned

analytically by illustrating how the same surveillance information operated differently depending on structural position and capacity to respond.

Importantly, heterogeneity did not produce fundamentally divergent understandings of air pollution as a health threat. Instead, it shaped whether information could be acted upon, absorbed emotionally, or dismissed as impractical. This distinction matters for interpretation, particularly in evaluating the protective value of surveillance systems: variation across participants is best understood not as attitudinal difference, but as evidence that the effectiveness of surveillance is mediated by feasibility, institutional trust, and everyday constraints.

Reflecting on heterogeneity at this stage clarifies the limits and strengths of generalization in this thesis. The findings are not intended to represent populations statistically, but to illuminate mechanisms through which surveillance enables or fails to enable protection in high-exposure contexts. Participant diversity strengthens this contribution by demonstrating that uneven outcomes arise within shared exposure environments, reinforcing the argument that surveillance operated as a conditional public good rather than a uniform intervention.

7.5.2. Analytic Rigour and Interpretive Credibility

This thesis is interdisciplinary, integrating public health, behavioural science, and machine learning within a partnership-based research context. While this integration enabled a more comprehensive understanding of air pollution surveillance as a socio-technical system, it also introduced analytic risks related to epistemological misalignment, interpretive fragmentation, and uneven standards of evidence across disciplines. Ensuring analytic rigour therefore required deliberate strategies to stabilize interpretation and maintain credibility across disciplinary and institutional boundaries.

Rigour and credibility in the qualitative components of this thesis were supported through a reflexive and contextually grounded analytic process. During interviews, detailed field notes were systematically recorded to capture non-verbal cues, including tone, affect, pauses, and body language. These observations were reviewed immediately following each interview in consultation with the translator to clarify meaning, interrogate ambiguity, and assess how language choice, emphasis, or cultural framing may have shaped participant accounts.

Analytic scrutiny continued throughout data collection. Field notes and emerging interpretations were regularly reviewed and discussed with local partners to contextualize preliminary insights, challenge early assumptions, and refine analytic focus using locally grounded knowledge. This process functioned as an interpretive check rather than a consensus-building exercise, allowing uncertainty, divergence, and contradiction to be retained as analytically meaningful rather than resolved prematurely.

Data collection and analysis proceeded iteratively. Insights from earlier interviews informed subsequent lines of inquiry, while variation in emphasis, affect, and interpretation was preserved to reflect differences in lived experience and institutional interaction. Together, these practices strengthened the credibility and interpretive integrity of the findings by making analytic decisions explicit, reflexive, and responsive to context.

Draft analytic summaries and written interpretations were reviewed with local partners to ensure accuracy of representation, contextual coherence, and fidelity to participants' meanings, particularly where translation, institutional critique, or culturally situated practices were central to interpretation.[286]

7.5.3. Cross-Disciplinary Integration and Epistemic Coherence

This thesis employed a multi-methods research design that combines qualitative inquiry, behavioural analyses, and technical system development. Bringing together the Social-Ecological Model, an adapted Technology Acceptance Model, and a machine learning-based monitoring pipeline demonstrated the value of methodological pluralism for studying public health and climate change surveillance. Each strand contributed a unique perspective: qualitative interviews illuminated lived experience and structural determinants of exposure; behavioural analyses revealed the institutional and perceptual conditions necessary for adoption; and the technical work demonstrated the feasibility of real-time monitoring using low-cost sensors. Only by holding these strands together could the complexity of surveillance as a socio-technical system be captured.

The interdisciplinary nature of this work also posed challenges. Bridging public health, computer science, and social science literatures required negotiating different epistemological assumptions and methodological standards. Ensuring technical outputs were interpretable in a social context and that the qualitative insights could meaningfully inform technical design required deliberate effort to move beyond juxtaposition and towards integration. These challenges are emblematic of the broader difficulties inherent in interdisciplinary research, where rigour must be balanced with the capacity to translate across disciplinary boundaries.

7.5.4. Knowledge Production Within Institutional Partnership Constraints

Institutional partnerships further shaped the methodological trajectory. Collaborating with UNICEF Mongolia and other local organizations provided access to data, networks, and practical insights, but also introduced constraints tied to partner priorities, timelines, and sensitivities. The position of this research, situated between academic inquiry and applied practice, requires balancing the expectations of scholarly rigour with the responsiveness demanded by policy and

programmatic partners. Acknowledging this reflective dimension is essential, as it underscores that methodological choices were influenced not only by technical considerations but also by the relational and institutional contexts in which the research unfolded.

7.5.5. Standards, Trust, and the Politics of Risk Communication

The decision to use the U.S. EPA AQI breakpoint framework rather than Mongolia's national air quality standard was not solely a technical choice, but a communicative one. Although national standards exist prior qualitative findings in this thesis indicate limited public trust and domestic air quality reporting an environmental governance. In this context, the use of an externally recognised framework functioned as a stabilizing reference for risk interpretation, enabling exposure information to be communicated in a form perceived as credible an intelligible by community members.

At the same time, the choice carries important consequences. Applying an external standard necessarily privileges one regulatory epistemology over others, reinforcing global hierarchies in knowledge production and potentially marginalizing local standard setting processes. This highlights that digital health systems do not simply transmit information; they actively shape credibility, authority, and public meaning of health risks.

7.6. Future Directions

Future research should be understood not only as filling empirical gaps but as extending the analytic and governance frameworks advanced in this thesis. Linking air quality data to health outcomes is not just a pragmatic step but also a way to close epistemic loops, ensuring connections between exposures and consequences. Comparative studies across LMICs would test the portability of concepts such as capability chains, adoption ecologies, and reconciliation protocols,

moving towards design principles that are adaptive rather than context-bound. The increasing reliance on digital systems and AI models also raises urgent questions about privacy, fairness, and accountability. These are not ancillary concerns but central determinants of legitimacy. Future research must therefore treat governance design, ensuring that systems evolve in ways that are both ethically grounded and technically robust.

Additionally, the analysis presented here generates a set of propositions that can be empirically evaluated. These include whether transparency mediates the relationship between expanded monitoring and policy responsiveness; whether institutional capacity conditions the effect of technical accuracy on budget allocation; whether reconciliation protocols between community and official data foster adoption more effectively than marginal improvements in model precision; and whether equity-weighted siting of monitors provides greater health protection than uniform distribution at the same cost. These propositions extend the theoretical contributions of this thesis into testable claims, offering pathways for comparative evaluation and the development of a science of equitable surveillance.

7.7. Conclusion

This thesis has argued that real-time air pollution surveillance is not a neutral technical intervention, but a socio-technical system shaped by context, innovation, and adoption. By integrating three distinct studies, it has provided a more comprehensive framework for understanding how surveillance can operate equitably in low-resource, high vulnerability settings.

The case of Ulaanbaatar, Mongolia, demonstrated both the urgency and the possibility of such an approach. It highlights the risks of inaction in one of the world's most polluted capitals, while also showing that innovation can create new opportunities when designed with attention to equity,

representation, and trust. More broadly, it provides a blueprint for how surveillance systems in LMICs can be designed to function as public goods: technically robust, socially legitimate, and institutionally embedded.

By combining social insight, technical feasibility, and institutional analysis, this work contributes to a growing recognition that public health surveillance must be understood as both infrastructure and process. It offers a pathway to transform air pollution from an invisible hazard into an actionable public health priority, demonstrating that the most effective systems will be those that connect data to lived realities and embed evidence into governance at all scales. Surveillance should therefore be understood not as a static infrastructure but as a dynamic bridge, whose value lies in its ability to integrate science, policy, and community experience in the pursuit of health equity.

8. Conclusion

The Conditions of Protection: Making Surveillance Work

Climate change is among the most pressing global health challenges of the twenty-first century. Hazards occur more frequently, compound across seasons, and demand decisions within windows shorter than the cycles of planning, procurement, and budgeting through which public institutions usually operate. Adaptation, therefore, has practical meaning only insofar as evidence can be translated into protection before those windows close. Where signals lag events, where guidance lacks social legitimacy for those who must act on it, or where institutional obligations remain unspecified, systems document harm rather than reduce it.

The distribution of harm is patterned rather than random. In many LMIC and low-resource contexts, exposure concentrates where feasible options are fewest and administrative visibility is thinnest. When monitoring, communication, and responses are organized around averages, attention and resources predictably flow toward existing power rather than toward need. An adaptation agenda that takes justice seriously must do more than assert moral priorities; it must specify operational choices that translate recognition of lived realities into representation in evidence and into responsibility for action that is visible to the public. Only under such conditions does adaptation move from recording inequity to reducing it.

Viewed through this lens, technology is valuable when it helps institutions keep time with risk and keep faith with residents. Precision and scale matter, but under constraint, different properties govern protective value. Timeliness determines whether a signal arrives while choices exist. Intelligibility determines whether the data can be understood and questioned by residents and front-line staff. Reach determines whether communication travels through channels that people actually use and trust. Follow-through determines whether alerts are bound to actions with identifiable owners and budgets. These are not embellishments but rather the conditions under which information becomes care, and they can be specified at the outset rather than justified after failures.

From that alignment, several analytic claims follow. First, adaptation in constrained settings should be valued by proportional protection rather than by aggregate performance, meaning that visibility, attention, and budget are allocated to the highest-risk group. The relevant question is whether attention and support increase where risk is greatest, and whether they do so in time to change outcomes. This changes evaluation from counting devices or reporting average error to judging whether visibility and resources are distributed towards those who bear the highest burden and

whether those shifts occur within decision windows that matter. Second, time itself becomes a determinant of validity. When hazards move quickly, speed and continuity often dominate marginal gains in precision; provenance and intelligibility become part of validity because evidence will be contested. Data that arrive quickly, can be explained, and map transparently to recognizable actions are more protective than exquisitely accurate signals that arrive too late or cannot be defended in public. Third, institutional design is decisive. Durable gains emerge from simple, explicit routines: thresholds that map to actions with named owners and budgets; outreach that makes highly exposed groups both visible and reachable; feedback that adjusts protocols across seasons. In this view, technical infrastructure earns its place by sustaining these routines – by keeping the right people in view at the right time and by producing explanations that practitioners and residents can use.

Some tensions cannot be eliminated but must be managed. Speed competes with deliberation; openness with privacy; standardization with local knowledge; new visibility with the risk of raising expectations that exceed capacity. Naming these tensions clarifies where the guardrails are required. Publishing calibration notes and decision rules protects legitimacy when evidence is disputed. Equity-aware sitting and challenge choices guard against drift back to averages. Budgeted responsibilities protect against the familiar fate of pilots that signal without service. None of these safeguards is conceptually dramatic; rather, all are operationally decisive.

The scope of these claims is intentionally conservative. The empirical base is Ulaanbaatar, a cold-climate city with sparse regulatory coverage; the qualitative analyses center on specific communities and institutions; and the technical platform demonstrates short-horizon forecasting and operational traceability rather than long-horizon forecasting. Within these boundaries, however, the argument is precise: adaptation becomes credible when social legitimacy,

institutional obligation, and technical capacity are designed to meet each other on the clock imposed by climate hazards. The contribution is a method for aligning justice with operations rather than a claim to universal generality.

This yields a different way to act and evaluate action. Programs should state in advance the population for whom protection is being prioritized, the time windows within which signals and services must arrive, the channels and rationales that make guidance intelligible, and the rules that link thresholds to visible response. They can then evaluate whether those commitments were kept where risk is greatest and adjust accordingly. Because these criteria are concrete, they can be monitored with routine information and audited across seasons. This shifts assessment from activity to consequence and provides a shared yardstick that travels across hazards and sites.

In that sense, the importance of this work is less a claim about one city than a practical grammar for aligning adaptation with justice. By insisting that recognition, representation, legitimacy, and responsibility operate as requirements rather than afterthoughts, and by requiring technology to earn its place by meeting those requirements, the thesis provides a way to move adaptation from recording inequity to reducing it where resources are thinnest, decision windows are shortest, and the stakes are highest.

References

1. GBD 2019 Risk Factors Collaborators. Global burden of 87 risk factors in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet Lond Engl. 2020 Oct 17;396(10258):1223–49.

2. Labaki WW, Han MK. Chronic respiratory diseases: a global view. Lancet Respir Med. 2020 June 1;8(6):531–3.

3. Lee BJ, Kim B, Lee K. Air Pollution Exposure and Cardiovascular Disease. Toxicol Res. 2014 June;30(2):71–5.

4. Ljungman PLS, Andersson N, Stockfelt L, Andersson EM, Nilsson Sommar J, Eneroth K, et al. Long-Term Exposure to Particulate Air Pollution, Black Carbon, and Their Source Components in Relation to Ischemic Heart Disease and Stroke. Environ Health Perspect. 2019 Oct;127(10):107012.

5. Long-term exposure to low-level ambient air pollution and incidence of stroke and coronary heart disease: a pooled analysis of six European cohorts within the ELAPSE project - The Lancet Planetary Health [Internet]. [cited 2025 Sept 27]. Available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00195-9/fulltext

6. Hao H, Yoo SR, Strickland MJ, Darrow LA, D'Souza RR, Warren JL, et al. Effects of air pollution on adverse birth outcomes and pregnancy complications in the U.S. state of Kansas (2000–2015). Sci Rep. 2023 Dec 6;13:21476.

7. Syama KP, Blais E, Kumarathasan P. Maternal mechanisms in air pollution exposure-related adverse pregnancy outcomes: A systematic review. Sci Total Environ. 2025 Mar 20;970:178999.

8. Sarizadeh R, Dastoorpoor M, Goudarzi G, Simbar M. The Association Between Air Pollution and Low Birth Weight and Preterm Labor in Ahvaz, Iran. Int J Womens Health. 2020 May 4;12:313–25.

9. Rani P, Dhok A. Effects of Pollution on Pregnancy and Infants. Cureus. 15(1):e33906.

10. Johnson NM, Hoffmann AR, Behlen JC, Lau C, Pendleton D, Harvey N, et al. Air pollution and children's health—a review of adverse effects associated with prenatal exposure from fine to ultrafine particulate matter. Environ Health Prev Med. 2021;26:72.

11. Kusters MSW, Essers E, Muetzel R, Ambrós A, Tiemeier H, Guxens M. Air pollution exposure during pregnancy and childhood, cognitive function, and emotional and behavioral problems in adolescents. Environ Res. 2022 Nov;214(Pt 2):113891.

12. Nováková Z, Novák J, Kitanovski Z, Kukučka P, Smutná M, Wietzoreck M, et al. Toxic potentials of particulate and gaseous air pollutant mixtures and the role of PAHs and their derivatives. Environ Int. 2020 June 1;139:105634.

13. Xing YF, Xu YH, Shi MH, Lian YX. The impact of PM2.5 on the human respiratory system. J Thorac Dis. 2016 Jan;8(1):E69–74.

14. Feng S, Huang F, Zhang Y, Feng Y, Zhang Y, Cao Y, et al. The pathophysiological and molecular mechanisms of atmospheric PM2.5 affecting cardiovascular health: A review. Ecotoxicol Environ Saf. 2023 Jan 1;249:114444.

15. Chen TM, Kuschner WG, Gokhale J, Shofer S. Outdoor Air Pollution: Ozone Health Effects. Am J Med Sci. 2007 Apr 1;333(4):244–8.

16. Chen TM, Kuschner WG, Gokhale J, Shofer S. Outdoor Air Pollution: Nitrogen Dioxide, Sulfur Dioxide, and Carbon Monoxide Health Effects. Am J Med Sci. 2007 Apr 1;333(4):249–56.

17. Hesterberg TW, Bunn WB, McClellan RO, Hamade AK, Long CM, Valberg PA. Critical review of the human data on short-term nitrogen dioxide (NO2) exposures: Evidence for NO2 no-effect levels. Crit Rev Toxicol. 2009 Oct 1;39(9):743–81.

18. Filonchyk M, Peterson MP, Zhang L, Hurynovich V, He Y. Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Sci Total Environ. 2024 July 20;935:173359.

19. Soeder DJ. Greenhouse Gas and Climate Change. In: Soeder DJ, editor. Energy Futures: The Story of Fossil Fuel, Greenhouse Gas, and Climate Change [Internet]. Cham: Springer Nature Switzerland; 2025 [cited 2025 Sept 27]. p. 97–141. Available from: https://doi.org/10.1007/978-3-031-83603-9_5

20. Mathew N, Somanathan A, Tirpude A, Arfin T. The impact of short-lived climate pollutants on the human health. Environ Pollut Manag. 2024 Oct 1;1:1–14.

21. Shaheryar M, Hayat M, Shah MN, Hayat HS, Rehman HU, Sheryar A, et al. Agricultural Pollution and Its Relation to Climate Change. In: Abdel Latef AAH, Zayed EM, Omar AA, editors. Bioremediation and Nanotechnology for Climate Change Mitigation [Internet]. Singapore: Springer Nature; 2025 [cited 2025 Sept 27]. p. 137–55. Available from: https://doi.org/10.1007/978-981-96-3069-1_6

22. Sivakumar MVK. Climate Extremes and Impacts on Agriculture. In: Agroclimatology [Internet]. John Wiley & Sons, Ltd; 2020 [cited 2025 Sept 27]. p. 621–47. Available from: https://onlinelibrary.wiley.com/doi/abs/10.2134/agronmonogr60.2016.0003

23. He C, Kumar R, Tang W, Pfister G, Xu Y, Qian Y, et al. Air Pollution Interactions with Weather and Climate Extremes: Current Knowledge, Gaps, and Future Directions. Curr Pollut Rep. 2024 Sept 1;10(3):430–42.

24. Caminade C, McIntyre KM, Jones AE. Impact of recent and future climate change on vector-borne diseases. Ann N Y Acad Sci. 2019 Jan;1436(1):157–73.

25. Mechanisms underlying food insecurity in the aftermath of climate-related shocks: a systematic review - The Lancet Planetary Health [Internet]. [cited 2025 Sept 27]. Available from: https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(23)00003-7/fulltext

26. Nguyen TT, Grote U, Neubacher F, Rahut DB, Do MH, Paudel GP. Security risks from climate change and environmental degradation: implications for sustainable land use transformation in the Global South. Curr Opin Environ Sustain. 2023 Aug 1;63:101322.

27. Bezgrebelna M, McKenzie K, Wells S, Ravindran A, Kral M, Christensen J, et al. Climate Change, Weather, Housing Precarity, and Homelessness: A Systematic Review of Reviews. Int J Environ Res Public Health. 2021 Jan;18(11):5812.

28. Desai BH, Mandal M. Role of Climate Change in Exacerbating Sexual and Gender-Based Violence against Women: A New Challenge for International Law. Environ Policy Law. 2021 Apr 16;51(3):137–57.

29. Caridade SMM, Vidal DG, Dinis MAP. Climate Change and Gender-Based Violence: Outcomes, Challenges and Future Perspectives. In: Leal Filho W, Vidal DG, Dinis MAP, Dias RC, editors. Sustainable Policies and Practices in Energy, Environment and Health Research: Addressing Cross-cutting Issues [Internet]. Cham: Springer International Publishing; 2022 [cited 2025 Sept 27]. p. 167–76. Available from: https://doi.org/10.1007/978-3-030-86304-3_10

30. Aithal SS, Bhargava V, Adekoya A, Chaudhary N, Tyagi SK, Kurmi OP. Air quality in low- and middle-income countries: what is the impact on respiratory morbidity and mortality? In: Inequalities in Respiratory Health [Internet]. European Respiratory Society; 2024 [cited 2025 Oct 12]. p. 203–13. Available from: https://publications.ersnet.org/content/book/monograph/978-1-84984-158-0/part/part_3/chapter/chapter_18

31. Yin H, Brauer M, Zhang J (Jim), Cai W, Navrud S, Burnett R, et al. Population ageing and deaths attributable to ambient PM2·5 pollution: a global analysis of economic cost. Lancet Planet Health. 2021 June 1;5(6):e356–67.

32. Lopez-Aparicio S, Grythe H, Drabicki A, Chwastek K, Toboła K, Górska-Niemas L, et al. Environmental sustainability of urban expansion: Implications for transport emissions, air pollution, and city growth. Environ Int. 2025 Feb 1;196:109310.

33. Hajat A, Hsia C, O'Neill MS. Socioeconomic Disparities and Air Pollution Exposure: A Global Review. Curr Environ Health Rep. 2015 Dec;2(4):440–50.

34. Preventing disease through healthy environments: towards an estimate of the environmental burden of disease [Internet]. [cited 2025 Oct 12]. Available from: https://www.who.int/publications/i/item/9241593822

35. Sheffield PE, Landrigan PJ. Global Climate Change and Children's Health: Threats and Strategies for Prevention. Environ Health Perspect. 2011 Mar;119(3):291–8.

36. Perera FP. Multiple Threats to Child Health from Fossil Fuel Combustion: Impacts of Air Pollution and Climate Change. Environ Health Perspect. 2017 Feb;125(2):141–8.

37. Air pollution costs European economies US$ 1.6 trillion a year in diseases and deaths, new WHO study says [Internet]. [cited 2025 Oct 12]. Available from: https://www.who.int/europe/news/item/28-04-2015-air-pollution-costs-european-economies-us-1-6-trillion-a-year-in-diseases-and-deaths-new-who-study-says

38. Concas F, Mineraud J, Lagerspetz E, Varjonen S, Liu X, Puolamäki K, et al. Low-Cost Outdoor Air Quality Monitoring and Sensor Calibration: A Survey and Critical Analysis. ACM Trans Sen Netw. 2021 May 29;17(2):20:1-20:44.

39. Irawan Y, Wahyuni R, Muhardi -, Fonda H, Hamzah ML, Muzawi R. Real Time System Monitoring and Analysis-Based Internet of Things (IoT) Technology in Measuring Outdoor Air Quality. Int J Interact Mob Technol IJIM. 2021 May 25;15(10):224–40.

40. Hubbell BJ, Kaufman A, Rivers L, Schulte K, Hagler G, Clougherty J, et al. Understanding social and behavioral drivers and impacts of air quality sensor use. Sci Total Environ. 2018 Apr 15;621:886–94.

41. Clark ML, Peel JL, Balakrishnan K, Breysse PN, Chillrud SN, Naeher LP, et al. Health and Household Air Pollution from Solid Fuel Use: The Need for Improved Exposure Assessment. Environ Health Perspect. 2013 Oct 1;121(10):1120–8.

42. Arvin M, Jalaei M, Taheri J, Badakhshan B, Ghane M, Sharifi A. Examining the relationship between urban form and social inequality: A neighborhood-level analysis. Appl Geogr. 2025 Mar 1;176:103532.

43. Perlin SA, Wong D, Sexton K. Residential proximity to industrial sources of air pollution: interrelationships among race, poverty, and age. J Air Waste Manag Assoc 1995. 2001 Mar;51(3):406–21.

44. Jayatilleke K. Challenges in Implementing Surveillance Tools of High-Income Countries (HICs) in Low Middle Income Countries (LMICs). Curr Treat Options Infect Dis. 2020;12(3):191–201.

45. Kassler WJ, Bowman CL. Overcoming Public Health "Surveillance": When Words Matter. Am J Public Health. 2023 Oct;113(10):1102–5.

46. Faiz F, Le V, Masli EK. Determinants of digital technology adoption in innovative SMEs. J Innov Knowl. 2024 Oct 1;9(4):100610.

47. Allen RW, Gombojav E, Barkhasragchaa B, Byambaa T, Lkhasuren O, Amram O, et al. An assessment of air pollution and its attributable mortality in Ulaanbaatar, Mongolia. Air Qual Atmosphere Health. 2013;6(1):137–50.

48. Sanduijav C, Ferreira S, Filipski M, Hashida Y. Air pollution and happiness: Evidence from the coldest capital in the world. Ecol Econ. 2021 Sept 1;187:107085.

49. Laumbach RJ, Kipen HM. Respiratory Health Effects of Air Pollution: Update on Biomass Smoke and Traffic Pollution. J Allergy Clin Immunol. 2012 Jan;129(1):3–13.

50. Ge Y, Lin Y, Tsogtbayar O, Khuyagaa SO, Khurelbaatar E, Galsuren J, et al. Interactive effects of air pollutants and viral exposure on daily influenza hospital visits in Mongolia. Environ Res. 2025 Mar 1;268:120743.

51. Burchard-Dziubińska M, Antczak E, Myagmarjav T. When nomads become migrants: A case study of Mongolia. Asian Pac Migr J. 2025 Sept 1;34(3):488–512.

52. Xu Y, Zhang Y, Chen J. Migration under economic transition and changing climate in Mongolia. J Arid Environ. 2021 Feb 1;185:104333.

53. Full article: In-Between the Rural and the Urban: Skill and Migration in Ulaanbaatar's Ger-Districts [Internet]. [cited 2025 Oct 12]. Available from: https://www.tandfonline.com/doi/full/10.1080/00141844.2021.1909628

54. Park H, Fan P, John R, Ouyang Z, Chen J. Spatiotemporal changes of informal settlements: *Ger* districts in Ulaanbaatar, Mongolia. Landsc Urban Plan. 2019 Nov 1;191:103630.

55. Uddin SMN, Li Z, Gaillard JC, Tedoff PF, Mang HP, Lapegue J, et al. Exposure to WASH-borne hazards: A scoping study on peri-urban Ger areas in Ulaanbaatar, Mongolia. Habitat Int. 2014 Oct 1;44:403–11.

56. Byambadorj T, Amati M, Ruming KJ. Twenty-first century nomadic city: Ger districts and barriers to the implementation of the Ulaanbaatar City Master Plan. Asia Pac Viewp. 2011;52(2):165–77.

57. Hamiduddin I, Plueckhahn R. From the ger districts to the city centre: contrasts and inequities of access and mobility in Ulaanbaatar, Mongolia. Local Environ. 2021 Dec 2;26(12):1546–63.

58. Sainnokhoi TA, Tuvshinbayar Y, Bat-ochir M, Eck-Varanka B, Hubai K, Teke G, et al. Indoor environments: Evaluating air quality in Ulaanbaatar's traditional gers. Chemosphere. 2025 May 1;377:144338.

59. Dickinson-Craig E, Bartington SE, Watts R, Mandakhbayar O, Khurelbaatar EO, Ochir C, et al. Carbon monoxide levels in households using coal-briquette fuelled stoves exceed WHO air quality guidelines in Ulaanbaatar, Mongolia. Int J Environ Health Res. 2023 Dec 2;33(12):1760–71.

60. Particulate pollution in Ulaanbaatar, Mongolia | Air Quality, Atmosphere & Health [Internet]. [cited 2025 Oct 12]. Available from: https://link.springer.com/article/10.1007/s11869-013-0198-7

61. Anenberg SC, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, et al. Cleaner Cooking Solutions to Achieve Health, Climate, and Economic Cobenefits. Environ Sci Technol. 2013 May 7;47(9):3944–52.

62. Soyol-Erdene TO, Ganbat G, Baldorj B. Urban Air Quality Studies in Mongolia: Pollution Characteristics and Future Research Needs. Aerosol Air Qual Res. 2021 Oct 26;21(12):210163.

63. Badarch J, Harding J, Dickinson-Craig E, Azen C, Ong H, Hunter S, et al. Winter Air Pollution from Domestic Coal Fired Heating in Ulaanbaatar, Mongolia, Is Strongly Associated with a Major Seasonal Cyclic Decrease in Successful Fecundity. Int J Environ Res Public Health. 2021 Jan;18(5):2750.

64. CREA. U.S. embassy AQ data halt: Ramped up government monitoring could save hundreds of millions of dollars per city [Internet]. Centre for Research on Energy and Clean Air. 2025 [cited 2025 Oct 12]. Available from: https://energyandcleanair.org/us-embassy-aq-data-halt/

65. Ariunsaikhan A, Batbold C, Chonokhuu S, Gil-Alana LA. Atmospheric pollution in Ulaanbaatar: Persistence and long-run trends. PLOS ONE. 2025 June 3;20(6):e0322991.

66. Air pollution in Mongolia. Bull World Health Organ. 2019 Feb 1;97(2):79–80.

67. Mongolia's air pollution is a child health crisis [Internet]. [cited 2025 Oct 12]. Available from: https://www.unicef.org/eap/press-releases/mongolias-air-pollution-child-health-crisis

68. Dickinson-Craig E, Badarch J, Bartington S, Hemming K, Thayakaran R, Day R, et al. Impact assessment of a raw coal ban on maternal and child health outcomes in Ulaanbaatar: a protocol for an interrupted time series study. BMJ Open. 2023 Apr 24;13(4):e061723.

69. Do LAH, Tsedenbal N, Khishigmunkh C, Tserendulam B, Altanbumba L, Luvsantseren D, et al. Impact of pneumococcal conjugate vaccine 13 introduction on severe lower respiratory tract infections associated with respiratory syncytial virus or influenza virus in hospitalized children in Ulaanbaatar, Mongolia. IJID Reg. 2024 Mar 19;11:100357.

70. Municipality States It Would Not Impose Another Migration Ban Based on IOM Research [Internet]. International Organization for Migration. [cited 2025 Oct 12]. Available from: https://www.iom.int/news/municipality-states-it-would-not-impose-another-migration-ban-based-iom-research

71. adbheadhoncho. Ulaanbaatar Urban Services and Ger Areas Development Investment Program - Tranche 2 [Internet]. Asian Development Bank; 2017 [cited 2025 Oct 12]. Available from: https://www.adb.org/projects/45007-005/main

72. Ramachandran P. 51199-001: Ulaanbaatar Air Quality Improvement Program | Asian Development Bank. 2018.

73. JICA. Capacity Development Project for Air Pollution Control in Ulaanbaatar City | Mongolia | Countries & Regions | JICA. 2013.

74. Braham WW, Hakkarainen M, Buyan M, Janjindorj G, Turner J, Erdenekhuyag S. Cooking, Heating, Insulating Products and Services (CHIPS) for Mongolian ger: Reducing energy, cost, and indoor air pollution. Energy Sustain Dev. 2022 Dec 1;71:462–79.

75. Altanzul E. Czech NGO to implement project on air pollution in Ulaanbaatar and Arkhangai. 2018.

76. A multiparty and global effort to address air pollution around the world [Internet]. [cited 2025 Oct 12]. Available from: https://journals.openedition.org/factsreports/6131

77. Mongolia Economic Update, November 2024: Sustaining the Gains - Special Focus : Distributional Impacts of Mongolia's Fiscal System. 2024 Dec 16 [cited 2026 Jan 14]; Available from: https://hdl.handle.net/10986/42544

78. Jansen A, Wang R, Behrens P, Hoekstra R. Beyond GDP: a review and conceptual framework for measuring sustainable and inclusive wellbeing. Lancet Planet Health. 2024 Sept 1;8(9):e695–705.

79. Martin Eigbike. Health research capacity strengthening in low and middle-income countries: current situation and opportunities to leverage data for better coordination and greater impact. [Internet]. ESSENCE for Health Research Initiative; 2020 Sept. Available from: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://tdr.who.int/docs/librariesprovider10/essence/essence-mechanism-consultant-report-2020.pdf

80. Franzen SRP, Chandler C, Lang T. Health research capacity development in low and middle income countries: reality or rhetoric? A systematic meta-narrative review of the qualitative literature. BMJ Open. 2017 Jan 27;7(1):e012332.

81. Low- and Middle-income Countries - List [Internet]. Wellcome. [cited 2026 Jan 15]. Available from: https://wellcome.org/research-funding/guidance/prepare-to-apply/low-and-middle-income-countries

82. Adger WN. Vulnerability. Glob Environ Change. 2006 Aug 1;16(3):268–81.

83. Underserved group [Internet]. Toolkit. [cited 2026 Jan 14]. Available from: https://toolkit.ncats.nih.gov/glossary/underserved-group

84. Bourke B. Positionality: Reflecting on the Research Process. Qual Rep. 2014 Aug 18;19(33):1–9.

85. Full article: Positionality and reflexivity: negotiating insider-outsider positions within and across cultures [Internet]. [cited 2026 Jan 14]. Available from: https://www.tandfonline.com/doi/full/10.1080/1743727X.2023.2266375

86. Haraway D. Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective. Fem Stud. 1988;14(3):575–99.

87. Lee CJG. Reconsidering Constructivism in Qualitative Research. Educ Philos Theory. 2012;44(4):403–12.

88. Crotty M. Foundations of Social Research: Meaning and perspective in the research process. London: Routledge; 2020. 256 p.

89. Kelly LM, Cordeiro M. Three principles of pragmatism for research on organizational processes. Methodol Innov. 2020 May 1;13(2):2059799120937242.

90. Goldkuhl G. Pragmatism vs interpretivism in qualitative information systems research. Eur J Inf Syst. 2012 Mar 1;21(2):135–46.

91. Olmos-Vega FM, Stalmeijer RE, Varpio L, Kahlke R. A practical guide to reflexivity in qualitative research: AMEE Guide No. 149. Med Teach. 2023 Mar 4;45(3):241–51.

92. Blank M. Writing with research partners 'from the field': Plural knowledges and epistemic justice in qualitative research. Prog Hum Geogr. 2025 Aug 1;49(4):359–75.

93. Ten threats to global health in 2019 [Internet]. [cited 2020 Sept 18]. Available from: https://www.who.int/vietnam/news/feature-stories/detail/ten-threats-to-global-health-in-2019

94. Air pollution and health - Air Pollution - Environmental Policy - UNECE [Internet]. [cited 2020 Oct 16]. Available from: https://www.unece.org/environmental-policy/conventions/envlrtapwelcome/cross-sectoral-linkages/air-pollution-and-health.html

95. Perera FP. Multiple threats to child health from fossil fuel combustion: Impacts of air pollution and climate change. Vol. 125, Environmental Health Perspectives. Public Health Services, US Dept of Health and Human Services; 2017. p. 141–8.

96. Boogaard H, Walker K, Cohen AJ. Air pollution: The emergence of a major global health risk factor. Vol. 11, International Health. Oxford University Press; 2019. p. 417–21.

97. Air Pollution and Climate Change | Institute for Advanced Sustainability Studies [Internet]. [cited 2020 Oct 16]. Available from: https://www.iass-potsdam.de/en/output/dossiers/air-pollution-and-climate-change

98. Fuller R, Landrigan PJ, Balakrishnan K, Bathan G, Bose-O'Reilly S, Brauer M, et al. Pollution and health: a progress update. Lancet Planet Health. 2022 June 1;6(6):e535–47.

99. Lelieveld J, Haines A, Burnett R, Tonne C, Klingmüller K, Münzel T, et al. Air pollution deaths attributable to fossil fuels: observational and modelling study. BMJ. 2023 Nov 29;383:e077784.

100. Qi G, Che J, Wang Z. Differential effects of urbanization on air pollution: Evidences from six air pollutants in mainland China. Ecol Indic. 2023 Feb 1;146:109924.

101. Anjum MS, Ali SM, Imad-ud-din M, Subhani MA, Anwar MN, Nizami AS, et al. An Emerged Challenge of Air Pollution and Ever-Increasing Particulate Matter in Pakistan; A Critical Review. J Hazard Mater. 2021 Jan 15;402:123943.

102. Lippmann M, Maynard RL. Air Quality Guidelines and Standards1. In: Holgate ST, Samet JM, Koren HS, Maynard RL, editors. Air Pollution and Health [Internet]. London: Academic Press; 1999 [cited 2025 Feb 6]. p. 983–1017. Available from: https://www.sciencedirect.com/science/article/pii/B9780123523358501186

103. Muindi K, Egondi T, Kimani-Murage E, Rocklov J, Ng N. "We are used to this": a qualitative assessment of the perceptions of and attitudes towards air pollution amongst slum residents in Nairobi. BMC Public Health. 2014 Mar 5;14(1):226.

104. Bayart NE, Pereira G, Reid CM, Nyadanu SD, Badamdorj O, Lkhagvasuren B, et al. Effects of outdoor air pollution on hospital admissions from cardiovascular diseases in the capital city of Mongolia. Atmospheric Pollut Res. 2025 Jan 1;16(1):102338.

105. Allen RW, Gombojav E, Barkhasragchaa B, Byambaa T, Lkhasuren O, Amram O, et al. An assessment of air pollution and its attributable mortality in Ulaanbaatar, Mongolia. Air Qual Atmosphere Health. 2013 Mar 1;6(1):137–50.

106. Air pollution in Mongolia: Opportunities for further actions [Internet]. UNDP. [cited 2025 Jan 7]. Available from: https://www.undp.org/mongolia/publications/air-pollution-mongolia-opportunities-further-actions

107. Mongolia's Air Pollution Crisis: A call to action to protection children's health [Internet]. Humanitarian UNICEF. [cited 2025 Jan 7]. Available from: https://www.corecommitments.unicef.org/kp/mongolia's-air-pollution-crisis

108. Sambuu T, Gunsmaa G, Badarch TU, Mukhtar Y, Ichikawa M. Carbon monoxide poisoning following a ban on household use of raw coal, Mongolia. Bull World Health Organ. 2023 July 1;101(7):470–7.

109. Ikelle II, Sunday NJ, Sunday NF, John J, Okechukwu OJ, Elom NI. Thermal Analyses of Briquette Fuels Produced from Coal Dust and Groundnut Husk. Acta Chem Malays. 2020 June 28;4(1):24–7.

110. Akamani K, Holzmueller EJ, Groninger JW. Managing Wicked Environmental Problems as Complex Social-Ecological Systems: The Promise of Adaptive Governance. In: Melesse AM, Abtew W, editors. Landscape Dynamics, Soils and Hydrological Processes in Varied Climates [Internet]. Cham: Springer International Publishing; 2016 [cited 2025 Jan 8]. p. 741–62. Available from: https://doi.org/10.1007/978-3-319-18787-7_33

111. Walls HL. Wicked problems and a 'wicked' solution. Glob Health. 2018 Apr 13;14(1):34.

112. edley, Litosseliti L. Edley, N. and Litosseliti, L. (2010). ‘Contemplating interviews and focus groups’. In Litosseliti, L. (ed.) Research Methods in Linguistics. London: Continuum. pp. 155-179. In 2010.

113. Karatsareas P. Semi-Structured Interviews. In: Kircher R, Zipp L, editors. Cambridge, UK: Cambridge University Press; 2022 [cited 2024 Nov 15]. p. 99–113. Available from: https://www.cambridge.org/gb/academic/subjects/languages-linguistics/research-methods-linguistics/research-methods-language-attitudes?format=PB

114. National Academies of Sciences E, Division H and M, Practice B on PH and PH, States C on CBS to PHE in the U, Baciu A, Negussie Y, et al. The Root Causes of Health Inequity. In: Communities in Action: Pathways to Health Equity [Internet]. National Academies Press (US); 2017 [cited 2025 Jan 20]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK425845/

115. Lu K, Xiong X, Horras A, Jiang B, Li M. Impact of financial barriers on health status, healthcare utilisation and economic burden among individuals with cognitive impairment: a national cross-sectional survey. BMJ Open. 2022 May 4;12(5):e056466.

116. Byambadorj T, Amati M, Ruming KJ. Twenty-first century nomadic city: Ger districts and barriers to the implementation of the Ulaanbaatar City Master Plan. Asia Pac Viewp. 2011;52(2):165–77.

117. Social Exclusion in the Ger Districts of Ulaanbaatar | UCL Emerging Subjects Blog [Internet]. [cited 2025 Jan 9]. Available from: https://blogs.ucl.ac.uk/mongolian-economy/2015/06/24/social-exclusion-in-the-ger-districts-of-ulaanbaatar/

118. From the ger districts to the city centre: contrasts and inequities of access and mobility in Ulaanbaatar, Mongolia. Local Environ. 2021;26(12):1546–63.

119. Squires A. Methodological challenges in cross-language qualitative research: A research review. Int J Nurs Stud. 2009 Feb 1;46(2):277–87.

120. Esposito N. From Meaning to Meaning: The Influence of Translation Techniques on Non-English Focus Group Research. Qual Health Res. 2001 July 1;11(4):568–79.

121. Fereday J, Muir-Cochrane E. Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. Int J Qual Methods. 2006 Mar 1;5(1):80–92.

122. Brod M, Tesler LE, Christensen TL. Qualitative research and content validity: developing best practices based on science and experience. Qual Life Res. 2009 Nov 1;18(9):1263–78.

123. Guest G, Namey E, Chen M. A simple method to assess and report thematic saturation in qualitative research. PLOS ONE. 2020 May 5;15(5):e0232076.

124. Zhang J, Ge S, Bai Z. Boiler Briquette Coal versus Raw Coal: Part II—Energy, Greenhouse Gas, and Air Quality Implications. J Air Waste Manag Assoc. 2001 Apr 1;51(4):534–41.

125. Kampa M, Castanas E. Human health effects of air pollution. Environ Pollut. 2008 Jan 1;151(2):362–7.

126. Mabahwi NAB, Leh OLH, Omar D. Human Health and Wellbeing: Human Health Effect of Air Pollution. Procedia - Soc Behav Sci. 2014 Oct 16;153:221–9.

127. Dominski FH, Lorenzetti Branco JH, Buonanno G, Stabile L, Gameiro da Silva M, Andrade A. Effects of air pollution on health: A mapping review of systematic reviews and meta-analyses. Environ Res. 2021 Oct 1;201:111487.

128. Bhui K, Newbury JB, Latham RM, Ucci M, Nasir ZA, Turner B, et al. Air quality and mental health: evidence, challenges and future directions. BJPsych Open. 2023 July 5;9(4):e120.

129. Andres L, Bryson JR, Bakare H, Pope F. Institutional logics and regional policy failure: Air pollution as a wicked problem in East African cities. Environ Plan C Polit Space. 2023 Mar 1;41(2):313–32.

130. Hofflinger Á, Boso À, Oltra C. The Home Halo Effect: how Air Quality Perception is Influenced by Place Attachment. Hum Ecol. 2019 Aug 1;47(4):589–600.

131. Jackson JE, Rawson R, Colman R, Kotera Y, Brooks-Ucheaga M. Parenting in a changing climate: The relationship between discussing climate change with children aged 5–11, family eco-behaviors, and climate change anxiety. Glob Health Econ Sustain. 2024 Sept 9;2(3):3172.

132. Stevens E, Cullinan P, Colvile R. Urban air pollution and children's asthma: what do parents and health professionals think? Pediatr Pulmonol. 2004 June;37(6):530–6.

133. Allen-Meares P, Lowry B, Estrella ML, Mansuri S. Health Literacy Barriers in the Health Care System: Barriers and Opportunities for the Profession. Health Soc Work. 2020 Jan 28;45(1):62–4.

134. Nutbeam D. Health literacy as a public health goal: a challenge for contemporary health education and communication strategies into the 21st century. Health Promot Int. 2000 Sept 1;15(3):259–67.

135. Shahid R, Shoker M, Chu LM, Frehlick R, Ward H, Pahwa P. Impact of low health literacy on patients' health outcomes: a multicenter cohort study. BMC Health Serv Res. 2022 Sept 12;22(1):1148.

136. Joo JY, Liu MF. Culturally tailored interventions for ethnic minorities: A scoping review. Nurs Open. 2020 Dec 9;8(5):2078–90.

137. Hogan MJ, Barton A, Twiner A, James C, Ahmed F, Casebourne I, et al. Education for collective intelligence. Ir Educ Stud. :1–30.

138. Is the Raw Coal Ban a Silver Bullet to Solving Air Pollution in Mongolia?: A Study of the Mongolian Government's Air Pollution Reduction Policies and Recommendations in the Context of COVID-19 | Journal of Public and International Affairs [Internet]. [cited 2025 Jan 15]. Available from: https://jpia.princeton.edu/news/raw-coal-ban-silver-bullet-solving-air-pollution-mongolia-study-mongolian-governments-air

139. LoMonte FD. Rebuilding Trust through Government Transparency and Accountability. Hum Rights. 2021 Apr;46(3):18–24.

140. Termeer CJAM, Dewulf A, Biesbroek R. A critical assessment of the wicked problem concept: relevance and usefulness for policy science and practice. Policy Soc. 2019 June 1;38(2):167–79.

141. Head BW, Alford J. Wicked Problems: Implications for Public Policy and Management. Adm Soc. 2015 Aug 1;47(6):711–39.

142. Sinskey JL, Margolis RD, Vinson AE. The Wicked Problem of Physician Well-Being. Anesthesiol Clin. 2022 June;40(2):213–23.

143. Niskanen VP, Rask M, Raisio H. Wicked Problems in Africa: A Systematic Literature Review. Sage Open. 2021 July 1;11(3):21582440211032163.

144. Chhabra D, Jahangiri K, Sohrabizadeh S, Ghomian Z, Shahsavani A. Exploring Strategies to Mitigate the Adverse Health Impacts of Air Pollution on Children in India: A Qualitative Study. Cureus. 16(7):e64630.

145. Rahim A. Exploring the Impact of Smog on Mental Health in Lahore: A Qualitative Study. Pak Soc Sci Rev. 2024 Nov 18;8(4):287–94.

146. Hashem RB, Siddique AB, Rasel SM, Hossain MdS. Assessment of knowledge, attitudes, and practices regarding air pollution among traffic polices in Dhaka city, Bangladesh: a cross-sectional study. BMC Public Health. 2024 Dec 27;24(1):3593.

147. Adiya A. Thousands Protest in Mongolia, Demanding Government Resignation [Internet]. Mongolia Weekly. 2025 [cited 2025 Jan 16]. Available from: https://www.mongoliaweekly.org/post/thousands-protest-in-mongolia-demanding-government-resignation

148. Fadnes LT, Taube A, Tylleskär T. How to identify information bias due to self-reporting in epidemiological research. Internet J Epidemiol [Internet]. 2008 Dec 31 [cited 2025 Jan 16];7(2). Available from: https://ispub.com/IJE/7/2/9194

149. Kaushal K. Social desirability bias in face to face interviews. J Postgrad Med. 2014;60(4):415–6.

150. van Nes F, Abma T, Jonsson H, Deeg D. Language differences in qualitative research: is meaning lost in translation? Eur J Ageing. 2010 Nov 19;7(4):313–6.

151. Clark SN, Anenberg SC, Brauer M. Global Burden of Disease from Environmental Factors. Annu Rev Public Health. 2025 Apr;46(1):233–51.

152. Jiang XQ, Mei XD, Feng D. Air pollution and chronic airway diseases: what should people know and do? J Thorac Dis. 2016 Jan;8(1):E31–40.

153. Miller MR. The cardiovascular effects of air pollution: Prevention and reversal by pharmacological agents. Pharmacol Ther. 2022 Apr;232:None.

154. Air Pollution During Pregnancy and Neonatal Outcome: A Review | Journal of Aerosol Medicine and Pulmonary Drug Delivery [Internet]. [cited 2025 July 15]. Available from: https://www.liebertpub.com/doi/abs/10.1089/jamp.2011.0932

155. Ha S, Yeung E, Bell E, Insaf T, Ghassabian A, Bell G, et al. Prenatal and early life exposures to ambient air pollution and development. Environ Res. 2019 July 1;174:170–5.

156. Rentschler J, Leonova N. Global air pollution exposure and poverty. Nat Commun. 2023 July 22;14:4432.

157. Chen F, Zhang W, Mfarrej MFB, Saleem MH, Khan KA, Ma J, et al. Breathing in danger: Understanding the multifaceted impact of air pollution on health impacts. Ecotoxicol Environ Saf. 2024 July 15;280:116532.

158. Balgansuren O, Arunotai N. Insights on energy, poverty, and gender nexus in urban *ger* district households: A case study from Ulaanbaatar, Mongolia. Glob Transit. 2025 Jan 1;7:189–98.

159. Taherdoost H. A review of technology acceptance and adoption models and theories. Procedia Manuf. 2018 Jan 1;22:960–7.

160. Shiferaw KB, Mengiste SA, Gullslett MK, Zeleke AA, Tilahun B, Tebeje T, et al. Healthcare providers' acceptance of telemedicine and preference of modalities during COVID-19

pandemics in a low-resource setting: An extended UTAUT model. PLOS ONE. 2021 Apr 22;16(4):e0250220.

161. Winkie MJ, Nambudiri VE. A tale of two applications: lessons learned from national LMIC COVID applications. J Am Med Inform Assoc. 2023 Apr 1;30(4):781–6.

162. Ngabo F, Nguimfack J, Nwaigwe F, Mugeni C, Muhoza D, Wilson DR, et al. Designing and Implementing an Innovative SMS-based alert system (RapidSMS-MCH) to monitor pregnancy and reduce maternal and child deaths in Rwanda. Pan Afr Med J. 2012 Oct 14;13:31.

163. Willcox M, Moorthy A, Mohan D, Romano K, Hutchful D, Mehl G, et al. Mobile Technology for Community Health in Ghana: Is Maternal Messaging and Provider Use of Technology Cost-Effective in Improving Maternal and Child Health Outcomes at Scale? J Med Internet Res. 2019 Feb 13;21(2):e11268.

164. Choudhury A, Asan O, Choudhury MM. Mobile health technology to improve maternal health awareness in tribal populations: mobile for mothers. J Am Med Inform Assoc. 2021 Nov 1;28(11):2467–74.

165. Bashi N, Fatehi F, Mosadeghi-Nik M, Askari MS, Karunanithi M. Digital health interventions for chronic diseases: a scoping review of evaluation frameworks. BMJ Health Care Inform. 2020 Mar 9;27(1):e100066.

166. Al-Emran M, Granić A. Is It Still Valid or Outdated? A Bibliometric Analysis of the Technology Acceptance Model and Its Applications From 2010 to 2020. In: Al-Emran M, Shaalan K, editors. Recent Advances in Technology Acceptance Models and Theories [Internet]. Cham: Springer International Publishing; 2021 [cited 2025 Oct 18]. p. 1–12. Available from: https://doi.org/10.1007/978-3-030-64987-6_1

167. Venkatesh V, Davis FD. A Theoretical Extension of the Technology Acceptance Model: Four Longitudinal Field Studies. Manag Sci. 2000;46(2):186–204.

168. Rosli MS, Saleh NS, Md. Ali A, Abu Bakar S, Mohd Tahir L. A Systematic Review of the Technology Acceptance Model for the Sustainability of Higher Education during the COVID-19 Pandemic and Identified Research Gaps. Sustainability. 2022 Jan;14(18):11389.

169. Vogelsang K, Steinhueser M, Hoppe U. A Qualitative Approach to Examine Technology Acceptance. ICIS 2013 Proc [Internet]. 2013 Dec 16; Available from: https://aisel.aisnet.org/icis2013/proceedings/GeneralISTopics/7

170. Portz JD, Bayliss EA, Bull S, Boxer RS, Bekelman DB, Gleason K, et al. Using the Technology Acceptance Model to Explore User Experience, Intent to Use, and Use Behavior of a Patient Portal Among Older Adults With Multiple Chronic Conditions: Descriptive Qualitative Study. J Med Internet Res. 2019 Apr 8;21(4):e11604.

171. Lee AT, Ramasamy RK, Subbarao A. Understanding Psychosocial Barriers to Healthcare Technology Adoption: A Review of TAM Technology Acceptance Model and Unified Theory of Acceptance and Use of Technology and UTAUT Frameworks. Healthcare. 2025 Jan 27;13(3):250.

172. Faryabi R, Rezabeigi Davarani F, Daneshi S, Moran DP. Investigating the effectiveness of protection motivation theory in predicting behaviors relating to natural disasters, in the households of southern Iran. Front Public Health [Internet]. 2023 Sept 7 [cited 2025 Oct 18];11. Available from: https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2023.1201195/full

173. Zhou LL, Owusu-Marfo J, Asante Antwi H, Antwi MO, Kachie ADT, Ampon-Wireko S. Assessment of the social influence and facilitating conditions that support nurses' adoption of

hospital electronic information management systems (HEIMS) in Ghana using the unified theory of acceptance and use of technology (UTAUT) model. BMC Med Inform Decis Mak. 2019 Nov 21;19(1):230.

174. Bawack RE, Kala Kamdjoug JR. Adequacy of UTAUT in clinician adoption of health information systems in developing countries: The case of Cameroon. Int J Med Inf. 2018 Jan 1;109:15–22.

175. Paul B, Kirubakaran R, Isaac R, Dozier M, Grant L, Weller D. A systematic review of the theory of planned behaviour interventions for chronic diseases in low health-literacy settings. J Glob Health. 13:04079.

176. Alyafei A, Easton-Carr R. The Health Belief Model of Behavior Change. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2025 [cited 2025 Oct 18]. Available from: http://www.ncbi.nlm.nih.gov/books/NBK606120/

177. Davis FD. Perceived usefulness, perceived ease of use, and user acceptance of information technology. MIS Q. 1989;13(3):319–40.

178. McKnight DH, Chervany NL. What Trust Means in E-Commerce Customer Relationships: An Interdisciplinary Conceptual Typology. Int J Electron Commer. 2001 Dec 1;6(2):35–59.

179. Bahmanziari T, Pearson JM, Crosby L. Is Trust Important in Technology Adoption? A Policy Capturing Approach. J Comput Inf Syst. 2003 Sept 1;43(4):46–54.

180. Shapiro SP. The Social Control of Impersonal Trust. Am J Sociol. 1987 Nov;93(3):623–58.

181. Zucker, L. G. (1986). Production of trust Institutional sources of economic structure, 1840-1920. In B. M. Straw, & L. L. Cumming (Eds.), Research in Organizational Behavior (pp. 53-111). Greenwich, CT JAI Press. - References - Scientific Research Publishing [Internet]. [cited 2025 July 17]. Available from: https://www.scirp.org/reference/referencespapers?referenceid=611921

182. Leichtmann B, Humer C, Hinterreiter A, Streit M, Mara M. Effects of Explainable Artificial Intelligence on trust and human behavior in a high-risk decision task. Comput Hum Behav. 2023 Feb 1;139:107539.

183. Wang R, Bush-Evans R, Arden-Close E, Bolat E, McAlaney J, Hodge S, et al. Transparency in persuasive technology, immersive technology, and online marketing: Facilitating users' informed decision making and practical implications. Comput Hum Behav. 2023 Feb 1;139:107545.

184. Dabrowski D, Basinska BA, Sikorski M. Impact of Usability Website Attributes on Users' Trust, Satisfaction and Loyalty. Soc Sci. 2014 Oct 7;85(3):22–32.

185. Fruhling AL, Lee SM. The influence of user interface usability on rural consumers' trust of e-health services. Int J Electron Healthc. 2006 Jan;2(4):305–21.

186. Christine Roy M, Dewit O, Aubert BA. The impact of interface usability on trust in Web retailers. Internet Res. 2001 Jan 1;11(5):388–98.

187. Casaló LV, Flavián C, Guinalíu M. Generating Trust and Satisfaction in E-Services: The Impact of Usability on Consumer Behavior. J Relatsh Mark. 2010 Nov 30;9(4):247–63.

188. Di Giacomo D, Ranieri J, D'Amico M, Guerra F, Passafiume D. Psychological Barriers to Digital Living in Older Adults: Computer Anxiety as Predictive Mechanism for Technophobia. Behav Sci. 2019 Sept;9(9):96.

189. Kim J, Jeon SW, Byun H, Yi E. Exploring E-Health Literacy and Technology-Use Anxiety among Older Adults in Korea. Healthcare. 2023 May 25;11(11):1556.

190. Samal L, Fu HN, Camara DS, Wang J, Bierman AS, Dorr DA. Health information technology to improve care for people with multiple chronic conditions. Health Serv Res. 2021 Oct;56(Suppl 1):1006–36.

191. Meyers N, Glick AF, Mendelsohn AL, Parker RM, Sanders LM, Wolf MS, et al. Parents' Use of Technologies for Health Management: A Health Literacy Perspective. Acad Pediatr. 2020;20(1):23–30.

192. A Step-by-Step Process of Thematic Analysis to Develop a Conceptual Model in Qualitative Research - Muhammad Naeem, Wilson Ozuem, Kerry Howell, Silvia Ranfagni, 2023 [Internet]. [cited 2025 Aug 16]. Available from: https://journals-sagepub-com.proxy.lib.uwaterloo.ca/doi/10.1177/16094069231205789

193. Hickman C, Marks E, Pihkala P, Clayton S, Lewandowski RE, Mayall EE, et al. Climate anxiety in children and young people and their beliefs about government responses to climate change: a global survey. Lancet Planet Health. 2021 Dec 1;5(12):e863–73.

194. Galway LP, Field E. Climate emotions and anxiety among young people in Canada: A national survey and call to action. J Clim Change Health. 2023 Jan 1;9:100204.

195. Maier SF, Seligman ME. Learned helplessness: Theory and evidence. J Exp Psychol Gen. 1976;105(1):3–46.

196. Sætra HS, Selinger E. Technological Remedies for Social Problems: Defining and Demarcating Techno-Fixes and Techno-Solutionism. Sci Eng Ethics. 2024 Dec 2;30(6):60.

197. Banwell N, Roelens C. Challenging techno-solutionism in engineering education. Ethical and pedagogical reflections for sustainability. GAIA - Ecol Perspect Sci Soc. 2024 Dec 30;33(4):357–62.

198. Tähtinen T. When Facebook Is the Internet: The Role of Social Media in Ethnic Conflict. World Dev. 2024 Aug 1;180:106633.

199. Nothias T. Access granted: Facebook's free basics in Africa. Media Cult Soc. 2020 Apr 1;42(3):329–48.

200. Chen S, Li J, Andrienko G, Andrienko N, Wang Y, Nguyen PH, et al. Supporting Story Synthesis: Bridging the Gap between Visual Analytics and Storytelling. IEEE Trans Vis Comput Graph. 2020 July;26(7):2499–516.

201. Veinot TC, Mitchell H, Ancker JS. Good intentions are not enough: how informatics interventions can worsen inequality. J Am Med Inform Assoc JAMIA. 2018 May 16;25(8):1080–8.

202. Lorenc T, Oliver K. Adverse effects of public health interventions: a conceptual framework. J Epidemiol Community Health. 2014 Mar;68(3):288–90.

203. Balance as Credibility? How Presenting One- vs. Two-Sided Messages Affects Ratings of Scientists' and Politicians' Trustworthiness: Health Communication: Vol 38 , No 12 - Get Access

[Internet]. [cited 2025 Aug 13]. Available from: https://www.tandfonline.com/doi/full/10.1080/10410236.2022.2111638

204. Sui Y, Zhang B. Determinants of the Perceived Credibility of Rebuttals Concerning Health Misinformation. Int J Environ Res Public Health. 2021 Jan;18(3):1345.

205. Blair RA, Morse BS, Tsai LL. Public health and public trust: Survey evidence from the Ebola Virus Disease epidemic in Liberia. Soc Sci Med. 2017 Jan 1;172:89–97.

206. Githinji P, MacMillan Uribe AL, Szeszulski J, Rethorst CD, Luong V, Xin L, et al. Public health communication during the COVID-19 health crisis: sustainable pathways to improve health information access and reach among underserved communities. Humanit Soc Sci Commun. 2024 Sept 15;11(1):1218.

207. Materia FT, Smyth JM, Puoane T, Tsolekile L, Goggin K, Kodish SR, et al. Implementing text-messaging to support and enhance delivery of health behavior change interventions in low- to middle-income countries: case study of the Lifestyle Africa intervention. BMC Public Health. 2023 Aug 10;23(1):1526.

208. Dada S, Aivalli P, De Brún A, Barreix M, Chelwa N, Mutunga Z, et al. Understanding communication in community engagement for maternal and newborn health programmes in low- and middle-income countries: a realist review. Health Policy Plan. 2023 Nov 1;38(9):1079–98.

209. Frontiers | Engaging faith communities in public health messaging in response to COVID-19: Lessons learnt from the pandemic in Ituri, Democratic Republic of Congo [Internet]. [cited 2025 Aug 14]. Available from: https://www.frontiersin.org/journals/public-health/articles/10.3389/fpubh.2022.916062/full

210. Geiger N. Do People Actually “Listen to the Experts”? A Cautionary Note on Assuming Expert Credibility and Persuasiveness on Public Health Policy Advocacy. Health Commun. 2022 May 12;37(6):677–84.

211. Rahman MI, Alam J, Khanom K, Emdad FB. Social Determinants Influencing Internet-Based Service Adoption Among Female Family Caregivers in Bangladesh: A Sociodemographic and Technological Analysis. Health Sci Rep. 2025 Apr 16;8(4):e70665.

212. Peng TQ, Zhu JJH, Tong JJ, Jiang SJ. Predicting Internet Non-Users’ Adoption Intention and Adoption Behavior: A panel study of theory of planned behavior. Inf Commun Soc. 2012 Oct 1;15(8):1236–57.

213. Zhang B, Zhu Y. Comparing attitudes towards adoption of e-government between urban users and rural users: an empirical study in Chongqing municipality, China. Behav Inf Technol. 2021 Aug 18;40(11):1154–68.

214. Zhang S, Wang Y, Wei Y. Follow or not? Descriptive norms and public health compliance: Mediating role of risk perception and moderating effect of behavioral visibility. Front Psychol [Internet]. 2022 Nov 18 [cited 2025 Aug 15];13. Available from: https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2022.1040218/full

215. De Groot JIM, Abrahamse W, Jones K. Persuasive Normative Messages: The Influence of Injunctive and Personal Norms on Using Free Plastic Bags. Sustainability. 2013 May;5(5):1829–44.

216. Bicchieri C, Xiao E. Do the right thing: but only if others do so. J Behav Decis Mak. 2009;22(2):191–208.

217. Rahimi B, Nadri H, Lotfnezhad Afshar H, Timpka T. A Systematic Review of the Technology Acceptance Model in Health Informatics. Appl Clin Inform. 2018 July;9(3):604–34.

218. Schaefer M, Schmitt Olabisi L, Arola K, Poitra CM, Matz E, Seigel M, et al. Understanding Socio-Technological Systems Change through an Indigenous Community-Based Participatory Framework. Sustainability. 2021 Jan;13(4):2257.

219. Creary MS. Bounded Justice and the Limits of Health Equity. J Law Med Ethics. 49(2):241–56.

220. Rakova B, Dobbe R. Algorithms as Social-Ecological-Technological Systems: an Environmental Justice Lens on Algorithmic Audits. In: 2023 ACM Conference on Fairness, Accountability, and Transparency [Internet]. 2023 [cited 2025 Aug 15]. p. 491–491. Available from: http://arxiv.org/abs/2305.05733

221. Van Horne YO, Alcala CS, Peltier RE, Quintana PJE, Seto E, Gonzales M, et al. An applied environmental justice framework for exposure science. J Expo Sci Environ Epidemiol. 2023;33(1):1–11.

222. Pauly B, Martin W, Perkin K, van Roode T, Kwan A, Patterson T, et al. Critical considerations for the practical utility of health equity tools: a concept mapping study. Int J Equity Health. 2018 Apr 23;17:48.

223. Kaushal K. Social desirability bias in face to face interviews. J Postgrad Med. 2014 Dec;60(4):415.

224. Manisalidis I, Stavropoulou E, Stavropoulos A, Bezirtzoglou E. Environmental and Health Impacts of Air Pollution: A Review. Front Public Health. 2020 Feb 20;8:14.

225. Program USGCR. Global Climate Change Impacts in the United States. Cambridge University Press; 2009. 193 p.

226. Kelishadi R, Poursafa P. Air pollution and non-respiratory health hazards for children. Arch Med Sci AMS. 2010 Aug 30;6(4):483–95.

227. Frazenburg C, Sepadi MM, Chitakira M. Investigating the Disproportionate Impacts of Air Pollution on Vulnerable Populations in South Africa: A Systematic Review. Atmosphere. 2025 Jan;16(1):49.

228. Ramírez AS, Ramondt S, Van Bogart K, Zuniga RP. Public Awareness of Air Pollution and Health Threats: Challenges and Opportunities for Communication Strategies to Improve Environmental Health Literacy. J Health Commun. 2019;24(1):75–83.

229. Badarch J, Harding J, Dickinson-Craig E, Azen C, Ong H, Hunter S, et al. Winter Air Pollution from Domestic Coal Fired Heating in Ulaanbaatar, Mongolia, Is Strongly Associated with a Major Seasonal Cyclic Decrease in Successful Fecundity. Int J Environ Res Public Health. 2021 Mar 9;18(5):2750.

230. Suriya, Natsagdorj N, Aorigele, Zhou H, Sachurila. Spatiotemporal Variation in Air Pollution Characteristics and Influencing Factors in Ulaanbaatar from 2016 to 2019. Atmosphere. 2022 June;13(6):990.

231. Castell N, Dauge FR, Schneider P, Vogt M, Lerner U, Fishbain B, et al. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environ Int. 2017 Feb 1;99:293–302.

232. Morawska L, Thai PK, Liu X, Asumadu-Sakyi A, Ayoko G, Bartonova A, et al. Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environ Int. 2018 July 1;116:286–99.

233. Lu T, Bechle MJ, Wan Y, Presto AA, Hankey S. Using crowd-sourced low-cost sensors in a land use regression of PM2.5 in 6 US cities. Air Qual Atmosphere Health. 2022 Apr 1;15(4):667–78.

234. Dewage PMH, Wijeratne LOH, Yu X, Iqbal M, Balagopal G, Waczak J, et al. Providing Fine Temporal and Spatial Resolution Analyses of Airborne Particulate Matter Utilizing Complimentary In Situ IoT Sensor Network and Remote Sensing Approaches. Remote Sens. 2024 Jan;16(13):2454.

235. Lu T, Garcia DA, Garcia A, Liu Y. Leveraging crowd-sourced environmental data to assess air pollution exposure disparity: A case of Los Angeles County. Int J Appl Earth Obs Geoinformation. 2023 Dec 1;125:103599.

236. Kramer AL, Liu J, Li L, Connolly R, Barbato M, Zhu Y. Environmental justice analysis of wildfire-related PM2.5 exposure using low-cost sensors in California. Sci Total Environ. 2023 Jan 15;856:159218.

237. O'Dell K, Ford B, Burkhardt J, Magzamen S, Anenberg SC, Bayham J, et al. Outside in: the relationship between indoor and outdoor particulate air quality during wildfire smoke events in western US cities. Environ Res Health. 2022 Nov;1(1):015003.

238. Kang Y, Aye L, Ngo TD, Zhou J. Performance evaluation of low-cost air quality sensors: A review. Sci Total Environ. 2022 Apr 20;818:151769.

239. Zhang B, Rong Y, Yong R, Qin D, Li M, Zou G, et al. Deep learning for air pollutant concentration prediction: A review. Atmos Environ. 2022 Dec 1;290:119347.

240. Pak U, Kim C, Ryu U, Sok K, Pak S. A hybrid model based on convolutional neural networks and long short-term memory for ozone concentration prediction. Air Qual Atmosphere Health. 2018 Oct 1;11(8):883–95.

241. Pak U, Ma J, Ryu U, Ryom K, Juhyok U, Pak K, et al. Deep learning-based PM2.5 prediction considering the spatiotemporal correlations: A case study of Beijing, China. Sci Total Environ. 2020 Jan 10;699:133561.

242. Particle Pollution Estimation from Images Using Convolutional Neural Network and Weather Features | IEEE Conference Publication | IEEE Xplore [Internet]. [cited 2025 Feb 20]. Available from: https://ieeexplore.ieee.org/document/8451306

243. Qi Y, Li Q, Karimian H, Liu D. A hybrid model for spatiotemporal forecasting of PM2.5 based on graph convolutional neural network and long short-term memory. Sci Total Environ. 2019 May 10;664:1–10.

244. Huang Y, Ying JJC, Tseng VS. Spatio-attention embedded recurrent neural network for air quality prediction. Knowl-Based Syst. 2021 Dec 5;233:107416.

245. Gao X, Li W. A graph-based LSTM model for PM2.5 forecasting. Atmospheric Pollut Res. 2021 Sept 1;12(9):101150.

246. Zhang J, Zheng Y, Qi D. Deep Spatio-Temporal Residual Networks for Citywide Crowd Flows Prediction [Internet]. arXiv; 2017 [cited 2025 July 7]. Available from: http://arxiv.org/abs/1610.00081

247. Yu B, Yin H, Zhu Z. Spatio-temporal graph convolutional networks: a deep learning framework for traffic forecasting. In: Proceedings of the 27th International Joint Conference on Artificial Intelligence. Stockholm, Sweden: AAAI Press; 2018. p. 3634–40. (IJCAI'18).

248. Vaswani A, Shazeer N, Parmar N, Uszkoreit J, Jones L, Gomez AN, et al. Attention Is All You Need [Internet]. arXiv; 2023 [cited 2025 Feb 3]. Available from: http://arxiv.org/abs/1706.03762

249. Nejad AS, Alaiz-Rodríguez R, McCarthy GD, Kelleher B, Grey A, Parnell A. SERT: A transformer based model for multivariate temporal sensor data with missing values for environmental monitoring. Comput Geosci. 2024 June 1;188:105601.

250. Kanchan, Gorai AK, Goyal P. A Review on Air Quality Indexing System. Asian J Atmospheric Environ. 2015 June 1;9(2):101–13.

251. TABLE 1 . EPA's breakpoint and AQI Index [Internet]. ResearchGate. [cited 2026 Jan 15]. Available from: https://www.researchgate.net/figure/EPAs-breakpoint-and-AQI-Index_tbl1_315006128

252. Zhou M, Cai M, Li G, Li M. An End-to-End Formula Recognition Method Integrated Attention Mechanism. Mathematics. 2023 Jan;11(1):177.

253. Kingma DP, Ba J. Adam: A Method for Stochastic Optimization [Internet]. arXiv; 2017 [cited 2025 Feb 6]. Available from: http://arxiv.org/abs/1412.6980

254. Castell N, Kobernus M, Liu HY, Schneider P, Lahoz W, Berre AJ, et al. Mobile technologies and services for environmental monitoring: The Citi-Sense-MOB approach. Urban Clim. 2015 Dec 1;14:370–82.

255. Shabbir M, Saeed T, Saleem A, Bhave P, Bergin M, Khokhar MF. A paradigm shift: Low-cost sensors for effective air quality monitoring and management in developing countries. Environ Int. 2025 June 1;200:109521.

256. Siddiqui MA, Baig MH, Yousuf MU. Performance and data acquisition from low-cost air quality sensors: a comprehensive review. Air Qual Atmosphere Health. 2025 Apr 1;18(4):1183–203.

257. Rabie R, Asghari M, Nosrati H, Emami Niri M, Karimi S. Spatially resolved air quality index prediction in megacities with a CNN-Bi-LSTM hybrid framework. Sustain Cities Soc. 2024 Aug 15;109:105537.

258. Zhu X, Zou F, Li S. Enhancing Air Quality Prediction with an Adaptive PSO-Optimized CNN-Bi-LSTM Model. Appl Sci. 2024 Jan;14(13):5787.

259. Wang J, Li X, Jin L, Li J, Sun Q, Wang H. An air quality index prediction model based on CNN-ILSTM. Sci Rep. 2022 May 19;12(1):8373.

260. Zhang J, Li S. Air quality index forecast in Beijing based on CNN-LSTM multi-model. Chemosphere. 2022 Dec 1;308:136180.

261. Wang J, Li J, Wang X, Wang J, Huang M. Air quality prediction using CT-LSTM. Neural Comput Appl. 2021 May 1;33(10):4779–92.

262. Kang Y, Aye L, Ngo TD, Zhou J. Performance evaluation of low-cost air quality sensors: A review. Sci Total Environ. 2022 Apr 20;818:151769.

263. Kalo M, Zhou X, Li L, Tong W, Piltner R. Chapter 8 - Sensing air quality: Spatiotemporal interpolation and visualization of real-time air pollution data for the contiguous United States. In:

Li L, Zhou X, Tong W, editors. Spatiotemporal Analysis of Air Pollution and Its Application in Public Health [Internet]. Elsevier; 2020 [cited 2025 Sept 27]. p. 169–96. Available from: https://www.sciencedirect.com/science/article/pii/B978012815822700008X

264. Moore J, Goffin P, Meyer M, Lundrigan P, Patwari N, Sward K, et al. Managing In-home Environments through Sensing, Annotating, and Visualizing Air Quality Data. Proc ACM Interact Mob Wearable Ubiquitous Technol. 2018 Sept 18;2(3):128:1-128:28.

265. Rollo F, Sudharsan B, Po L, Breslin JG. Air Quality Sensor Network Data Acquisition, Cleaning, Visualization, and Analytics: A Real-world IoT Use Case. In: Adjunct Proceedings of the 2021 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2021 ACM International Symposium on Wearable Computers [Internet]. New York, NY, USA: Association for Computing Machinery; 2021 [cited 2025 Sept 27]. p. 67–8. (UbiComp/ISWC '21 Adjunct). Available from: https://doi.org/10.1145/3460418.3479277

266. Li H, Fan H, Mao F. A Visualization Approach to Air Pollution Data Exploration—A Case Study of Air Quality Index (PM2.5) in Beijing, China. Atmosphere. 2016 Mar;7(3):35.

267. Tékouabou SCK, Chenal J, Azmi R, Diop EB, Toulni H, Nsegbe A de P. Towards air quality particulate-matter monitoring using low-cost sensor data and visual exploration techniques: case study of Kisumu, Kenya. Procedia Comput Sci. 2022 Jan 1;215:963–72.

268. Full article: Deep learning for spatiotemporal forecasting in Earth system science: a review [Internet]. [cited 2025 Sept 27]. Available from: https://www.tandfonline.com/doi/full/10.1080/17538947.2024.2391952

269. Amato F, Guignard F, Robert S, Kanevski M. A novel framework for spatio-temporal prediction of environmental data using deep learning. Sci Rep. 2020 Dec 17;10(1):22243.

270. Wikle CK, Zammit-Mangion A. Statistical Deep Learning for Spatial and Spatiotemporal Data. Annu Rev Stat Its Appl. 2023 Mar 9;10(Volume 10, 2023):247–70.

271. Koziel S, Pietrenko-Dabrowska A, Wojcikowski M, Pankiewicz B. Efficient calibration of cost-efficient particulate matter sensors using machine learning and time-series alignment. Knowl-Based Syst. 2024 July 8;295:111879.

272. Liu X, Jayaratne R, Thai P, Kuhn T, Zing I, Christensen B, et al. Low-cost sensors as an alternative for long-term air quality monitoring. Environ Res. 2020 June 1;185:109438.

273. Qualters JR, Strosnider HM, Bell R. Data to Action: Using Environmental Public Health Tracking to Inform Decision Making. J Public Health Manag Pract. 2015 Apr;21:S12.

274. Mahajan S, Chung MK, Martinez J, Olaya Y, Helbing D, Chen LJ. Translating citizen-generated air quality data into evidence for shaping policy. Humanit Soc Sci Commun. 2022 Apr 7;9(1):122.

275. Muhamad Khair NK, Lee KE, Mokhtar M. Sustainable City and Community Empowerment through the Implementation of Community-Based Monitoring: A Conceptual Approach. Sustainability. 2020 Jan;12(22):9583.

276. Hsu YC, Dille P, Cross J, Dias B, Sargent R, Nourbakhsh I. Community-Empowered Air Quality Monitoring System. In: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems [Internet]. New York, NY, USA: Association for Computing Machinery; 2017 [cited 2025 Sept 27]. p. 1607–19. (CHI '17). Available from: https://doi.org/10.1145/3025453.3025853

277. Empowering Local People through Community-based Resource Monitoring: a Comparison of Brazil and Namibia a Comparison of Brazil and Namibia on JSTOR [Internet]. [cited 2025 Sept 27]. Available from: https://www.jstor.org/stable/26269211?seq=1

278. Use of Information Technology for Community Empowerment: Transforming Geographic Information Systems into Community Information Systems - Ghose - 2001 - Transactions in GIS - Wiley Online Library [Internet]. [cited 2025 Sept 27]. Available from: https://onlinelibrary.wiley.com/doi/abs/10.1111/1467-9671.00073?casa_token=yAgriELMv0cAAAAA%3AkZtchiMxWL3dnv26BiOGbpmU2kUDi9cv0TbGhG6w76wECUJIZWJFO6ErJ37fsqv8ACisU65xLOt516M

279. Shatas A, Hubbell B. Using Low-Cost Sensor Networks: Considerations to Help Reveal Neighborhood-Level Exposure Disparities. Am J Public Health. 2022 Dec;112(12):1693–5.

280. Considine EM, Braun D, Kamareddine L, Nethery RC, deSouza P. Investigating Use of Low-Cost Sensors to Increase Accuracy and Equity of Real-Time Air Quality Information. Environ Sci Technol. 2023 Jan 9;10.1021/acs.est.2c06626.

281. Lu T, Liu Y, Garcia A, Wang M, Li Y, Bravo-villasenor G, et al. Leveraging Citizen Science and Low-Cost Sensors to Characterize Air Pollution Exposure of Disadvantaged Communities in Southern California. Int J Environ Res Public Health. 2022 Jan;19(14):8777.

282. Alhassan JAK, Wills O. Public health surveillance through community health workers: a scoping review of evidence from 25 low-income and middle-income countries. 2024 Apr 1 [cited 2025 Oct 19]; Available from: https://bmjopen.bmj.com/content/14/4/e079776

283. Jayatilleke K. Challenges in Implementing Surveillance Tools of High-Income Countries (HICs) in Low Middle Income Countries (LMICs). Curr Treat Options Infect Dis. 2020;12(3):191–201.

284. The history, geography, and sociology of slums and the health problems of people who live in slums - The Lancet [Internet]. [cited 2026 Jan 15]. Available from: https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(16)31650-6/abstract

285. Manikam L, Faijue DD, Shringarpure K, Sheth M, Factor-Livak P, Parikh P, et al. Understanding one health challenges in marginalized urban settings: A patient and public involvement (PPI) approach from the CHIP consortium activities across four global cities. One Health. 2024 Oct 18;19:100919.

286. Johnson JL, Adkins D, Chauvin S. A Review of the Quality Indicators of Rigor in Qualitative Research. Am J Pharm Educ. 2020 Jan;84(1):7120.

Appendices

Appendix 1. Participant demographics and living arrangements, including district of residence, age range, family structure, and housing type. Highlighted Participant IDs indicate residents of ger areas.

Participant ID	Location (district)	Age	Gender	Occupation	Education	Salary	Household size	Children	Residence type	Time in UB (Years)
1	Bayangol	30	M	Financial officer	MBA	> 5 million	4	2	Apartment	
2	Chigeltei	44	F	Cleaner	Highschool	1 million	3	1	Moved to an apt. close to the office. Was living in the Ger district previously.	6
3	Songinokhairkhan	49	M	Handyman	Highschool	1-2 million	5	3	House	24
4	Khan-uul	30	M	Café manager	Masters	2-3 million	4	2	Apartment	20
5	Sukhbaatar	24	F	Pediatric ER doctor	Post-residency	1-2 million	7	2	Apartment	24
6	Sukhbaatar	20	F	Student at NUM	Completing bachelors	<1 million	1	0	Dorm with 4 other girls	2
7	Khan-uul	32	F	Teacher/trainer at National Energy Center	Masters	1-2 million	3	1	Apartment	21

8	Sukhbaatar	38	M	GIS/remote sensing PhD researcher	Masters	1-2 million	5	3	Apartment	13
9	Sukhbaatar	51	F	Mechanic at the power plant	College	2-3 million	3	0	House in a compound. Ger in the compound with her mother lives	51
10	Khan-uul	23	M	Real estate agent	Bachelors	3-4 million	3	1	Apartment	23
11	Sukhbaatar	26	F	Project manager	Bachelors	4-5 million	4	0	Apartment	12
12	Bayanzurkh	39	F	Program coordinator	College	Unknown	4	2	Ger	16
13	Bayanzurkh	33	F	Community teacher	Highschool	<1	5	3	House in the Ger district	24
14	Bayanzurkh	43	M	Craftsman and carver	Highschool/technical school	1-2 million	2	0	Ger	39
15	Bayanzurkh	40	F	Unemployed	Highschool	1-2 million	6	4	Ger	40
16	Bayanzurkh	48	F	Area coordinator	College	<1 million	4	3	House	32
17	Bayanzurkh	40	M	Assistant at a metal company	Highschool	1-2 million	2	1	House with roommates	40
18	Bayanzurkh	52	M	Personal cab driver	Highschool	<1 million	3	1	House	20
19	Bayanzurkh	66	M	Retired coal miner	Grade 3	<1 million	1	0	Clay house	23

20	Bayanzurkh	58	F	School hallway monitor	Technical college	<1 million	2	0	Ger	58
21	Bayanzurkh	36	F	Language and script teacher on maternity leave	Bachelors	1-2 million	7	5	Ger	4
22	Bayanzurkh	66	F	Retired teacher	Unknown	<1 million	1	0	Ger	25
23	Bayanzurkh	66	F	Retired tailor	College	<1 million	1	0	Ger	15
24	Bayangol	26	F	NGO project manager	Bachelors	1-2 million	2	1	Apartment	26
25	Bayangol	37	F	Energy sector researcher	Masters	3-4 million	2	1	Apartment	8

Appendix 2. Interview guide for Studies 1 and 2

Interview Guide – Air Quality in Ulaanbaatar, Mongolia	
Date: Pseudonym (Or number):	Age: Sex: Occupation: Highest level of education: Length of time in UB: Household size/presence of children/ older adults:
*Residence: **Housing Quality:** What are the things inside your house that help with air **Environmental Settings:** Outside, what are things that you're concerned about? Districts and Khooros	

Intro	Before we start, I want to learn more about your daily activities.
Interview Questions: 1. Can you tell me about your usual daily activities outside your home?	Prompts (use whatever you feel is necessary/what goes with the conversation) - Take me through a typical day of yours. What do you do/what locations do you frequent during a regular day or week?
Interviewer Notes: - Do you have a good sense of what the participant's daily life is? - Do you have an understanding of the major locations the participants travel to daily/weekly? You can mention these locations in other questions you plan on asking. - Can you visualize what a day/week looks like for the participant?	

Section 1.1: Perception of Air Pollution Exposure	I want to learn more about what you know about air pollution.

Interview Questions:	Prompts (use whatever you feel is necessary/what goes with the conversation)
1. When you hear "good air quality" and "bad air quality," what comes to your mind? 2. Have you noticed any changes in the air around you in the past few years? 3. Do you notice a change in air quality in different parts of UB? 4. Have you ever checked air quality information online? If so, what are your impressions of them?	- When did you learn about air pollution in UB? - How often do you think about air pollution? - When do you remember hearing about, or first learning about air pollution?

Interviewer Notes:

- Is air pollution mentioned by the participant?
- Does the participant mention the history of their experience of air pollution in Mongolia/UB?
- Do you have a sense of the background/previous knowledge the participant has on air pollution?
- If the participant has limited knowledge, do you have a sense of where their knowledge gaps are?
- Where does knowledge of air pollution come from for the participant?

Section 1.2: Pollution Exposure Management	I want to learn more about how you manage exposure to air pollution.

Interview Questions:	Prompts (use whatever you feel is necessary/what goes with the conversation)
● How do you protect your health against air pollution? ● How do you manage air pollution exposure within your household? ● Who in your family are you most worried about regarding exposure to air pollution? ● How do you mange this? ● Have you ever visited the (agaar.mn) to learn more about air pollution in your area? ○ How often do you check it?	● What are the biggest challenges in addressing, or understanding air pollution? ● How do you learn about air pollution? ● Where do you get your information on how to manage air pollution and/or exposure? ● How you help manage exposure within your family? How do you ensure the safety of children? Elderly? Family members with disabilities?

<table>
<tr><td>

- What specific information about air pollution in Mongolia are you most interested in?
  - Why would this information be helpful?

</td><td></td></tr>
<tr><td colspan="2">Interviewer Notes:

- Do you understand/get a sense of how participants protect themselves against, or manage pollution?
- Do you know how the participant uses information they know about pollution?
- Do you get a sense that knowing the level of air pollution experienced by the participant limits their mobility?</td></tr>
<tr><td>Section 2:
Technology</td><td>We are interested in understanding how air pollution tracking technology can help inform what people do, or, how they plan their daily lives.

We want to learn more about this to ensure that people can easily access information about the air that they breathe. We are hoping to learn more about your thoughts on this.</td></tr>
<tr><td>Interview Questions:

- Have you ever thought about getting updates about how clean or polluted the air is around to via an update on your phone or computer?
- How else would you like this information to be conveyed to you?

- How often do you check the air quality in your area? When do you do this and how does this impact your daily activities?

- Can you think of times when knowing about the air quality right in the moment would be helpful for you, your family, or your neighbors?

</td><td>Prompts (use whatever you feel is necessary/what goes with the conversation)

- How do you think it could help people in places like Ulaanbaatar if they could know right away how good or bad the air quality is?

- Are you familiar with similar products or websites about air pollution? If yes, tell me about them briefly.

</td></tr>
</table>

● Some people also wonder if it would be helpful to know about the air quality in advance, like before they go out for the day. What are your thoughts on that? Do you think it would be useful? ● Would having this kind of instant air quality information change how you go about your day? If yes, how?	

Interviewer Notes:

- Are you able to get a sense of the qualities of an ideal air quality system?
- What preferences are mentioned by the participant regarding how they'd like to access information on, or learn more about air pollution?

Conclusion	

Interview Questions:

- Is there anything else you'd like to share about how air pollution affects you and your community?
- Would you be open to sharing more about your experiences or thoughts in the future?
- Is there anything else you'd like to share before ending the interview?

Appendix 3. Ethics approval for Studies 1 and 2

UNIVERSITY OF WATERLOO

Notification of Ethics Clearance to Conduct Research with Human Participants

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Principal Investigator: Plinio Morita

Student investigator: Shahan Salim

Faculty supervisor: Thokozani Hanjahanja-Phiri

Faculty supervisor: Warren Dodd

File #: 45755

Title: Exploring Air Quality Awareness and Information Dissemination: Exploring Perspectives in Ulaanbaatar, Mongolia

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The Human Research Ethics Board is pleased to inform you this study has been reviewed and given ethics clearance.

Initial Approval Date: 09/15/23 (m/d/y)

University of Waterloo Research Ethics Boards are composed in accordance with, and carry out their functions and operate in a manner consistent with, the institution's guidelines for research with human participants, the Tri-Council Policy Statement for the Ethical Conduct for Research Involving Humans (TCPS2 2022), the Ontario Personal Health Information Protection Act (PHIPA), and all laws and regulations of the province of Ontario (as applicable). Additionally, CREB operates in a manner consistent with the International Conference for Harmonization of Technical Requirements for Pharmaceuticals for Human Use (ICH) Guidance E6(R2): Good Clinical Practice , the International Organization for Standardization of Good Clinical Practices (GCP) as set out by ISO 14155 - Clinical investigation of medical devices for human subjects, Part C, Division 5 of the Food and Drug Regulations, Part 4 of the Natural Health Products Regulations, Part 3 of the Medical Devices Regulations. Both Boards are registered with the U.S. Department of Health and Human Services under the Federal Wide Assurance, FWA00021410, and IRB registration number IRB00002419 (HREB) and IRB00007409 (CREB).

Expiry Date: 09/16/24 (m/d/y)

Multi-year research must be renewed at least once every 12 months unless a more frequent review has otherwise been specified. Studies will only be renewed if the renewal report is received and approved before the expiry date. Failure to submit renewal reports will result in the investigators being notified ethics clearance has been suspended and Research Finance being notified the ethics clearance is no longer valid.

Level of review: Delegated Review

Signed on behalf of the Human Research Ethics Board



Joanna Eidse, Research Ethics Officer, jeidse@uwaterloo.ca, 519-888-4567, ext. 47163

This above named study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Documents reviewed and received ethics clearance for use in the study and/or received for information:

Appendix 4. Ethics approval for Study 3

UNIVERSITY OF WATERLOO

Notification of Ethics Clearance to Conduct Research with Human Participants

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Principal Investigator: Plinio Morita (School of Public Health Sciences)

Student investigator: Shahan Salim (School of Public Health Sciences)

Study coordinator: Thokozani Hanjahanja-Phiri (School of Public Health Sciences)

File #: 44356

Title: AI-Based Modelling of the Impact of Extreme Air Pollution Events on Student Education and Heath Systems Use

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The Human Research Ethics Board is pleased to inform you this study has been reviewed and given ethics clearance.

Initial Approval Date: 08/10/22 (m/d/y)

University of Waterloo Research Ethics Boards are composed in accordance with, and carry out their functions and operate in a manner consistent with, the institution's guidelines for research with human participants, the Tri-Council Policy Statement for the Ethical Conduct for Research Involving Humans (TCPS, 2nd edition), International Conference on Harmonization: Good Clinical Practice (ICH-GCP), the Ontario Personal Health Information Protection Act (PHIPA), the applicable laws and regulations of the province of Ontario. Both Boards are registered with the U.S. Department of Health and Human Services under the Federal Wide Assurance, FWA00021410, and IRB registration number IRB00002419 (HREB) and IRB00007409 (CREB).

This study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Expiry Date: 08/11/23 (m/d/y)

Multi-year research must be renewed at least once every 12 months unless a more frequent review has otherwise been specified. Studies will only be renewed if the renewal report is received and approved before the expiry date. Failure to submit renewal reports will result in the investigators being notified ethics clearance has been suspended and Research Finance being notified the ethics clearance is no longer valid.

Level of review: Delegated Review

Signed on behalf of the Human Research Ethics Board



Joanna Eidse, Research Ethics Officer, jeidse@uwaterloo.ca, 519-888-4567, ext. 47163

This above named study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Documents reviewed and received ethics clearance for use in the study and/or received for information:

file: List of partners.docx

file: List of partners_v2_20220809.docx