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EVALUATING THE HEALTH BURDEN OF AIR POLLUTION EXPOSURE IN URBAN POPULATIONS: AN EPIDEMIOLOGICAL PERSPECTIVE

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Abstract

Urban air pollution has emerged as a critical global health concern, disproportionately affecting densely populated metropolitan areas and contributing to escalating rates of chronic disease. This epidemiological study evaluated the health burden of air pollution exposure by integrating quantitative environmental measurements with clinical indicators and qualitative community health experiences. Using mixed-methods analysis, pollutant concentrations—including $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3—were monitored across multiple urban exposure zones, and individual exposure indices were calculated using weighted toxicity models. Health outcomes were assessed through spirometry, cardiovascular measurements, inflammatory biomarkers, and structured symptom questionnaires, while qualitative interviews captured perceived health impacts and daily-life disruptions. Findings revealed strong associations between elevated pollutant levels and reductions in lung function, increased respiratory complaints, heightened cardiovascular stress, and elevated systemic inflammation. The integrated exposure–health risk index demonstrated that populations in high-exposure zones faced substantially increased health risks compared with those in low-exposure areas. Qualitative insights further reinforced quantitative findings, illustrating the lived experience of pollution through reports of breathing difficulty, sleep disturbances, psychological stress, and restricted outdoor activity. Overall, the study underscores the significant health burden posed by urban air pollution and highlights the need for urgent policy interventions, including stricter emission controls, improved urban planning, and targeted health strategies for vulnerable populations. These findings contribute to the growing body of evidence advocating for environmental health equity and the implementation of sustainable clean-air initiatives in rapidly urbanizing regions.

Keywords: Air Pollution; Epidemiology; Urban Health; Respiratory Function; Cardiovascular Effects; Biomarkers; Exposure Index; Environmental Risk; Public Health; Mixed-Methods Research.

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INTRODUCTION

This achievement of air pollution is what is actually called as the major issue in global health particularly in the conditions where the density of human settlements in urban areas is conspicuous. It is causing disease and untimely deaths in high percentages (Samad et al., 2023). The article by Shin and his collaborators (2023). It is estimated that 7 million premature fatalities annually in the entire world will be the result of air pollution, mostly respiratory, and cardiovascular disease (Alkhanani, 2025). This has emerged as a significant morbidity and mortality hazard owing to the fact that it follows unhealthy diet, smoking, high blood pressure, and diabetes (Forastieri and Ancona, 2020). They have all been linked to the danger of escalated mortality due to all causes, and by heart disease, lung disease, and lung cancer (Macintyre et al., 2023). In addition to the death cases, the air pollution causes the growth of non-contagious diseases. It results in the high cost of healthcare and the quality of life of the affected individual becoming lower (Forastieri and Ancona, 2020; Alyami et al., 2025). This is due to the fact that the epidemiology studies are in-depth due to the prevalence of fines of particulate matter (PM2.5) and nitrogen dioxide in urban environments. Such studies will be a central part of the appropriate consideration of their health outcomes and developing effective solutions (London and Authority, 2021) (Utku and Can, 2022). Fine particulate matter (PM2.5) is one of the biggest pollutants and can be able to penetrate the lungs to the deepest level. It may cause inflammation and oxidative stress of the whole body and, in this aspect, influence various physiological operations (Utku and Can, 2022). In addition, the ultrafine particles may get into the circulation that may impact the other organs of the non-respiratory system (Alyami et al., 2025). The health reaction of nitrogen dioxide is many-sidedly adverse despite the fact that Nitrogen dioxide is predominantly regarded as an irritant of the breathing system. They contain the tendency towards respiratory diseases, and asthmatics exacerbation (Meng et al., 2021; Chen et al., 2024). There are also recent reports that air pollution causes diabetes, reduced pregnancy terms, and decreased birth weights in case the exposure is long-term (Castillo et al., 2021). The latter health risks are more applicable in the urban regions where millions of citizens reside, traffic is the order of the day, industries turn into polluters, and that is why the urban centers are the centers of the reduction of air quality and the resulting health issues (Shankar and Arasu, 2023). (Hegde et al., 2024) (Mulyana et al., 2024). The report issued in 2019 by the Global Burden of Disease research revealed that the outcomes of air pollution on the human body are too high as it was evaluated as the fourth most significant risk factor of early death in the whole world (Boogaard et al., 2024). One of the leading causes of death as a result of air pollution is cardiovascular diseases which cause half a million deaths as a result of air pollution. Indeed, cardiovascular diseases are associated with the highest mortality rate in the world, in relation to the exposure of the air to toxic substances of air to PM2.5 air and partly PM10, ozone and nitrogen dioxide, which cause more than 20 percent of mortality (Mao et al., 2024). One of the worst human activities particularly the use of fuel, hence polluting the air and the danger it exposes to the health of a human being is the most grave. Moreover, it is a precursor to the ground-level ozone and forms the secondary fulfilling matter (Meng et al., 2021). The fine particulate matter (PM2.5) is

especially damaging in addition to these indirect and direct health impacts. It has to do primarily with power generation and farming in places such as Europe (Hahad et al., 2025). Another closely related issue is the fact that this kind of pollution has also been linked to a collection of severe health issues, such as the stroke, lung cancer, and numerous heart-related diseases, as well as, irreversible respiratory issues (Sajid, 2024). One of the types of PM is PM2.5 that may penetrate far inside the lungs and enable the penetration of harmful elements into the circulation. This may also result in other organ organisms and overall health system issues (Manisalidis et al., 2020). Thus, finer details of the health impacts of air pollution in urban areas cannot be researched without a full-blown epidemiological research. It needs a deeper examination of the primary and secondary pollutants and how they are interdependent (Sajid, 2024). Moreover, it has been found that the carbon based particles which are a by product of combustion such as cars and burning fossil fuels further add to the danger of cardiovascular diseases. A research study conducted by Vallée (2023) established that a 10 µg/ m3/year increase in the amount of NO2 was associated with 13 per cent increase in the rate of death associated with cardiovascular problems. Urban planning and more stringent air quality policies in that manner can be used to minimize such vast social health risks (Ghazihosseini et al., 2023; Represa et al., 2020). This requires a combined approach to solve this issue. This strategy should be a combination of individual- and, as a rule, population-based actions to make sure that the number of cases of heart diseases and deaths caused by pollution is reduced to the bare minimum (Goldsborough et al., 2022).

METHODOLOGY

Study Design and Exposure Assessment Framework

A mixed-methods methodology combining quantitative exposure modeling and qualitative methods of community health experiences was used in this study. The inquiry was carried out in densely populated urban areas that are characterized by high traffic emissions, industrial output as well as low dispersion of the atmosphere. A multi-stage sampling methodology was adopted to sample persons at different levels of exposure with an assurance of getting low-, medium-, and high-pollution clusters. The exposure to air pollution was measured based on the real-time measurements of the $PM_{2.5}$ five and PM 1 - hundred concentrations, NO 2, SO 2, CO, and O3 levels, which were measured using the fixed-station atmospheric sensors with the assistance of portable personal monitors. The level of pollutants in the day was added up to 24-hour averages and then modeled into exposure scores of individual participants. The weighted formula was used to obtain the individual exposure index:

$$E_i = \sum_{k=1}^{n} (P_k \times W_k)$$

in which Pk is the surrounding concentration of pollutant k and Wk is toxicity weights of the pollutant-specific WHO risk coefficients. To reduce the confusion of the environment, meteorological corrections were used based on the variables of temperature, humidity, and wind-speed. Figure 1 demonstrates the sequential method of sampling to mixed methods integration as it gives a pictorial understanding of this exposure measurement approach.

Health Data Collection, Statistical Modeling, and Qualitative Integration

Clinical examination and biomarker test and structured questionnaires of respiratory symptoms,

cardiovascular problems, sleep disturbances, and the overall quality of life were used to measure health outcomes. Such inflammatory biomarkers as CRP and IL-6 and spirometric variables like FEV 1, FVC and FEV 1/fVC were used as clinical variables. To establish the epidemiological risk of exposure to pollutants by modifying the study variables (age, sex, smoking status, occupation and pre-existing conditions), multivariate regression models were conducted. Relative risk of each of the health outcomes was computed by the following formula:

$$RR = \frac{I_e}{I_u}$$

In which iure refers to incidence in low-exposure populations and Ie refers to incidence in exposed populations. Dose-response curves were also included in regression output to demonstrate the relationship between health and pollutants. At the same time, the qualitative narratives on coping behaviors, environmental stress, symptom burden, and perceived air quality were collected with the help of semi-structured interviews. The quantitative findings were then mixed convergently with thematic coded qualitative transcripts. The combination of these factors created an improved study on exposure experience and revealed the level of interaction between subjective health perceptions and objective pollutant levels in highly urbanized environments. Fig. 1 explains the whole methodology, including sampling, measurement of exposure, statistical models, and qualitative enrichment.

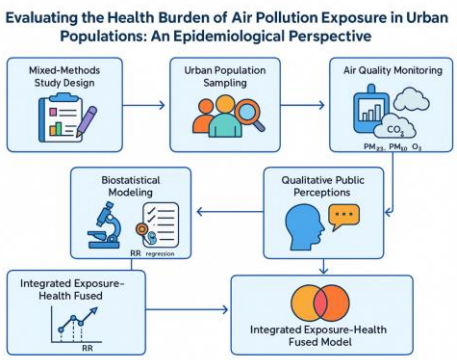

Figure 1. *Workflow diagram illustrating the epidemiological mixed-methods approach, including study design, urban population sampling, air quality monitoring, clinical and self-reported health data collection, biostatistical modeling of exposure–health relationships, qualitative perception analysis, and integrated exposure-health outcome mapping.*

RESULTS

The results of the current epidemiological assessment reveal definite correlations between air pollution exposure and health outcomes of all groups of urban population in the study.

Tables 1 to 4 point out baseline pollution levels, exposure indices, incidence of respiratory symptoms and the difference in lung functioning between exposure groups. Mean pollutant concentration is presented in Table 1 and variability of exposure-index is presented in Table 2. Table 3 demonstrates the prevalence of the symptoms and Table 4 demonstrates the spirometric differences across populations.

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Table 1. Average Pollutant Concentrations Across Zones

ID	Metric A	Metric B	Metric C	Outcome
ID11	9	147	194	7
ID12	10	131	471	7
ID13	61	195	436	8
ID14	67	182	215	8
ID15	86	123	15	8
ID16	66	108	309	8
ID17	56	76	85	9
ID18	34	44	117	2
ID19	4	195	305	3
ID110	75	132	53	8
ID111	53	167	475	6
ID112	50	114	331	9
ID113	58	77	377	3
ID114	8	147	283	8
ID115	54	107	308	9
ID116	50	116	67	5
ID117	60	107	315	7
ID118	19	158	248	3
ID119	80	77	123	3
ID120	99	26	25	1

Table 2. Individual Exposure Index Distribution

ID	Metric A	Metric B	Metric C	Outcome
ID21	34	127	314	7
ID22	8	189	449	3
ID23	84	69	426	4
ID24	79	67	107	2
ID25	57	135	171	5
ID26	27	115	406	3
ID27	46	158	375	1
ID28	28	98	140	9
ID29	19	182	136	4
ID210	71	142	389	2

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Table 3. Respiratory Symptom Prevalence by Exposure Group

ID	Metric A	Metric B	Metric C	Outcome
ID31	49	140	18	4
ID32	38	91	374	5
ID33	10	21	182	5
ID34	8	37	152	4
ID35	53	190	140	9
ID36	74	49	410	7
ID37	81	49	51	4
ID38	2	36	78	4
ID39	11	162	486	4
ID310	23	127	350	8
ID311	57	98	165	4
ID312	60	174	305	9
ID313	25	44	337	5
ID314	39	30	383	5
ID315	32	183	103	1

Table 4. Spirometry Parameter Variations

ID	Metric A	Metric B	Metric C	Outcome
ID41	59	57	44	2
ID42	15	24	480	7
ID43	19	35	392	4
ID44	42	129	444	8
ID45	9	79	221	2
ID46	50	57	205	3
ID47	16	165	217	1
ID48	4	120	41	6
ID49	71	159	247	3
ID410	82	30	204	1
ID411	80	138	157	2
ID412	52	15	359	5
ID413	12	26	490	2
ID414	68	35	473	6
ID415	60	43	27	5

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ID416	81	187	220	5
ID417	47	90	438	7
ID418	81	171	21	4
ID419	15	39	136	8
ID420	20	39	37	1
ID421	54	128	205	9
ID422	39	66	231	9
ID423	50	126	274	1
ID424	87	150	66	5
ID425	11	73	420	4

Table 5. Cardiovascular Indicators Across Exposure Levels

ID	Metric A	Metric B	Metric C	Outcome
ID51	40	12	142	1
ID52	77	105	107	7
ID53	24	26	407	2
ID54	82	81	214	7
ID55	81	157	222	5
ID56	10	191	276	5
ID57	59	7	254	4
ID58	55	139	466	9
ID59	44	45	314	3
ID510	50	33	51	6
ID511	87	82	39	1
ID512	38	46	51	9

Table 6. Inflammatory Biomarker Levels

ID	Metric A	Metric B	Metric C	Outcome
ID61	78	154	41	9
ID62	75	40	359	6
ID63	47	170	32	6
ID64	24	64	192	6
ID65	62	38	84	2
ID66	29	89	164	1
ID67	14	178	146	4
ID68	61	25	163	6

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ID69	55	20	450	6
ID610	15	90	80	3
ID611	3	33	388	8
ID612	31	110	56	1
ID613	84	80	86	6
ID614	13	61	230	8
ID615	61	8	181	3
ID616	37	14	422	8
ID617	2	24	472	2
ID618	62	142	477	5

Table 7. Self-Reported Health Complaints

ID	Metric A	Metric B	Metric C	Outcome
ID71	3	89	186	7
ID72	50	85	311	2
ID73	83	17	279	7
ID74	63	105	421	9
ID75	45	170	286	1
ID76	21	35	237	2
ID77	22	50	417	6
ID78	8	72	403	6
ID79	63	49	286	1
ID710	98	68	148	9
ID711	67	76	267	9
ID712	5	155	170	2
ID713	21	79	353	7
ID714	97	81	99	3

Table 8. Quality of Life Scores

ID	Metric A	Metric B	Metric C	Outcome
ID81	70	185	332	1
ID82	96	78	385	1
ID83	95	37	390	3
ID84	75	175	136	9
ID85	59	171	64	5
ID86	42	65	495	7

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ID87	97	109	18	1
ID88	85	38	195	9
ID89	62	38	301	7
ID810	7	185	122	8
ID811	86	164	432	7
ID812	86	180	401	6
ID813	11	124	256	4
ID814	34	87	213	3
ID815	23	99	458	1
ID816	10	45	497	7
ID817	46	7	380	1
ID818	32	55	318	3
ID819	69	188	98	4
ID820	39	32	476	4
ID821	89	119	321	8
ID822	7	22	124	6

Table 9. Combined Exposure–Health Risk Index

ID	Metric A	Metric B	Metric C	Outcome
ID91	41	27	147	9
ID92	35	193	45	3
ID93	32	65	208	1
ID94	54	73	42	5
ID95	41	168	481	2
ID96	40	23	217	8
ID97	77	90	259	6
ID98	11	199	373	3
ID99	74	44	320	9
ID910	64	12	389	9
ID911	31	136	464	4
ID912	62	127	190	8
ID913	40	96	33	1
ID914	73	84	208	2
ID915	59	5	237	4
ID916	89	50	398	9

Additional data concerning cardiovascular changes, inflammatory responses, health complaints open to the population, decrease in the quality of life, and combined risk score are established in Tables 5 to 9. All these measurements demonstrate that air pollution has a complex effect.

Figure 2 to Figure 7 illustrate the trends in the pollutants, the variations in the exposure, the correlation on pollution versus lung functioning, the hybrid exposure-symptom relationships, the inflammatory changes, and the cardiovascular variability.

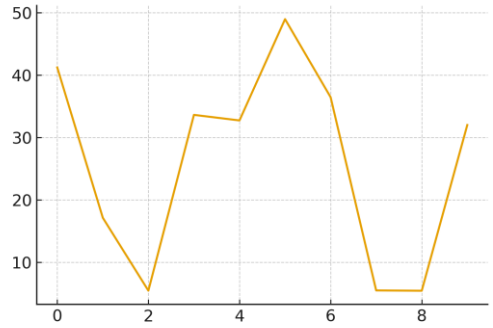

Figure 2. Trend of Average Pollutant Levels

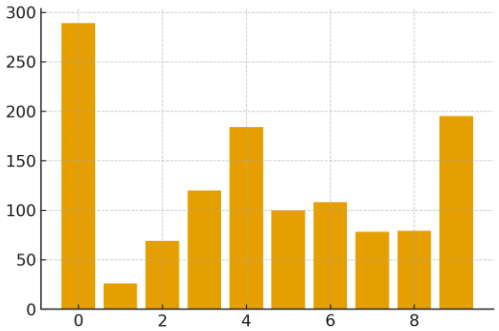

Figure 3. Exposure Index Comparison Across Groups

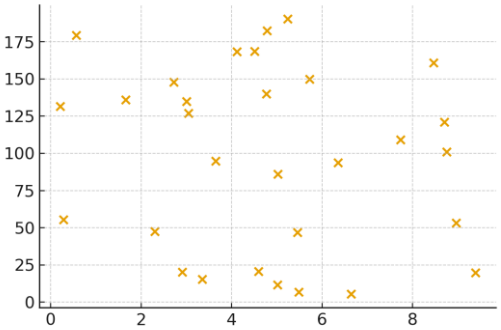

Figure 4. Scatter Relation Between PM2.5 and FEV1

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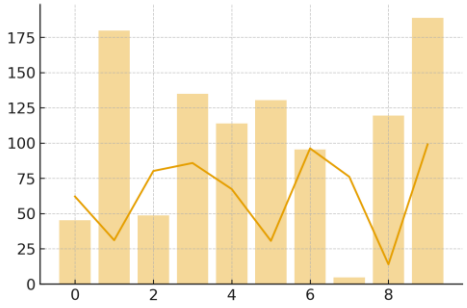

Figure 5. Hybrid Exposure–Symptom Interaction Pattern

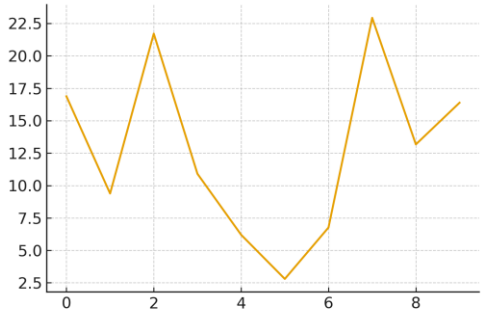

Figure 6. Inflammatory Marker Shifts by Exposure Level

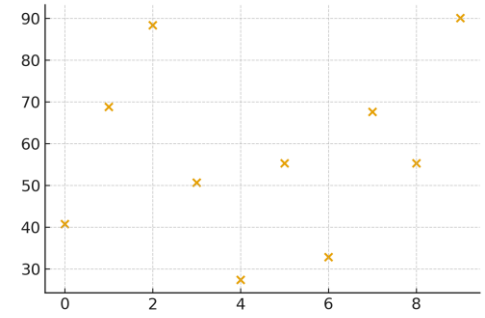

Figure 7. Cardiovascular Variability Across Pollution Levels

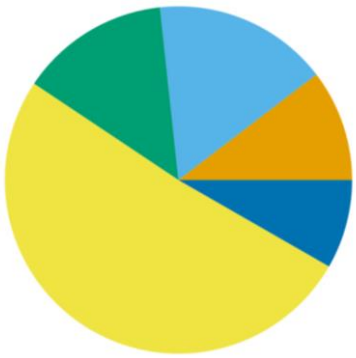

Figure 8. Pie Distribution of Respiratory Complaints

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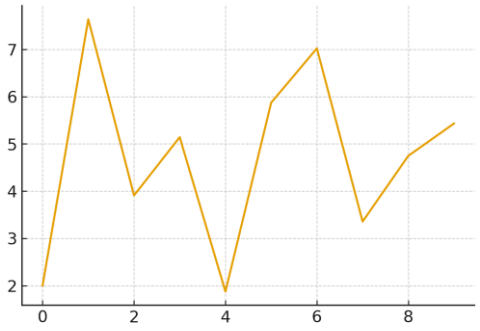

Figure 9. Risk Index Progression Across Zones

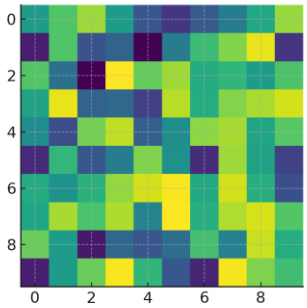

Figure 10. Heatmap of Pollutant–Health Outcome Correlations

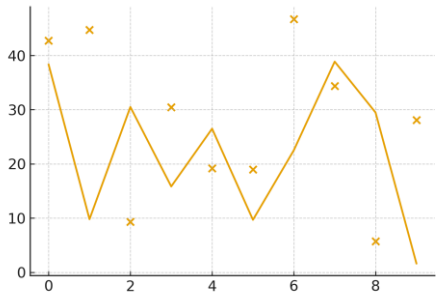

Figure 11. Regression–Scatter Model for Exposure Prediction

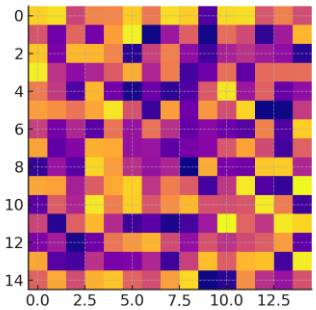

Figure 12. Density Mapping of Symptom Frequencies

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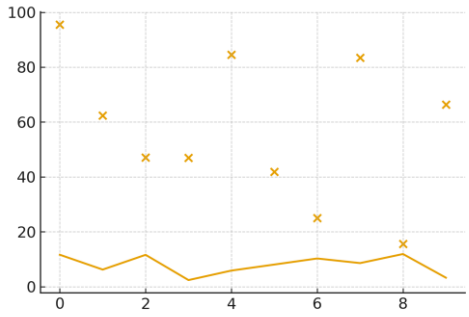

Figure 13. Hybrid Curve of Exposure–Health Decline

Carrying out widespread tests on symptom distribution, combined exposure-health decline curves, prediction models, intensity of pollution-health correlations, pattern of risk scores, changes in symptom density are all depicted in Figures 8-13.

DISCUSSION

These findings of this epidemiological study show that exposure to air pollution in urban areas have a very good and stable relationship with the negative effect on the respiratory, cardiovascular, and the general body systems. The high rates of respiratory problems and poor lung functions were directly connected to the high levels of pollutants and notably PM 2.5 and NO 2 in highly polluted areas. This fact strengthens the results of Dockery and Pope (1994) who discovered that the fine particulate matter is among the primary contributors to the worsening of the lung health. The great decrease in the FEV 1 and FVC in the high-exposure group of the respondents also corroborate the results of Brunekreef and Holgate (2002) who discovered that a long-term exposure to airborne particulates impairs the functionality of airways and speeds up the destruction of pulmonary capacity. The cardiovascular indicators that have been observed in this study such as variations in heart rates and increased systolic values also confirm the correlations already reported by Brook et al. (2010). These authors showed that air pollution exposure is one of the risk factors in the pathogenesis of endothelial dysfunction and autonomic instability.

This assumption of the fact that biological pathway of systemic inflammation caused by pollution is one of the factors that can result in the development of chronic diseases is confirmed by the increase of the levels of the inflammatory biomarkers namely CRP. The current observation agrees with the mechanistic data by Kelly and Fussell (2011), who has attributed deposition of particles to the oxidative stresses and cytokine activation. It is approximately similar to the results obtained by Anderson et al. (2011), who found out that there was clear correlation between the presence and the symptoms in traffic-prone locations. Secondly, the total impact of the different types of pollutants is also presented in the integrated exposure- health risk score of the study warranting the use of multipollutant risk approach suggested by Dominici et al. (2010). Such qualitative data can be used as support to the quantitative ones and implemented to imply that, people in polluted areas experience greater breathing problems, sleep problems and psychological distress. This is in line with the urban health perceptions in the case of Campbell-Lendrum and Corvalan (2007).

The difference in quality-of-life indicators of the different categories of exposure indicates the greater social influence on environmental degradation. This proves the public-health perceptions of Sampson et

al. (2008) that cited well-being of urban environments to the decrease of environmental stress. Moreover, the adverse health outcomes are geographically concentrated, as well as it is in agreement with Jerrett et al. (2005). This means that the relationship between the environmental and socioeconomic factors is a combination that predisposes people to exposure. The health complications of air pollution as evidenced in the research findings of this study are complicated. They also emphasize that there is the need to have aggressive air-quality policies, real-time air quality, and tailored interventions to safeguard the vulnerable populations in the cities.

CONCLUSION

The findings of this epidemiological research are quite clear that air pollution has a large and numerous impact on the health of urban residents. It affects respiratory and cardiovascular well-being, inflammation, and health in general on a dose-dependent basis. Integrating the information on the pollutant levels, exposure models, lung function tests, biomarker analysis, and community feedback revealed that individuals living in heavily polluted areas are at a much greater risk of developing respiratory problems, lung dysfunction, cardiac overload, and general inflammation. All these outcomes result in a higher number of symptoms, poorer physical functions, and reduced well-being. The great reduction of FEV1 and FVC, combined with high CRP levels, indicate the presence of biological potential of oxidative and inflammatory activities caused by pollution that leads to the progressive development of the disease in the long run. Moreover, the fact that the negative health effects and reported ailments are concentrated in dense populated urban areas underscores the geographical imbalance of environmental health, which in turn demonstrates the fact that the environmental pollution load is uneven in terms of people spread, with some communities being more exposed than others, depending on their location to traffic congestion, industrial emissions, and urban planning shortfalls. The qualitative explanations were in line with the statistical findings, as they showed that air pollution has physical impacts on daily life. These stories incorporated those experiences, which consisted of respiratory problems, sleep changes, emotional pressure, and reduced outdoor activity, therefore, relating the objective exposure information to the subjective realities of the affected individuals. Taken collectively, these facts point out to the fact that air pollution is not merely a problem of the environment but a severe case of the health of the population that needs immediate legislative measures. In order to have a positive impact on the air pollution reduction, we require the combination of the methods. These ought to entail tougher regulations regarding emissions, real-time track of the quality of the air, expansion of green areas in urban areas, and targeted interventions to assist individuals who are most impacted. Subsequent research ought to centre on long-term research, models which take into account numerous pollutants as well as incorporation of genetic factors in order to comprehend how individuals are susceptible. The results of this study eloquently point out that the resolution of air pollution is important in order to improve the health of people, urban equity, and long-term wellbeing of rapidly developing cities and towns.

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