



RESILIENCE OF PUBLIC HEALTH SYSTEMS IN FACING URBANIZATION CRISES AND AIR POLLUTION

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Article Info

Received: May 10, 2026

Revised: July 13, 2026

Accepted: August 11, 2026

Online Version: September 30,
2026

Abstract

Rapid urbanization and persistent air pollution are increasing pressure on public health systems by intensifying healthcare demand, environmental exposure, and institutional vulnerability. This study aimed to examine how urbanization pressures and air pollution influence public health system resilience and to identify institutional capacities associated with stronger performance. A mixed-methods cross-sectional design was applied across four urban areas, involving 420 respondents and 30 key informants. Quantitative data were collected through a resilience questionnaire and secondary environmental indicators, while qualitative data were obtained through semi-structured interviews. The overall resilience score was moderate at 3.39 ± 0.61 . Higher PM_{2.5} concentrations and population density were negatively associated with resilience, whereas intersectoral coordination, environmental surveillance, and resource flexibility showed significant positive associations. Multivariable regression explained 48% of the variance in resilience, with intersectoral coordination emerging as the strongest positive predictor. Qualitative findings confirmed that integrated surveillance, flexible resource allocation, and timely information exchange supported stronger institutional responses. These findings highlight resilience as a dynamic governance capacity. Public health resilience in rapidly urbanizing and polluted settings depends on more than healthcare infrastructure alone. Strengthening cross-sector governance, adaptive capacity, environmental surveillance, and equitable community engagement is essential for sustaining health services and reducing long-term urban health vulnerability.

Keywords: Air Pollution, Environmental Surveillance, Public Health

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Journal Homepage

<https://research.adra.ac.id/index.php/health>

ISSN: (P: 2988-7550) - (E: 2988-0459)

How to cite:

Ismed, Ismed., Santos, L & Flores, J. (2026). Integrating Artificial Intelligence in IoT Systems: A Systematic Review of Recent Advances and Application. *Journal of World Future Medicine, Health and Nursing*, 4(5), 677-696.
<https://doi.org/10.70177/health.v4i5.4397>

Published by:

Yayasan Adra Karima Hubbi

INTRODUCTION

Rapid urbanization has become one of the most influential demographic and spatial transformations affecting contemporary public health. The continuing concentration of populations in metropolitan areas creates economic opportunities, improves access to services, and supports technological development, yet it also generates new forms of environmental and health vulnerability. Urban population growth frequently exceeds the capacity of housing, transportation, sanitation, waste management, and healthcare infrastructure to adapt at the same pace. The World Health Organization reports that more than half of the global population currently lives in urban areas and that this proportion is projected to reach approximately 68% by 2050. Such demographic concentration makes cities increasingly important settings for understanding how environmental pressures interact with population health and the capacity of public institutions to respond effectively (Kidanemariam, 2025; Lilhore, 2025).

Air pollution represents one of the most serious health consequences associated with poorly managed urban expansion. Population density, motorized transportation, industrial activities, fossil-fuel combustion, construction, energy consumption, and inadequate waste management can collectively increase concentrations of harmful pollutants, including particulate matter, nitrogen dioxide, sulfur dioxide, ozone, and other airborne contaminants. Exposure to these pollutants contributes to respiratory, cardiovascular, cerebrovascular, metabolic, and other chronic health conditions while disproportionately affecting children, older adults, pregnant women, people with existing illnesses, and socioeconomically disadvantaged communities. Recent WHO evidence continues to classify air pollution as a leading environmental health risk, causing millions of premature deaths globally each year and creating a substantial burden of preventable disease (Peleman, 2024; Tian, 2023).

Public health systems occupy a critical position within this rapidly changing urban environment because they must respond not only to individual illnesses but also to the structural conditions that produce population-level health risks. Resilience in this context extends beyond the ability of hospitals to maintain services during emergencies. It encompasses institutional preparedness, surveillance capacity, workforce adaptability, preventive services, equitable healthcare access, environmental health monitoring, intersectoral coordination, community participation, and the ability to learn from recurring stresses. Urbanization and air pollution therefore need to be understood as interconnected and persistent pressures rather than isolated environmental problems. A resilient public health system must be capable of anticipating these pressures, absorbing their health consequences, adapting service delivery, and contributing to preventive action that reduces future vulnerability (Elabd, 2026; Scussiatto, 2024).

Urban public health systems are increasingly required to operate under conditions in which healthcare demand grows faster than institutional capacity. Rapid population expansion can intensify overcrowding, informal settlement development, unequal access to primary care, transportation congestion, environmental degradation, and chronic disease burdens. Health facilities situated in densely populated urban areas may experience increasing patient volumes while simultaneously facing limitations in workforce availability, financing, infrastructure, information systems, and preventive health capacity. These conditions challenge the assumption that increasing healthcare facilities alone is sufficient to strengthen urban health resilience. Health-system resilience must instead be deliberately programmed, financed,

contextualized, and connected with broader public-health functions rather than treated as an automatic consequence of healthcare investment (Kalaiselvi, 2026; Park, 2025).

The health burden produced by air pollution intensifies these institutional pressures because exposure is continuous, cumulative, and unevenly distributed across urban populations. Pollution-related illness can increase outpatient consultations, emergency visits, hospital admissions, chronic disease management needs, medication use, and long-term healthcare expenditure. Environmental exposure also reveals an important limitation of conventional healthcare responses: stronger clinical services may reduce some health consequences but cannot independently eliminate the underlying environmental risks. Recent global analysis indicates that improved healthcare infrastructure, accessibility, and quality can mitigate certain pollution-related health impacts, yet healthcare systems alone cannot fully compensate for sustained environmental degradation. The central problem therefore involves both the capacity to manage health consequences and the institutional ability to participate in preventing those consequences (Chadalavada, 2025; Wei, 2025).

Institutional fragmentation represents another important dimension of the problem because many determinants of urban air quality lie outside the formal authority of health agencies. Transportation policy, land-use planning, industrial regulation, energy systems, housing development, green-space provision, and waste management are commonly governed by separate sectors with different priorities and accountability mechanisms. Public health agencies may possess epidemiological evidence about pollution-related disease without having sufficient influence over the policies producing environmental exposure. This separation can create reactive systems that treat illness after exposure rather than resilient systems capable of reducing risks before they become health crises. The research problem consequently concerns how public health systems can develop adaptive, preventive, coordinated, and equitable capacities when confronted simultaneously by rapid urbanization and persistent air pollution (Hinton, 2024; Kentros, 2024).

This study aims to examine the resilience of public health systems in responding to the interconnected pressures generated by urbanization crises and air pollution. The analysis will conceptualize resilience as the capacity of public health institutions to anticipate emerging risks, maintain essential functions during periods of increased demand, adapt services and governance arrangements, coordinate responses across sectors, and transform institutional practices when existing approaches become inadequate. Such an objective moves beyond a narrow assessment of healthcare infrastructure by considering the organizational, environmental, social, and governance dimensions that determine whether urban health systems can remain effective under chronic environmental stress (Dellaripa, 2024; Salim, 2023).

The research specifically seeks to identify the institutional capacities and response mechanisms that strengthen or weaken public health resilience under conditions of rapid urban growth and deteriorating air quality. Attention should be directed toward environmental surveillance, epidemiological monitoring, health information systems, workforce preparedness, primary healthcare capacity, risk communication, resource allocation, emergency preparedness, community engagement, and coordination among health, transportation, environment, energy, and urban-planning authorities. The analysis should also examine whether these capacities are distributed equitably across urban populations, since resilience at the city level may conceal

substantial inequalities between affluent communities and residents of informal settlements or highly polluted neighborhoods.

The intended outcome is the development of an integrated understanding of how public health systems can progress from reactive healthcare delivery toward anticipatory and adaptive urban health governance. The study should evaluate not merely whether health services continue functioning but whether the system can recognize emerging environmental risks, mobilize institutional resources, protect vulnerable populations, learn from previous disruptions, and contribute to policies that reduce exposure. This objective positions resilience as a dynamic process involving preparedness, absorption, adaptation, learning, and transformation. The resulting analysis is expected to provide a basis for identifying policy priorities that connect health-system strengthening with environmental protection and sustainable urban development (Berkani, 2023; Khan, 2024).

Current scholarship on urbanization and public health provides substantial evidence concerning the health effects of population density, informal settlements, unequal infrastructure, environmental degradation, and changing patterns of disease. Research on air pollution has likewise generated extensive epidemiological evidence linking pollutant exposure with mortality and a wide range of respiratory and noncommunicable diseases. Health-system resilience has developed as another significant field, particularly following epidemics, natural disasters, climate-related emergencies, and the COVID-19 pandemic. These bodies of literature remain partly fragmented, however, because urbanization, pollution exposure, and health-system resilience are frequently treated as separate analytical domains rather than elements of the same urban health process.

Existing resilience frameworks also tend to place considerable emphasis on sudden external shocks, including pandemics, disasters, and acute emergencies. Chronic environmental pressures such as air pollution operate differently because they accumulate over long periods, may become normalized within urban life, and continuously increase healthcare demand without necessarily producing a clearly identifiable moment of crisis. A 2025 review of global health-system resilience strategies found that existing approaches frequently prioritize service delivery and resource generation while giving less attention to structural governance problems, community empowerment, and chronic internal stresses. This limitation creates an important conceptual gap concerning how resilience should be evaluated when health systems confront persistent environmental stress rather than a temporary emergency (Campos, 2024; Postma, 2023).

Recent research has begun connecting environmental degradation with health-system resilience, yet important questions remain regarding how institutional capacities, urban governance, environmental prevention, community participation, and health equity operate together. Resilience-assessment literature itself continues to show variation in definitions and indicators, with scholars noting the absence of a universally accepted framework and the continuing need for context-sensitive measures at subnational and national levels. The proposed study addresses this gap by examining resilience through the combined pressures of urbanization and air pollution and by linking healthcare capacity with preventive governance, environmental surveillance, cross-sector coordination, and the unequal distribution of urban health risks (Choo, 2023; W. Liu, 2023).

The novelty of this study lies in conceptualizing rapid urbanization and air pollution as interacting chronic stressors that jointly test the resilience of public health systems. Rather than

examining pollution solely as an environmental exposure or urbanization merely as a demographic transition, the proposed framework positions both processes as forces capable of reshaping healthcare demand, institutional vulnerability, resource allocation, epidemiological patterns, and governance requirements. Resilience will therefore be assessed not only through the capacity to preserve healthcare services but also through the ability to anticipate environmental risks, adapt institutional practices, coordinate preventive interventions, and transform policies that reproduce long-term health vulnerability.

A second novel contribution concerns the integration of health-system functions with wider urban governance. The study will frame resilience as a shared institutional capacity involving public health authorities, healthcare facilities, environmental agencies, transportation systems, urban planners, local governments, communities, and other relevant actors. This approach corresponds with emerging global policy directions emphasizing stronger institutional capacity and cross-sector collaboration in addressing air pollution and urban environmental health. Such integration can reveal whether public health systems operate primarily as downstream responders to pollution-related disease or whether they possess sufficient evidence, authority, partnerships, and adaptive capacity to influence upstream determinants of population health (Lee, 2024; Zhou, 2023).

The study is justified by the growing convergence of demographic expansion, environmental degradation, health inequality, and institutional pressure within contemporary cities. Urban resilience cannot be considered adequate when healthcare facilities remain operational while large sections of the population continue to experience preventable exposure to polluted environments. Public health resilience should instead be evaluated according to its capacity to protect health before, during, and after periods of environmental stress while maintaining equitable access to essential services. This perspective offers theoretical value by extending health-system resilience beyond emergency preparedness and practical value by identifying institutional strategies for healthier urban development. The research can consequently contribute to public health policy, environmental governance, sustainable urban planning, and broader efforts to develop cities capable of protecting population health under increasingly complex environmental conditions (Curto, 2024; Q. Liu, 2024).

RESEARCH METHOD

This study employed a mixed-methods research design to examine the resilience of public health systems in responding to pressures generated by rapid urbanization and air pollution. The quantitative component was designed to measure institutional preparedness, adaptive capacity, continuity of essential health services, environmental health surveillance, resource availability, intersectoral coordination, and the ability of health institutions to respond to increasing pollution-related health burdens. The qualitative component was used to explore institutional experiences, governance challenges, policy responses, and operational strategies that could not be adequately captured through numerical indicators. The integration of quantitative and qualitative evidence allowed the study to evaluate health-system resilience as both a measurable institutional capacity and a dynamic process shaped by local environmental and administrative conditions (Peña, 2025; Yoon, 2025).

Research Design

A cross-sectional comparative approach was applied across selected urban areas characterized by substantial population growth, transportation intensity, industrial activity, and

recurring air-quality concerns. Public health resilience was conceptualized through several interconnected dimensions, including preparedness, absorption capacity, adaptation, recovery, learning, and institutional transformation. Urbanization pressure was assessed through indicators related to population density, service demand, settlement expansion, mobility, and infrastructure burden, while air-pollution pressure was examined using available environmental monitoring data on particulate matter and other relevant pollutants. This design enabled the study to investigate associations between environmental pressures and the capacity of public health institutions to maintain effective and equitable services.

Population and Samples

The study population consisted of professionals and stakeholders involved directly or indirectly in urban public health management, including public health officers, healthcare professionals, hospital and primary healthcare administrators, environmental health personnel, local government officials, urban-planning representatives, and community health stakeholders. Participants were eligible when they had at least one year of professional or institutional experience related to public health services, environmental health, urban governance, healthcare management, or pollution-related health programs. Individuals without direct knowledge of public health operations or urban environmental issues were excluded to ensure that the collected information reflected relevant institutional experience (Hu, 2024; Soubeyrand, 2024).

A multistage sampling strategy was used to obtain adequate representation from different institutional levels and professional groups. Urban areas were initially selected according to predefined criteria concerning urban population pressure, air-quality challenges, healthcare service demand, and the availability of institutional and environmental data. Stratified sampling was subsequently used for the quantitative component to represent hospitals, primary healthcare facilities, public health agencies, and relevant local-government institutions. The study targeted approximately 420 respondents for the questionnaire survey, providing sufficient observations for multivariable analysis while allowing representation across institutional categories. A purposive subsample of approximately 30 key informants was selected for in-depth interviews based on their expertise, decision-making responsibilities, and direct involvement in public health preparedness, environmental health management, or urban policy implementation.

Instruments

Data were collected using a structured Public Health System Resilience Questionnaire developed from established concepts of health-system resilience and adapted to the context of urbanization and environmental health pressures. The questionnaire consisted of several domains covering institutional preparedness, workforce capacity, continuity of essential services, surveillance and information systems, resource flexibility, risk communication, intersectoral collaboration, community engagement, environmental health response, learning capacity, and policy adaptation. Responses were measured primarily using a five-point Likert scale ranging from strongly disagree to strongly agree. Additional items collected institutional and professional characteristics required for subgroup and multivariable analyses.

An institutional assessment checklist was used to document the availability of emergency plans, pollution-related surveillance mechanisms, environmental health programs, referral systems, health information infrastructure, workforce arrangements, and inter-agency coordination mechanisms. Secondary environmental data were obtained from officially

available air-quality monitoring records and included indicators such as PM2.5, PM10, nitrogen dioxide, sulfur dioxide, ozone, and other pollutants when reliable measurements were available. Urbanization indicators were derived from officially reported demographic and administrative statistics, including population density, urban population growth, healthcare utilization, settlement expansion, and transportation-related characteristics.

A semi-structured interview guide was developed for the qualitative component to explore how institutions understood and managed the combined pressures of rapid urbanization and air pollution. The interview questions addressed perceived vulnerabilities, institutional bottlenecks, workforce challenges, service disruptions, environmental surveillance, intersectoral cooperation, protection of vulnerable populations, policy implementation, and organizational learning. Instrument validity was evaluated through expert review involving specialists in public health, health-system management, environmental health, epidemiology, and research methodology. A pilot test was conducted with respondents outside the final study sample to assess item clarity, internal consistency, response time, and contextual suitability before full-scale data collection.

Procedures

Data collection began after ethical approval and institutional permission had been obtained from the relevant authorities. Potential participants received information concerning the objectives, procedures, voluntary nature, confidentiality provisions, and intended use of the study data. Written or electronically documented informed consent was obtained before participation. Trained research personnel administered the questionnaires using either secure electronic forms or supervised paper-based instruments according to local accessibility and institutional requirements. Institutional checklists were completed through document review and consultation with designated representatives, while environmental and demographic indicators were compiled from verified governmental or officially recognized monitoring sources (Münzel, 2024; Nalakurthi, 2024).

Quantitative data were screened for completeness, coding errors, missing values, and potential outliers before analysis. Descriptive statistics were used to summarize respondent characteristics, resilience indicators, urbanization pressures, and air-pollution conditions. Internal consistency of multi-item resilience domains was examined using Cronbach's alpha, while construct validity was assessed using exploratory or confirmatory factor analysis when the sample characteristics permitted such analysis. Correlation and multivariable regression analyses were applied to examine relationships among urbanization pressure, air-pollution exposure, institutional characteristics, and public health system resilience. Group differences across institutional categories or urban settings were assessed using appropriate parametric or non-parametric statistical procedures based on the distribution and measurement level of the data.

Qualitative interviews were conducted individually, audio-recorded with participant permission, transcribed verbatim, and anonymized before analysis. Thematic analysis was applied through systematic coding, category development, comparison of recurring patterns, and interpretation of institutional experiences related to resilience. Coding focused on preparedness, adaptive capacity, governance fragmentation, intersectoral coordination, environmental surveillance, equity, institutional learning, and transformational responses. Quantitative and qualitative findings were integrated during the interpretation stage through methodological triangulation, allowing statistical patterns to be examined alongside

stakeholder explanations and institutional experiences. The final analysis emphasized areas of convergence, divergence, and complementarity to provide a comprehensive understanding of how public health systems respond to the interconnected challenges of urbanization and air pollution (Khatib, 2023; Liao, 2024).

RESULTS AND DISCUSSION

The quantitative analysis included 420 valid responses collected from public health institutions and related urban governance agencies across four urban areas. The distribution consisted of 108 respondents from Urban Area A, 102 from Urban Area B, 106 from Urban Area C, and 104 from Urban Area D. The overall public health system resilience score was 3.39 ± 0.61 on a five-point scale, indicating a moderate level of institutional resilience. Secondary environmental data showed substantial variation in population density and annual PM2.5 concentration across the study sites. Urban Area A recorded the lowest annual PM2.5 concentration at $28.7 \mu\text{g}/\text{m}^3$ and the highest resilience score at 3.61 ± 0.54 , whereas Urban Area D recorded the highest PM2.5 concentration at $39.2 \mu\text{g}/\text{m}^3$ and the lowest resilience score at 3.12 ± 0.66 . Essential health-service continuity followed a similar pattern, ranging from 81.7% in Urban Area D to 91.4% in Urban Area A.

Table 1. Urbanization, Air Pollution, and Public Health System Resilience Across the Study Areas

Urban Area	Respondents (n)	Population Density (persons/km ²)	Annual PM2.5 (μg/m ³)	Resilience Score, Mean ± SD	Essential Service Continuity (%)
Urban Area A	108	8,450	28.7	3.61 ± 0.54	91.4
Urban Area B	102	11,230	34.9	3.37 ± 0.59	86.2
Urban Area C	106	9,780	31.5	3.44 ± 0.57	88.1
Urban Area D	104	13,640	39.2	3.12 ± 0.66	81.7
Overall	420	10,744	33.5	3.39 ± 0.61	86.9

Secondary air-quality records also demonstrated differences in PM10, nitrogen dioxide, and ozone concentrations among the four urban settings. Areas with higher transportation intensity and population density consistently recorded less favorable air-quality indicators. The average PM10 concentration across the study sites was $57.8 \mu\text{g}/\text{m}^3$, while mean nitrogen dioxide levels were higher in the two most densely populated areas. Health-service records indicated that respiratory outpatient visits were approximately 18.6% higher during periods when monthly PM2.5 concentrations exceeded the annual urban-area average. These descriptive patterns provided an initial indication that environmental pressure and healthcare demand were distributed unevenly across the study locations.

Public health resilience differed across its institutional dimensions. Environmental surveillance received the highest mean score at 3.66 ± 0.65 , followed by continuity of essential services at 3.58 ± 0.63 and institutional preparedness at 3.51 ± 0.68 . Lower scores were recorded for intersectoral coordination at 3.21 ± 0.74 , community engagement at 3.18 ± 0.72 , and resource flexibility at 3.09 ± 0.76 . The pattern suggests that participating institutions were

relatively capable of maintaining routine services and monitoring environmental health risks but faced greater difficulty in reallocating resources, coordinating decisions across agencies, and involving communities in preparedness and pollution-response activities.

Variation between urban areas also reflected differences in institutional organization rather than environmental exposure alone. Urban Area A combined lower pollution levels with stronger surveillance systems, established emergency response protocols, and more regular coordination between health and environmental agencies. Urban Area D experienced greater urbanization pressure while reporting weaker resource flexibility and lower inter-agency coordination. The difference of 0.49 points in mean resilience scores between these areas indicates that environmental burden was accompanied by differences in institutional capacity. The results therefore suggest that urbanization and air pollution created greater strain where governance and adaptive mechanisms were relatively weak.

The respondent profile represented a broad range of professional backgrounds relevant to urban public health management. Public health officers constituted 31.2% of the sample, healthcare professionals 24.8%, hospital and primary healthcare administrators 18.6%, environmental health personnel 13.1%, and representatives of local government or urban-planning institutions 12.3%. The average professional experience was 8.6 ± 5.3 years, with 64.5% of respondents reporting more than five years of involvement in health services, environmental health, or urban governance. Approximately 58.1% had participated in emergency preparedness or environmental-health response programs during the previous three years.

Measurement testing demonstrated satisfactory reliability across the resilience domains. The overall Public Health System Resilience Questionnaire produced a Cronbach's alpha coefficient of 0.91, while domain-specific coefficients ranged from 0.78 for community engagement to 0.88 for institutional preparedness. Factorability was supported by a Kaiser-Meyer-Olkin value of 0.89 and a statistically significant Bartlett's test of sphericity ($p < 0.001$). The instrument therefore demonstrated adequate internal consistency and construct structure for subsequent inferential analysis. The qualitative component involved 30 key informants comprising senior public health officers, health-facility managers, environmental-health specialists, urban planners, and local-government representatives.

One-way analysis of variance identified a statistically significant difference in public health resilience scores among the four urban areas, $F(3,416) = 14.72$, $p < 0.001$, $\eta^2 = 0.096$. Post hoc comparisons showed that Urban Area A had a significantly higher resilience score than Urban Area D ($p < 0.001$), while the difference between Urban Areas B and C was not statistically significant ($p = 0.38$). Pearson correlation analysis revealed a moderate negative association between annual PM_{2.5} concentration and resilience scores ($r = -0.43$, $p < 0.001$). Population density was also negatively associated with resilience ($r = -0.29$, $p < 0.001$), while intersectoral coordination ($r = 0.52$, $p < 0.001$) and environmental surveillance capacity ($r = 0.49$, $p < 0.001$) showed positive associations with overall resilience.

Multivariable linear regression explained 48% of the variance in public health system resilience (adjusted $R^2 = 0.47$; $F(5,414) = 76.40$, $p < 0.001$). Intersectoral coordination emerged as the strongest positive predictor ($\beta = 0.31$, $p < 0.001$), followed by environmental surveillance capacity ($\beta = 0.26$, $p < 0.001$) and resource flexibility ($\beta = 0.18$, $p < 0.001$). Annual PM_{2.5} concentration was independently associated with lower resilience ($\beta = -0.21$, $p < 0.001$), while population density showed a smaller but statistically significant negative

association ($\beta = -0.12$, $p = 0.008$). These results indicate that stronger institutional capacities were associated with greater resilience even after differences in environmental and urbanization pressures were statistically controlled.

Public health system resilience showed a strong positive relationship with continuity of essential healthcare services ($r = 0.61$, $p < 0.001$), suggesting that institutions with stronger preparedness, coordination, and adaptive capacity were more successful in maintaining routine services under urban environmental pressure. Environmental surveillance capacity was positively related to preparedness ($r = 0.55$, $p < 0.001$) and risk communication ($r = 0.46$, $p < 0.001$). Resource flexibility was also associated with service continuity ($r = 0.44$, $p < 0.001$), indicating that institutions capable of reallocating personnel, budgets, or operational resources were better positioned to respond to changing patterns of healthcare demand.

Air-pollution indicators demonstrated a different pattern of relationships. PM_{2.5} concentration was positively associated with pollution-related respiratory outpatient visits ($r = 0.47$, $p < 0.001$) and negatively associated with essential service continuity ($r = -0.36$, $p < 0.001$). The association between PM_{2.5} exposure and service continuity became weaker among institutions with high intersectoral coordination scores, suggesting that coordination capacity may partially buffer the operational pressure associated with environmental exposure. The findings support an interpretation in which environmental burden and institutional capability operate simultaneously, rather than functioning as independent dimensions of urban public health resilience.

The qualitative case analysis revealed clear contrasts between urban areas with relatively high and low resilience scores. Urban Area A had established an integrated environmental-health surveillance mechanism linking public health offices, healthcare facilities, environmental agencies, and local-government authorities. Air-quality alerts were routinely incorporated into health-service preparedness, allowing facilities to adjust staffing levels, reinforce respiratory-care capacity, and distribute public health information during periods of elevated pollution. Community health workers were also used to communicate risk information to vulnerable populations, particularly older adults, children, and residents with existing respiratory conditions.

Urban Area D displayed a more fragmented institutional response. Environmental monitoring information was available, yet interviewees reported that data were not consistently incorporated into operational decisions by healthcare facilities. Several informants described delays in information exchange between environmental agencies and health authorities, limited flexibility in deploying additional personnel, and insufficient coordination with transportation and urban-planning agencies. Informants also reported that residents of densely populated and lower-income neighborhoods experienced greater barriers to preventive services and timely health information. These conditions were consistent with the lower quantitative resilience and service-continuity scores observed in the area.

Thematic analysis identified four recurring factors that influenced resilience: intersectoral coordination, adaptive resource management, integrated surveillance, and equitable community engagement. Twenty-three of the 30 informants identified coordination across institutional boundaries as a major determinant of effective response, while 19 emphasized staffing and resource constraints during periods of increased pollution-related healthcare demand. Seventeen informants described limitations in real-time data sharing between environmental

and health institutions, and 14 highlighted unequal access to preventive information and services among socially or geographically vulnerable urban communities.

Institutional experiences provided a plausible explanation for the statistical relationships identified in the quantitative analysis. Higher resilience was not characterized solely by greater infrastructure or larger healthcare facilities; it was also associated with the ability to convert environmental information into timely operational decisions. Respondents from better-performing institutions described regular coordination meetings, predefined communication channels, flexible staffing mechanisms, and stronger engagement with community-level health networks. Institutions with lower resilience scores more frequently described fragmented authority, delayed decision-making, and dependence on reactive responses after healthcare demand had already increased.

The overall findings indicate that public health resilience under conditions of rapid urbanization and air pollution is shaped by both environmental pressure and institutional capacity. Higher population density and PM_{2.5} concentrations were associated with lower resilience and weaker continuity of health services, yet these relationships were not uniform across study areas. Institutions with stronger surveillance, coordination, resource flexibility, and preparedness demonstrated greater ability to maintain essential services despite environmental stress. The results therefore support a multidimensional interpretation of resilience that extends beyond physical healthcare capacity.

The findings also suggest that the effect of urban environmental pressure cannot be addressed through healthcare expansion alone. Stronger institutional coordination, timely environmental-health information, adaptive resource allocation, and community-oriented risk communication appear to be important components of resilient urban health systems. The cross-sectional design does not establish causal relationships between air pollution, urbanization, and institutional resilience, meaning that the reported associations should be interpreted cautiously. The convergence of statistical and qualitative evidence nevertheless indicates that strengthening governance and adaptive capacity may reduce the operational vulnerability of public health systems facing persistent urbanization and air-pollution pressures.

The findings demonstrate that public health system resilience under conditions of urbanization and air pollution remained at a moderate level across the investigated urban settings. The overall resilience score of 3.39 indicated that health institutions retained a reasonable capacity to maintain routine functions, yet substantial differences emerged between urban areas. Urban Area A showed the strongest resilience, the lowest annual PM_{2.5} concentration, and the highest continuity of essential services, whereas Urban Area D exhibited the lowest resilience alongside the highest population density and pollution level. This pattern indicates that the capacity of an urban health system cannot be separated from the intensity of environmental and demographic pressures within which the system operates.

The dimensional assessment revealed an uneven distribution of institutional strengths. Environmental surveillance, continuity of essential services, and institutional preparedness achieved relatively favorable scores, while resource flexibility, community engagement, and intersectoral coordination remained weaker. The imbalance is important because resilience requires more than the preservation of basic service delivery. A system may continue functioning during periods of pressure but remain structurally vulnerable when it lacks flexible resources, meaningful community participation, or reliable mechanisms for coordinating decisions across government sectors. WHO guidance similarly emphasizes that resilience must

be intentionally developed through integrated capabilities rather than assumed to arise automatically from routine health-system investment.

The inferential results strengthened the descriptive evidence by identifying statistically significant relationships between environmental pressures and institutional resilience. Higher PM_{2.5} concentrations were moderately associated with lower resilience scores, while population density also demonstrated a negative relationship with institutional capacity. Intersectoral coordination, environmental surveillance, and resource flexibility were significant positive predictors of resilience after environmental and urbanization pressures were considered simultaneously. The regression model explained a substantial proportion of variation in resilience, suggesting that institutional characteristics may meaningfully influence how urban health systems perform under environmental stress rather than merely reflecting differences in pollution exposure or population density.

The qualitative evidence reinforced these quantitative patterns by illustrating how resilience was enacted within institutional practice. Higher-performing urban settings used environmental information to anticipate service demand, adjust staffing, activate communication mechanisms, and protect vulnerable groups, whereas lower-performing settings displayed fragmented information flows and delayed responses. The convergence between survey scores, environmental indicators, service-continuity measures, and stakeholder accounts strengthens the interpretation that resilience emerges from the interaction between physical resources, organizational practices, governance arrangements, and the ability to convert information into timely action. Such convergence also reduces the likelihood that the observed differences were attributable to a single institutional dimension alone.

The relationship between pollution exposure and increased healthcare pressure is consistent with a substantial body of environmental-health research. A 2024 systematic review found significant associations between exposure to PM_{2.5}, PM₁₀, NO₂, SO₂, and ozone and increased respiratory hospital or emergency visits among children, including effects at pollution concentrations below existing health-based thresholds. Recent evidence concerning multimorbid populations also indicates that air-pollution exposure contributes to increased hospital attendance across several clinical categories. The present findings extend this evidence from individual health outcomes toward an institutional perspective by suggesting that repeated pollution-related increases in healthcare demand can become a resilience problem when health systems lack adaptive operational capacity.

The importance of surveillance, workforce preparedness, institutional learning, and adaptive operational planning observed in this study corresponds with research examining health-system responses to broader environmental threats. A recent systematic review of health-system preparedness for climate-related risks identified surveillance systems, structural adaptation, professional training, operational planning, leadership, and learning from previous events as important components of resilience, while limited human, material, and financial resources were repeatedly identified as barriers. The similarity suggests that air pollution and climate-related disruptions may share several institutional pathways even though their temporal patterns differ. Pollution often operates as a persistent and cumulative stressor rather than as a discrete event, requiring resilience mechanisms that function continuously rather than only during declared emergencies.

The prominence of intersectoral coordination in the regression and qualitative findings is also consistent with contemporary urban-health guidance. WHO's urban health capacity

framework emphasizes connective capacities that enable actors operating across organizational and governmental boundaries to work toward common health objectives. The present findings provide empirical logic for that recommendation because health institutions with stronger coordination appeared better able to translate environmental information into preparedness and service adjustments. Air pollution originates substantially from sectors such as transportation, energy, industry, land use, and waste management, meaning that the health sector cannot independently control many upstream determinants of exposure. Resilience therefore depends partly on relationships extending beyond the conventional boundaries of healthcare administration.

An important difference from much previous resilience research concerns the character of the stressor examined. Health-system resilience literature has often developed around pandemics, disasters, conflicts, and other identifiable shocks, although contemporary scholarship increasingly recognizes chronic stressors as equally relevant. A recent analysis of empirical health-system resilience research confirms that the field has expanded from acute shocks toward chronic and complex stress conditions. Critical scholarship has similarly cautioned against treating resilience merely as a return to pre-crisis performance and has emphasized relationships, equity, governance, and transformative capacity when persistent stressors are involved. The present study contributes to that shift by treating urbanization and air pollution as continuous pressures capable of progressively weakening institutional performance without producing a single clearly defined crisis moment.

The moderate resilience level identified in this study signals a condition of functional capability accompanied by latent institutional vulnerability. Essential services may remain available under ordinary environmental pressure, yet the lower scores for resource flexibility and coordination suggest limited room for responding when several stressors intensify simultaneously. Urban health systems can therefore appear stable while operating close to institutional thresholds that are not immediately visible through routine service indicators. Resilience should not be inferred solely from whether facilities remain open or whether services continue because operational continuity can coexist with workforce exhaustion, delayed prevention, unequal access, and declining adaptive capacity.

The negative relationship between environmental pressure and resilience signals that urbanization can become a public health systems issue rather than merely a demographic or planning issue. Growing populations expand the number of people requiring health services while simultaneously changing exposure patterns, mobility, housing conditions, infrastructure requirements, and environmental risks. Dense urbanization does not inherently produce weaker health systems, but rapid growth without corresponding institutional adaptation can widen the gap between service demand and response capacity. The findings therefore challenge an overly deterministic interpretation of urban density. Governance quality, infrastructure, planning, resource distribution, and institutional learning determine whether density becomes a health burden or can be managed as part of sustainable urban development.

The comparatively strong role of coordination signals that resilience is fundamentally relational. Hospitals, primary healthcare facilities, environmental agencies, municipalities, transport authorities, urban planners, and communities each possess only a portion of the information and authority necessary to address pollution-related health risks. Fragmentation between these actors can weaken resilience even when individual institutions perform adequately. A 2025 scoping review of health-system governance and resilience similarly shows

that governance relationships are central to how systems anticipate and respond to shocks, while conceptual approaches differ in the extent to which they address power, coordination, and institutional interaction. Resilience consequently emerges not only from organizational capacity but from the quality of connections between organizations.

The qualitative evidence concerning vulnerable neighborhoods also signals that resilience must be evaluated through an equity lens. An urban system cannot be considered fully resilient when average service indicators remain stable while specific populations experience greater pollution exposure, weaker access to preventive care, or delayed risk communication. Critical resilience scholarship has warned that aggregate measures can conceal who bears the costs of adaptation and whose needs are protected during periods of stress. The findings suggest that equity should be treated as a core characteristic of resilience rather than a secondary social outcome, especially in urban environments where environmental hazards and healthcare access are often distributed unevenly.

The first practical implication concerns the need to redefine public health preparedness for polluted and rapidly growing cities. Preparedness should include environmental-health surveillance, pollution-sensitive demand forecasting, flexible workforce arrangements, and predefined procedures for maintaining essential services during periods of poor air quality. WHO's resilience indicator framework explicitly supports monitoring health-system performance during both routine operations and disruptive stressors, providing a useful basis for incorporating chronic environmental pressures into institutional performance assessment. Urban health departments could therefore treat air-quality deterioration as an operational planning variable rather than solely as an environmental indicator.

The second implication concerns data integration. Air-quality monitoring systems have limited public health value when environmental measurements remain administratively separated from epidemiological surveillance and health-service planning. Urban health systems would benefit from platforms connecting pollution concentrations, respiratory and cardiovascular morbidity, emergency visits, pharmaceutical demand, absenteeism, and facility capacity. Such integration could support threshold-based alerts and short-term projections of service demand. WHO already provides tools for assessing the health impacts of air pollution and incorporating health considerations into transportation and urban policy, demonstrating that technical mechanisms for stronger integration are increasingly available.

The third implication concerns institutional governance rather than technological expansion alone. Investments in additional hospital beds or equipment may reduce immediate service pressure, but they cannot address pollution sources or prevent future exposure without coordinated upstream action. Public health authorities require formal mechanisms for participating in transportation, energy, housing, industrial, waste-management, and land-use decisions. WHO's environmental-health guidance emphasizes interventions across multiple sectors and levels of implementation, reinforcing the principle that environmental health improvement depends on policy actions extending beyond healthcare facilities. Health-system resilience should therefore become one consideration within broader urban governance rather than remain an internal objective of health ministries or hospitals.

The fourth implication relates to resource allocation and environmental justice. Health authorities should identify neighborhoods where high pollution exposure overlaps with poverty, population density, chronic disease, limited primary-care access, and other forms of social vulnerability. Targeted mobile services, community health workers, risk communication,

respiratory screening, medication availability, and enhanced primary-care capacity may produce greater benefits when prioritized toward these areas. A uniform city-wide response can unintentionally reproduce inequalities because equal resource allocation does not necessarily correspond to equal need. Resilience-oriented planning must therefore incorporate vulnerability mapping and differentiated interventions if it is intended to protect the population rather than merely preserve aggregate system performance.

The negative association between PM_{2.5} concentration and health-system resilience can be understood through a demand-pressure mechanism. Higher pollution exposure contributes to respiratory and cardiovascular morbidity and can increase outpatient consultations, emergency visits, and hospital admissions. Evidence from systematic reviews consistently associates particulate matter exposure with increased cardiovascular and respiratory morbidity and healthcare utilization. Recurrent increases in demand can consume staff time, medicines, diagnostic capacity, beds, and financial resources that would otherwise be available for routine preventive and curative services. Chronic exposure therefore creates cumulative operational pressure even when no individual pollution episode reaches the level of a formal emergency.

The lower resilience observed in more densely populated settings may reflect a mismatch between the pace of urban growth and the speed at which public institutions can expand. Population growth can occur rapidly, while recruitment, infrastructure construction, budget reform, surveillance development, and institutional coordination generally require longer administrative processes. Informal or peripheral urban expansion can intensify this imbalance when new settlements emerge beyond the effective coverage of existing health and environmental services. Population density itself should not be interpreted as the direct cause of reduced resilience because well-planned high-density cities may provide efficient services. The more plausible explanation is that unmanaged or insufficiently supported density magnifies institutional pressure when service capacity fails to develop proportionately (Li, 2025; Xie, 2023).

The positive influence of intersectoral coordination can be explained by the distribution of authority across urban systems. Health agencies can identify disease patterns, yet environmental authorities often control pollution monitoring, transportation authorities influence vehicle emissions, urban planners determine spatial development, and local governments regulate numerous sources of environmental exposure. Coordinated institutions can pool information, align policies, reduce duplication, and respond earlier than institutions operating through isolated administrative channels. WHO's urban-health guidance describes these cross-organizational connections as essential capacities precisely because many determinants of health are generated beyond the formal health sector. The stronger performance of coordinated institutions in the present study is therefore theoretically plausible rather than merely statistical.

The observed importance of resource flexibility can be understood as the operational expression of adaptive capacity. Fixed budgets, rigid staffing arrangements, and highly centralized decisions may function adequately under stable conditions but become limitations when demand changes rapidly. Flexible systems can redeploy staff, extend clinic capacity, shift supplies, modify risk communication, and prioritize vulnerable populations according to changing environmental conditions. The cross-sectional nature of the present analysis means that these mechanisms cannot be interpreted as definitive causal pathways. Reverse relationships are also possible, since better-performing systems may acquire stronger

coordination and resource flexibility over time. Longitudinal evidence would be required to determine whether these institutional capacities precede improvements in resilience or develop partly as a consequence of them.

Immediate institutional action should focus on transforming environmental-health surveillance into an operational component of routine public health management. Urban health authorities should establish protocols linking air-quality thresholds with health-service preparedness, workforce allocation, medication stocks, public warnings, and targeted interventions for vulnerable populations. Routine resilience assessments could be conducted at municipal and facility levels using standardized indicators adapted to local environmental conditions. WHO's current resilience guidance supports precisely this contextual approach, stressing that resilience requires intentional programming, investment, measurement, and adaptation rather than generic solutions applied uniformly across settings (Liao, 2024; Moore, 2025).

Medium-term policy action should establish durable governance arrangements connecting health authorities with environmental agencies, transportation departments, energy planners, housing institutions, and urban-development bodies. Joint indicators and shared accountability mechanisms could reduce the tendency for each sector to optimize its own objectives while transferring health costs to another part of the urban system. Health-impact assessment should become a routine component of major transportation, industrial, land-use, and infrastructure decisions. The goal should not be to expand the authority of the health sector over every urban policy domain, but to ensure that credible health evidence has an institutional pathway into decisions that shape exposure and vulnerability.

Future research should move beyond cross-sectional measures toward longitudinal and multilevel designs capable of testing how resilience changes as urbanization and air pollution evolve. Repeated measurements could examine whether improvements in coordination, surveillance, workforce flexibility, and community engagement reduce service disruption during periods of elevated pollution. Quasi-experimental research could evaluate health-system changes before and after clean-air interventions, transportation reforms, integrated surveillance systems, or major urban-planning policies. Comparative studies across cities with different governance arrangements would also clarify whether similar pollution burdens produce different health-system consequences because of institutional design rather than environmental conditions alone (Khatib, 2023; Liao, 2024).

Future conceptual development should treat resilience as the capacity to anticipate, absorb, adapt, learn, and transform rather than simply return to a previous state. Returning to pre-existing conditions is inadequate when those conditions already include high pollution exposure, unequal access to healthcare, fragmented governance, and preventable disease. WHO recovery guidance similarly recognizes disruptive periods as opportunities to address pre-existing weaknesses and inequities instead of merely restoring previous performance. The central implication of the present study is therefore that resilient urban public health systems must do more than withstand environmental pressure. They must develop the institutional capacity to reduce the conditions that repeatedly generate that pressure, protect populations unequally exposed to risk, and participate actively in the creation of healthier and more sustainable cities.

CONCLUSION

The most important finding of this study is that public health system resilience is determined not only by the intensity of urbanization and air pollution but also by the capacity of institutions to coordinate, adapt, and translate environmental information into operational responses. Higher PM_{2.5} concentrations and greater population density were associated with lower resilience and weaker continuity of essential health services, while intersectoral coordination, environmental surveillance, and resource flexibility emerged as important positive predictors of system performance. The findings also reveal that cities experiencing comparable environmental pressures may demonstrate different levels of resilience when institutional preparedness, information sharing, and community engagement vary. This pattern indicates that environmental exposure alone does not determine health-system vulnerability; institutional capacity strongly influences how effectively urban health systems absorb, manage, and respond to persistent environmental stress.

The principal contribution of this research lies in its conceptual and methodological integration of urbanization pressure, air pollution, and public health system resilience within a single analytical framework. Conceptually, the study extends resilience beyond conventional emergency preparedness by treating rapid urban growth and air pollution as chronic, cumulative stressors that continuously influence healthcare demand, institutional capacity, and population vulnerability. Methodologically, the combination of quantitative resilience measurement, secondary environmental and demographic indicators, and qualitative institutional evidence provides a more comprehensive assessment than approaches based exclusively on healthcare performance or pollution exposure. This integrated perspective offers a useful foundation for evaluating whether public health systems merely maintain services under pressure or possess the adaptive and transformative capacities required to reduce future vulnerability.

The limitations of this study should be considered when interpreting its findings. The cross-sectional design limits causal inference and does not capture changes in institutional resilience across different phases of urban growth or fluctuations in air-pollution exposure. Variations in monitoring quality, institutional reporting practices, and self-reported perceptions may also influence the consistency of measurements across study settings. Future research should employ longitudinal, multilevel, and comparative designs to examine how resilience develops over time and whether improvements in surveillance, coordination, workforce flexibility, and community participation reduce the health-system consequences of environmental pressure. Further studies should also incorporate neighborhood-level exposure, socioeconomic inequality, climate-related stressors, and intervention-based evaluations to determine which combinations of governance and public health strategies are most effective in strengthening resilient, equitable, and environmentally responsive urban health systems.

DECLARATION OF AI AND AI ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the author(s) used Google Assisted to assist in improving grammar, language quality, and overall readability of the text. After using this tool, the author(s) Carefully reviewed and edited the content as necessary and take full responsibility for the content of the publication.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.

Author 3: Data curation; Investigation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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