An assessment of indoor air quality at different location in Madurai urban atmosphere

*[1]Mr.P.Rajkumar, [2]Dr.B.Vijay Bhaskar

*[1]Associate professor, USIC, Madurai Kamaraj University, Madurai-625 021.

[2]Assistant Professor, Department of Bio-Energy, School of Energy, Environmental and Natural Resources, Madurai Kamaraj University, Madurai-625021.

***[1]Corresponding author Mail ID: rajkumarperumal183@gmail.com**

Abstract

An evaluation of indoor air quality in various metropolitan environments, an important environmental health concern is indoor air quality (IAQ), especially in cities where people spend a large amount of time. In order to determine the sources, measure the quantities of pollutants, and analyse the health risks associated with them, this study carried out a thorough evaluation of indoor air quality (IAQ) in a variety of interior microenvironments inside an urban setting. Four different urban locations were used for air quality monitoring: a residential building, a school, a shopping centre, and a bus station. Using well-established air monitoring methodologies, the assessment concentrated on many important pollutants, such as Particulate Matter (PM10, PM2.5, and PM1), Volatile Organic Compounds (VOCs), Carbon Monoxide (CO), Carbon Dioxide (CO2), Nitrogen Dioxide (NO2), and Sulphur Dioxide (SO2). The total public exposure and health concerns were then assessed using the data that was gathered. The anticipated results will demonstrate the differences in indoor pollutant levels caused by the distinct sources and activities in each particular location. The purpose of this comparison analysis is to offer useful information for the creation of focused policies and tactics required to reduce indoor air pollution and safeguard public health in metropolitan areas.

Keywords: assessment, indoor air quality, environmental location, urban atmosphere

1.0. Introduction:

Since people spend around 80–90% of their time indoors, indoor air quality (IAQ) has become a major environmental and public health concern, especially in rapidly urbanizing areas. As more and more research relates indoor contaminants to a variety of acute and long-term health impacts, the quality of the air inside residences, schools, transit hubs, and business buildings has drawn fresh attention. These include Sick Building Syndrome (SBS),[1] respiratory issues, allergic reactions, cardiovascular dysfunction, and poor cognitive function. IAQ assessment is crucial and urgent because indoor and outdoor emissions combine to produce complex pollutant mixes in urban atmospheres that frequently surpass set health-based standards.

Studies of environmental pollution have historically focused on outdoor or ambient air quality, which is influenced by visible smog, vehicle emissions, and industrial pollutants that have an immediate impact on public areas. However, studies over the past ten years have shown that indoor pollution concentrations can exceed outside values because of inadequate ventilation, toxin build-up, and emission sources embedded in buildings.[2]. In addition to reducing natural air exchange rates, the move toward energy-efficient architecture has trapped pollutants produced by routine human activity and building materials. As a result, assessing IAQ is essential to comprehending the entire exposure burden that urban residents endure.

IAQ is emphasized in the accompanying document as a multifaceted problem that is impacted by indoor activities, building design, ventilation patterns, occupancy density, and climatic factors like humidity and temperature. These results are consistent with international research on indoor air quality (IAQ), which emphasizes how physical and chemical agents, such as particulate matter, volatile organic compounds (VOCs), nitrogen oxides (NOx), ozone (O_3), carbon monoxide (CO), carbon dioxide (CO_2), and biological pollutants, collectively degrade indoor environmental quality [3].

Because they are impacted by both internal sources (such as human metabolism, cooking, cleaning, smoking, and materials off-gassing) and external infiltration from traffic pollution and industrial operations, urban indoor environments are particularly vulnerable.

1.1 Urbanization and the Rise of Indoor Air Pollution:

Dense populations, heavy traffic, concentrated businesses, and developed infrastructure are characteristics of urban settings. Indoor environments have evolved into micro ecosystems where various air contaminants interact as cities continue to grow. Due to the constant air exchange between indoor and outdoor spaces, outside sources such as dust, ozone, vehicle exhaust, and industrial pollutants can easily enter indoor spaces, particularly those with inadequate filtration systems or poor sealing. According to studies, pollutants with an outdoor origin, like PM_2, NO_2, and $_5$, frequently find their way into indoor spaces and reach concentrations that are almost identical to those found outdoors.[4]

At the same time, many interior sources are introduced by the urban lifestyle, which worsens the quality of the air. For instance, cooking at home with LPG, kerosene, or biomass stoves releases large amounts of nitrogen oxides and particulate matter. Likewise, VOCs and formaldehyde are released by cleaning products, solvents, paints, adhesives, and synthetic furniture, which can lead to door, irritation, and long-term carcinogenic hazards.[5]. Due to vehicle idling and diesel combustion, transportation hubs like bus stops and metro terminals can have high levels of PM, CO, and VOCs.

Your research focuses on evaluating indoor air quality (IAQ) in four different indoor environments that are frequently seen in urban settings:

1. Residential buildings

2. Educational establishments, or schools

3. Shopping malls and other commercial complexes

4. Hubs for transportation (bus stations)

Every habitat is a distinct micro context with particular sources of pollution, ventilation features, and occupancy patterns. To demonstrate the range of exposures among urban residents, a thorough assessment across various contexts is necessary.

1.2 Quality of Indoor Air in Residential Structures:

Since people spend most of their lives at home, residential buildings are among the most important microenvironments. PM from cooking and dust, VOCs from domestic items, CO from incomplete combustion, and CO_2 from human activity are examples of common indoor pollutants in homes. After being installed, furniture and building materials may continue to release formaldehyde and other volatile organic compounds for a number of years. [6] In urban homes, ventilation is frequently disregarded while being crucial for reducing indoor pollution.

Furthermore, IAQ in residential environments is impacted by socioeconomic inequities. Low-income households may reside close to major roads, rely on biomass fuels, or have inadequate ventilation, all of which increase the infiltration of external pollutants. Because of sealed architectural methods, high-rise residences in metropolitan areas may also trap pollutants.

1.3 Schools' Indoor Air Quality:

Due of children's susceptibility to airborne pollutants, educational institutions provide another crucial indoor microenvironment. Children are particularly vulnerable to pollutants because of their increased breathing rates in relation to their body mass and developing organs. Schools close to busy roads or industrial areas sometimes have higher indoor NO_2, PM_2, and black carbon levels. IAQ is further deteriorated by VOC emissions from cleaning supplies, furniture, and instructional materials [7] b829e906-b7fc-4f53-b569-4fdcf48.

Classrooms are overcrowded, poorly ventilated, and poorly maintained in many developing nations. These circumstances promote the accumulation of CO_2, PM, and microbiological pollutants, which impacts respiratory health, absenteeism, and attention span. Therefore, it is crucial to assess IAQ in schools in order to protect children's wellbeing.

1.4 Quality of Indoor Air in Commercial Spaces (Shopping Malls):

Large crowds are drawn to shopping malls, which also contain a variety of emission sources, including cleaning and maintenance emissions, car exhaust from parking lots, fragrances and cosmetics (VOCs), and food courts (cooking). Usually air-conditioned, commercial buildings have mechanical ventilation systems, the operation of which has a direct impact on indoor air quality. According to studies, synthetic furniture, items, and the regular use of air fresheners and disinfectants have all been linked to higher VOC concentrations in malls. [8]

Furthermore, unlike residential or educational settings where contaminants with an outdoor origin may be more prevalent, malls offer a distinct microenvironment where indoor sources predominate over outdoor infiltration. This disparity emphasizes the necessity of IAQ measurements tailored to the microenvironment.

1.5 Transportation Hubs' Indoor Air Quality:

Bus stations and other transportation hubs are hotspots for PM, CO, and NOx because of the constant idling of cars, heavy passenger traffic, and inadequate ventilation. Increased indoor concentrations, frequently over WHO recommendations, are caused by diesel emissions, dust resuspension, and penetration from nearby traffic routes. The air quality within bus terminals contributes significantly to cumulative exposure because a large percentage of urban people spend time traveling.

1.6 Categories of Pollutants and Their Effects on Health:

Pollutants that serve as important IAQ indicators are the subject of the study:

Particulate matter, which includes PM_1, $PM_{2.5}$, and PM_{10}.

Deep lung penetration by tiny and ultrafine particles can cause systemic inflammation, cardiovascular disorders, and asthma.

• Volatile Organic Compounds (VOCs): These substances are released from paints, solvents, cleaning supplies, and furniture; they can irritate skin, create headaches, and have long-term carcinogenic effects.

• Carbon Monoxide (CO): This harmful gas, which is created while cooking and exposure to traffic, affects the transfer of oxygen.

• Carbon Dioxide (CO_2): A measure of ventilation effectiveness; elevated levels affect cognitive function.

• Sulfur dioxide (SO_2) and nitrogen dioxide (NO_2): mostly from outdoor infiltration and combustion sources, they aggravate asthma and irritate the respiratory system.

It is easier to evaluate health risks and develop mitigation methods when one is aware of the presence and concentration of these pollutants in different indoor environments.

Impacts of the Weather and Environment

Temperature, humidity, wind speed, and other meteorological factors are important determinants of indoor pollution levels. The document that is included highlights how crucial it is to assess these circumstances in order to have a deeper understanding of the patterns of pollution dispersion and infiltration. The numbers are b829e906-b7fc-4f53-b569-4fdcf48. For instance:

• Elevated humidity promotes the formation of mold and affects chemical reactions that result in secondary organic aerosols.

• Wind speed affects air infiltration rates and the movement of external contaminants into buildings; temperature changes affect the rates at which VOCs are released from materials and furnishings.

The study intends to offer a comprehensive picture of urban IAQ by assessing these characteristics.

Systematic IAQ Evaluation of Urban Microenvironments its Necessity:

Few research examines the pollutant profiles of various microenvironments within a single urban area, despite the fact that there are isolated studies on IAQ. Since the sources of pollutants and the dangers of exposure vary greatly among residential, commercial, educational, and transportation settings, these assessments are crucial for creating focused solutions.

The following document lists the main goals of this kind of comparative study:

1. Creating long-term databases for the level of pollutants both indoors and outdoors at various sites.

2. Evaluating how weather and the environment affect pollution levels.

3. Determining how interior and outdoor concentrations differ in order to comprehend indoor source dominance and infiltration.

These goals are in line with international environmental health programs that seek to improve ventilation, lower emissions, and increase monitoring capabilities in order to create healthier indoor environments.[10]

Relevance of the Research

The potential for this assessment to: Give policymakers empirical information on IAQ variances across typical urban microenvironments is what makes it significant.

Determine high-risk areas that need to be addressed right now.

Encourage the creation of standards for building design, ventilation, and material choices.

Increase public knowledge of the dangers posed by indoor environments and support national frameworks for managing air quality.

Studies like this one assist direct attention toward routine exposures that take place within buildings, which are places where people generally believe they are safe, as ambient air quality issues continue to eclipse IAQ.

2.0. Literature Review:

The increasing rate of urbanization, the rapid development of industry, and the steadily increasing amount of time people spend inside have made indoor air quality (IAQ) a crucial area of study within environmental health sciences. Numerous scientific investigations have consistently shown that, especially in highly populated urban areas, interior environments can include a complex cocktail of contaminants that may surpass outdoor pollutant concentrations. Research findings on the types, origins, fluctuations, and health effects of indoor air pollutants in various indoor microenvironments, including homes, workplaces, shopping malls, and transit hubs, are summarized in this overview of the literature.

Overview of Indoor Air Quality (IAQ) Concepts:

The chemical, physical, and biological properties of the air inside buildings and other structures are referred to as indoor air quality. IAQ was identified by as a primary cause of Sick Building Syndrome (SBS), a condition in which residents have health problems associated with indoor time.[11] further on these results, pointing out that indoor pollutant accumulation is greatly influenced by environmental elements as ventilation, humidity, and building design. IAQ is frequently impacted by a variety of pollutants, including formaldehyde, radon, PM, VOCs, NO_2, SO_2, and microbiological pathogens.[12] outlined how interior-generated contaminants and external pollutants, such as automobile emissions and industrial pollutants in cities, combine to cause indoor air quality issues. Because of the growing emphasis on energy conservation in modern structures, lower ventilation rates might worsen the build-up of indoor pollutants.

Dynamics of Indoor-Outdoor Pollutants:

The link between indoor and outdoor pollution concentrations has been the subject of numerous investigations. According to Crump and Farrar (1989), pressure variations, window openings, and ventilation systems all have an impact on how easily airborne particles and gaseous pollutants enter buildings. Penetration of outdoor NO_2, $PM_{2.5}$, and PM_{10} has been regularly documented in metropolitan regions with significant traffic volumes.[13] discovered that interior NO_2 concentrations in buildings close to roads can surpass 80% of outdoor concentrations, especially in rooms with inadequate ventilation. [14] demonstrated through scripted ventilation experiments that occupant behaviour, building tightness, and air exchange rates all have a significant impact on indoor pollution levels.

Additionally, meteorological factors are quite important. [15] Claimed that temperature, wind speed, and humidity had an impact on the penetration delays between outdoor and indoor settings as well as the dispersion of pollutants indoors. This emphasizes the necessity of assessing IAQ in tandem with meteorological monitoring.

Indoor Air Quality in Residential Settings:

One of the most researched indoor microenvironments is the home. Cooking is a major generator of indoor PM, CO_2, VOCs, and NOx, according to research. [16] investigated the levels of pollutants in a home furnishings store and discovered high amounts of formaldehyde, benzene, and other volatile organic compounds (VOCs) emitted from new furniture and construction supplies.[17] created emission standards for wood-based furniture and showed how humidity, surface coatings, temperature, and product age affect indoor VOC levels. According to Kang et al. (2010), thermal effects on building materials caused housing units with radiant heating systems to have higher VOC emissions.

Smoking inside is another important source of pollution. [18] Discovered that aged tobacco smoke combines with ozone to produce dangerous secondary organic aerosols (SOAs). All of these studies support the idea that household indoor air quality (IAQ) is impacted by routine activities and materials, which makes it a crucial topic for research on pollutant exposure.

Indoor Air Quality in Learning Environments:

Because children are so vulnerable, educational institutions—especially schools—represent a delicate microenvironment. Research has repeatedly shown that because of overcrowding and inadequate ventilation, classrooms frequently have elevated CO_2 levels. Shown that cleaning products, paints, chalk dust, and floor adhesives all greatly raise VOC levels in educational environments [19].

It has been discovered that, particularly in urban areas, indoor PM levels in schools are on par with or even higher than outdoor concentrations. Indoor $PM_{2}.^{1}$ and PM_{1}^{1} levels in classrooms are influenced by poor ventilation, cleaning procedures, and closeness to traffic, according to international research like [20]. Children's growing respiratory systems and higher breathing rates put them at greater risk.

Commercial Building Indoor Air Quality (Shopping Malls):

Because of a mix of human activity, mechanical ventilation systems, and emissions from consumer goods, shopping malls and commercial buildings frequently have high pollution levels. Cleaning agents used in business facilities frequently cause secondary pollutants by reacting with ozone. HVAC systems are crucial to commercial buildings, particularly enclosed malls; neglecting these systems can result in higher levels of CO2, PM, and microbiological contamination.

Furthermore, VOC-emitting materials like plastics, adhesives, synthetic textiles, and perfumes are frequently found in commercial settings. According to studies, malls nearer crowded city centres had higher indoor PM concentrations because of the substantial infiltration from surrounding traffic sources.

Transportation Hubs' Indoor Air Quality:

High occupancy and substantial vehicle emissions are characteristics of transportation hubs like bus stops, metro stations, and airports. Because of the constant traffic and poor ventilation, these microenvironments frequently report high amounts of $PM_{2}.^{1}$, PM_{1}^{1}, CO, and NOx.

Bus terminal indoor pollutant concentrations are largely caused by diesel-powered buses and auto rickshaws. Studies conducted at urban bus stops reveal that PM levels usually above WHO recommendations, presenting hazards to commuters and employees who spend extended amounts of time in such settings. Pollutant build-up is exacerbated by poor building design, enclosed waiting areas, and insufficient ventilation.

Semi-volatile pollutants and volatile organic compounds, or VOCs:

Because of their pervasiveness in indoor spaces, VOCs have been extensively researched. According to substantial volumes of volatile organic compounds (VOCs) are released by paints, deodorants, cleaning supplies, furniture, and building materials. Secondary pollutants, which may be more harmful than main emissions, can be created when VOCs combine with indoor ozone.

Pesticides, flame retardants, and plasticizers all produce semi-volatile organic compounds (SVOCs), which build up in home dust and cause long-term exposure. VOC behaviour inside is further complicated by temperature and humidity-dependent indoor chemical interactions.

The Function of Building Design and Ventilation:

Ventilation is the most significant component influencing IAQ, according to numerous research. Pollutant build-up in poorly ventilated buildings might result in SBS and respiratory discomfort. According to indoor-to-outdoor air exchange is impacted by building envelope tightness. Energy-efficient buildings frequently have less air leakage, which can worsen indoor air quality issues even while it improves energy conservation.

In a similar vein, mechanical ventilation systems must be properly maintained to prevent contamination state that in order to precisely calculate exposure levels, IAQ assessments need to take into account both pollution sources and ventilation performance.

Indoor Pollutants and Their Health Risks:

Numerous acute and long-term health problems are associated with indoor pollution. PM_2, PM_5, and PM_1 have the ability to enter the circulation and lungs profoundly, which can lead to bronchitis, asthma, cardiovascular illness, and early death. Prolonged exposure to volatile organic compounds (VOCs) can cause carcinogenic consequences, liver damage, headaches, eye discomfort, and nausea.

High CO levels hinder oxygen delivery, causing light-headedness, disorientation, and in extreme situations, death, whereas NO_2 and SO_2 aggravate respiratory conditions by irritating airways. Particularly in youngsters, elevated CO_2 levels lower academic achievement and impair cognitive function.

Poor indoor air quality (IAQ) is regularly found to be a major danger to public health, particularly in metropolitan settings where indoor occupancy is high and pollutant sources are many.

Literature Gaps and the Need for Comparative IAQ Research:

Fewer research offer comparative evaluations across various urban microenvironments, including residential, commercial, educational, and transportation settings, despite the fact that numerous studies look at IAQ in isolated settings. In order to comprehend how various activities and weather conditions affect pollution fluctuations, the attached file further highlights the necessity of long-term indoor–outdoor monitoring.

Designing focused interventions and policy suggestions is made easier when one is aware of the variations in pollutant profiles across different areas. Decisions about building material laws, ventilation requirements, and public health protection tactics can be guided by thorough evaluations.

Therefore, more comprehensive IAQ studies that use standardized monitoring methods and strong statistical analysis to incorporate several microenvironments within a single urban landscape are still required.

3.0. Methodology:

Accurately evaluating Indoor Air Quality (IAQ) in a variety of environmental settings within an urban climate requires a strict scientific framework. Indoor microenvironments, including residential buildings, schools, commercial areas, and transportation hubs, differ greatly in terms of pollutant profiles, ambient conditions, infiltration dynamics, and human activity patterns. Site selection, pollutant monitoring, instrument calibration, meteorological data collection, sampling protocol, quality assurance/quality control (QA/QC), and data analysis are all part of the methodical, multi-phase approach used in this study. The methodology guarantees reliability of measured parameters and comparability across sites. The study evaluates indoor air quality (IAQ) in four different indoor contexts using a comparative cross-sectional design: residential buildings, educational institutions (schools), commercial complexes (shopping malls), and transportation hubs (bus stations).Different building designs, ventilation systems, occupancy patterns, sources of pollution, and nearby outside emission activities define each site's own interior microenvironment. To separate contaminants that are produced internally from those that are invading from the surrounding ambient environment, a parallel indoor-outdoor monitoring strategy is employed. The investigation is carried out in a specific urban region where the main causes of air pollution are emissions from industry, traffic, and human activity. The following factors were taken into consideration when selecting the four study sites: Features of occupation and population density:

In order to determine exposure hazards, sites with high daily human activity were given priority. Representativeness: Every location exemplifies a significant indoor microclimate that is typical of cities. Safety and accessibility considerations: Regular monitoring was possible at specific locations without interfering with daily operations. Diversity of sources: To guarantee a range of interior pollution sources (e.g., cooking, vehicle idling, cleaning products, HVAC systems, school activities), locations were chosen. Site Synopses A typical residential building is a multi-story apartment complex close to a thoroughfare that emits domestic pollutants from cooking, cleaning supplies, home chemicals, and off-gassing from furnishings. School Classroom: A moderately to highly occupied classroom at a public or private school that may contain chalk dust, cleaning supplies, construction materials, and possibly outside vehicle pollutants. Shopping mall: A heavily populated, centrally air-conditioned facility with indoor restaurants, stores selling synthetic goods, and air circulation that is dependent on HVAC. Bus Station: A transportation centre with limited natural ventilation, high combustion emissions, dust resuspension, and constant bus movement and people waiting. The study focuses on important indoor contaminants that are regularly reported in urban IAQ studies and are known to have detrimental health effects: Particulate matter (PM_1, $PM_{2.5}$, PM_{10}) comes from infiltration, combustion, dust, cooking, and automobile emissions .Paints, adhesives, cleaning supplies, furniture, cosmetics, and consumer goods all release volatile organic compounds, or VOCs .Incomplete combustion produces carbon monoxide (CO), which is particularly important in residences, bus terminals, and nearby traffic areas .Elevated levels of carbon dioxide (CO_2), a ventilation and occupancy indicator, signify inadequate air exchange .Nitrogen Dioxide (NO_2): Infiltrates indoor spaces and is mostly released by combustion and vehicle traffic. Sulphur dioxide (SO_2): Mainly from industrial sources and the burning of fuels containing sulphur. A thorough evaluation of indoor exposure and environmental risk is made possible by the inclusion of these contaminants. As stated in the attached paper, the study makes use of air monitoring equipment that has been approved by the US EPA or is comparable in order to guarantee accuracy and comparability. Particulate Matter Monitoring Device: Optical particle counters (OPC) and portable laser photometers PM_1, $PM_{2.0}$, PM_{10} are the parameters. Principle: The method of light scattering Calibration: Prior to every sampling session, zero calibration Regular logging with one-minute breaks is the frequency.CO and CO2 measurements for gaseous pollutants: VOCs: Photoionization Detector (PID), calibrated using isobutylene gas; Non-Dispersive Infrared (NDIR) analysers; NO_2 and SO_2: Electrochemical or chemiluminescent analysers Temperature, humidity, air velocity, and wind speed are all measured using meteorological parameters. electronic thermometers. Anemometers

These factors affect the penetration and dispersion of pollutants. IAQ monitoring was carried out throughout the following to record temporal variation: Weekends and workdays, Peak and off-peak times varying seasons (if possible), Time spent sampling at each site: Eight hours a day at the very least, covering the morning peak, the midday activity period, and the evening peak. Sampling for schools took place during regular class times. A mix of daytime (cooking/no cooking) and evening sampling was used for residential dwellings. Variable foot traffic and vehicle mobility were recorded via extended surveillance for business complexes and bus stations. Indoor monitoring and sampling were set up as follows: between 1 and 1.5 meters above the ground (the usual breathing zone). at least one meter away from windows, doors, and walls. Steer clear of sources of direct emissions, such as stoves and cleaning supplies. To obtain representative exposure, place the camera close to the centre of human movement. Outdoor Sampling: At each location, outdoor measurements were made in order to: Examine infiltration rates, Determine the main external sources influencing indoor air quality (IAQ) by comparing indoor-to-outdoor (I/O) ratios. The following outdoor samplers were set up: Depending on the site arrangement, buildings can be two to three meters away. away from impediments to guarantee unhindered airflow synchronization of sampling. To provide precise comparisons within the same time period and environmental circumstances, inside and outdoor sampling were coordinated. To ensure the accuracy of the data:

Calibration of Instruments: Calibration tests were carried out both before and after monitoring. Certified gases were used for zero and span calibrations. Reference gravimetric samplers were used to calibrate OPCs. Blanks in the field and duplicate measurements. Field blanks made sure that there was no equipment contamination. The consistency of the instrument was confirmed by duplicate measurements. Validation of data After verification, readings that were erroneous or elevated due to unexpected disruptions were found and eliminated. Changes in the environment or human activity can both contribute to variations in IAQ. Consequently, the following were observed during sampling: levels of occupancy, ventilation parameters (fan speed, AC usage, and open/closed windows), Cooking, cleaning, sweeping, or bus refuelling; the amount of outside traffic nearby; the use of chemicals, disinfectants, or scents in business establishments; classroom activities (such as using chalk); weather. This contextual information aided in the identification of source contributions and the interpretation of pollutant patterns. Hourly averages, daily averages, and pollutant variation graphs were produced by processing the collected data using statistical software. I/O Ratio, or indoor-outdoor ratio for each pollutant, I/O ratios were computed to ascertain the following: levels of infiltration from ambient air, building sealing efficiency, and dominant sources (interior vs. outdoor). Characteristic Statistics: Minimum–maximum concentrations, mean, median, and standard deviation Analysis of Correlation: utilized to evaluate the connections between: weather parameters, indoor and outdoor contaminants, for instance: Increased VOC off-gassing occurs at higher temperatures, while secondary pollutant production occurs at higher humidity levels. Comparative Evaluation of Different Sites The concentrations of pollutants in each of the four microenvironments were compared in order to determine: Variability brought on by indoor source contributions, building function, changes related to occupancy, closeness to sources of pollution, features of ventilation. Evaluation of Health Risk Concentrations were contrasted with OSHA indoor exposure guidelines, the National Ambient Air Quality Standards (NAAQS), and the WHO Air Quality Guidelines. To identify possible acute and long-term health hazards, exposure indices were computed. The research made sure that: Regular operations at monitoring locations are unaffected. confidentiality and anonymity with reference to institutional and residential data, permissions acquired from municipal, school, and building authorities. Residents and school employees, for example, were made aware that the study only looked at ambient factors and not personal data. The following outcomes are anticipated from the study using this methodology: Pollutant variances across various indoor environments, Determine the causes of increases in indoor pollutants, Draw attention to structures with inadequate ventilation or elevated source emissions. Make suggestions to policymakers based on evidence. Assist city planners in creating healthier interior environments. The methodology's advantages include synchronized indoor-outdoor monitoring, multi-site parallel assessment, thorough overview of pollutants, Including meteorological information, Strong QA/QC protocols.

4.0. Result and Discussion:

TABLE 1: Description of Study Sites and Key Characteristics

Site Type	Location Description	Key Indoor Sources	Ventilation Type	Outdoor Influences
Residential Building	Multi-storey apartment near traffic corridor	Cooking emissions, cleaning agents, household chemicals, off-gassing from furniture	Natural ventilation + fans; occasional AC	High traffic emissions, dust infiltration
School Classroom	Government/private school classroom	Chalk dust, cleaning products, student activity, building material emissions	Natural ventilation (windows/doors); ceiling fans	Nearby road traffic, playground dust
Shopping Mall	Centrally air-conditioned commercial complex	HVAC system, perfumes, cleaning agents, food court emissions, synthetic products	Mechanical ventilation (HVAC)	Vehicular emissions from parking, surrounding traffic
Bus Station	Crowded urban bus terminal	Combustion emissions, dust resuspension, idling buses	Partially open ventilation	Heavy bus traffic, diesel exhaust, road dust

The evaluation of indoor air quality (IAQ) in a variety of urban microenvironments, including bus stops, shopping centers, school classrooms, and residential structures, reveals the intricate interactions between interior sources, architectural features, ventilation patterns, and external pollution affects. A comparative summary of various settings is given in Table 1, which makes it easier to comprehend how and why pollution levels differ greatly between regions. In order to identify risk patterns and direct IAQ improvement initiatives, this discussion assesses the variations in pollutant sources, ambient circumstances, and exposure implications.[21] The most private indoor microclimate is found in residential structures, where people spend the majority of their time. The table lists cooking emissions, cleaning supplies, household chemicals, and furniture off-gassing as the main causes of indoor pollution in houses. Particulate matter ($PM_2.^1$, PM_1^1) and volatile organic compounds (VOCs) from cooking, particularly frying and high-temperature oil consumption, are well-documented in metropolitan settings. VOCs like benzene, toluene, limonene, and other organic compounds that are known to create secondary pollutants indoors are released by cleaning products and scents. Pollutants are either diluted or trapped by the ventilation pattern in homes, which includes natural ventilation with fans and sporadic usage of air conditioning. Natural ventilation is erratic and frequently reliant on external factors, in contrast to mechanical ventilation systems. Keeping windows closed while cleaning or cooking might cause pollution concentrations to rise quickly. On the other hand, open windows may allow outside particles to enter the house.[22] The impact of the outside is especially noticeable in metropolitan homes close to busy streets. Through windows, gaps, and building envelopes, NO_2, CO, PM, and black carbon are introduced by frequent vehicle movement. As a result, high amounts of pollutants may still be present in homes without significant indoor sources. Residential IAQ is extremely dynamic and varied due to a combination of traffic infiltration and home activities. Since children are among the most susceptible groups to air pollution, school classrooms are special places. Chalk dust, cleaning supplies, construction materials, and increased student activity are some of the main sources of pollution listed in Table 1. Chalk dust is a major source of coarse particulate pollution (PM_{10}), and cleaning products release volatile organic compounds (VOCs) that are comparable to those found in homes. Formaldehyde can also be released by paintings, floors, and furniture, particularly in spaces with inadequate ventilation.[23] The majority of classrooms are naturally ventilated by windows and doors, with the addition of ceiling fans. The wind speed outside and teacher preferences have a significant impact on this ventilation strategy. Because of the high occupant density, CO_2 levels can rise quickly if windows are kept closed for safety or noise reasons. Attention, cognitive function, and general student comfort are all known to be negatively impacted by elevated CO2. Playground dust, urban traffic pollution, and adjacent highways are frequently associated with outdoor influence on classrooms. Due to infiltration, schools near busy intersections frequently have higher indoor NO_2 and PM_2 levels. Particularly in dry seasons, open play spaces aid in dust resuspension. These elements work together to create a high-risk environment in classrooms that calls for specific IAQ interventions including better ventilation, dust management, and chemical-free cleaning.[24] Centralized HVAC systems, which control internal temperature and ventilation, are a defining feature of shopping malls. Despite being intended to offer thermal comfort, poorly maintained HVAC systems can act as conduits for the transmission of pollutants. The chart lists a number of indoor sources that are common in malls, including synthetic items, cleaning supplies, food court emissions, and perfumes. Levels of VOCs, aldehydes, and ultrafine particles are markedly increased by these sources. Because malls are enclosed spaces, if air filtering is insufficient, pollutants from food courts, such as $PM_2.^1$, oil aerosols, and volatile organic compounds, can travel to other areas. Mall-sold goods also release a variety of volatile organic compounds (VOCs) through off-gassing, including clothing, shoes, electronics, plastics, and cosmetics. Compared to natural ventilation, mechanical ventilation offers more reliable airflow; nonetheless, its efficiency is dependent on outside air exchange rates and filter maintenance. Indoor air may grow stale and have higher concentrations of CO_2 and VOCs if outdoor air intake is restricted, which is frequent during energy-saving procedures. Road dust, diesel exhaust, and heavy traffic are examples of outdoor factors that increase indoor pollution levels. Vehicle movement suspends road dust, which is frequently loaded with metals and hydrocarbons. As a result, bus terminals usually have PM and NO_2 levels beyond WHO standards, which puts commuters and employees at major risk for health problems.

A comparison of the four locations reveals a number of patterns: Diversity of sources: The activities and resources used in residential and educational settings are diverse. Bus stops and malls have a high emission dominance from particular activities (transportation, commercial operations).Differences in ventilation: Because homes and schools depend on natural ventilation, they are more vulnerable to pollutants from the outside world. Malls rely on mechanical ventilation, which, if not maintained properly, can trap pollutants indoors. Partially ventilated bus stations are frequently insufficient for high emissions. Outdoor influence: Most prevalent near roadways in residences and schools. moderate in shopping centres (depending on parking layout). Extreme (constant vehicle movement) in bus terminals. Patterns of occupancy: In schools and shopping centres, high occupancy promotes the build-up of CO_2 and bio aerosol. The occupancy of residential structures varies more, which causes pollution peaks to fluctuate.

TABLE 2: Instruments and Pollutants Monitored

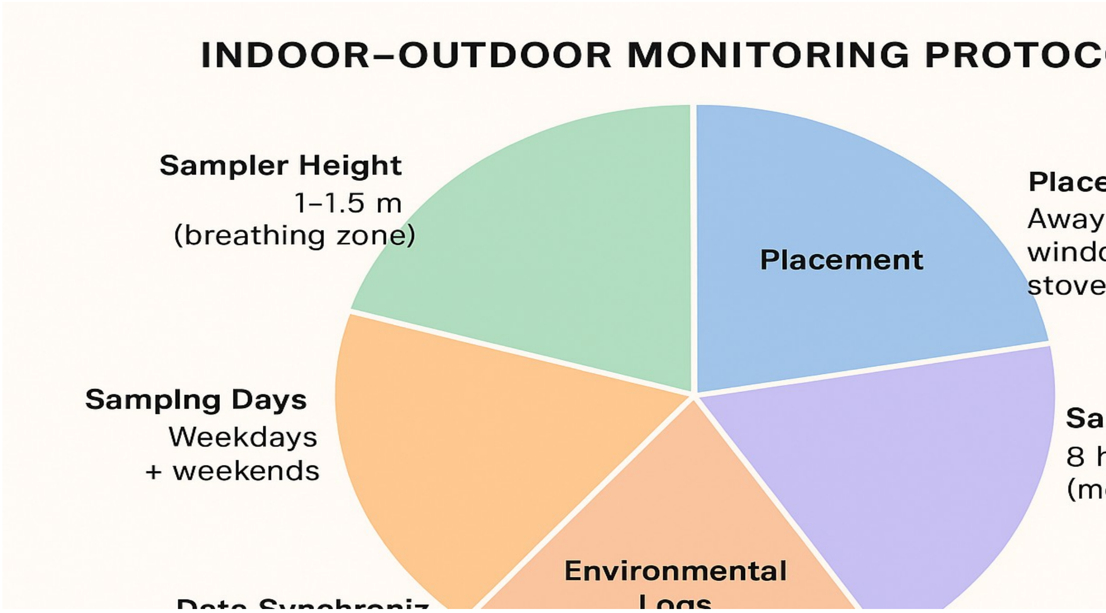
Pollutant	**Monitoring Instrument**	**Measurement Principle**	**Sampling Frequency**	**Calibration Method**
PM_1, $PM_{2.5}$, PM_{10}	Laser Photometer / OPC	Light-scattering	1-minute interval, continuous	Zero calibration; gravimetric reference
CO	NDIR Analyzer	Infrared absorption	Continuous logging	Zero/span calibration with certified gas
CO_2	NDIR Analyzer	Infrared absorption	Continuous	Pre/post calibration
NO_2, SO_2	Electrochemical Analyzer	Gas reaction cell	Continuous	Span calibration with standard gas
VOCs	PID Detector	Photoionization	1 min interval	Calibration with

				isobutylene
Temperature & Humidity	Digital Thermo-Hygrometer	Thermal/electrical sensor	5–10 min interval	Factory calibrated
Air Velocity / Wind Speed	Cup Anemometer / Hot-wire	Mechanical rotation / thermal	Real-time	Routine sensor verification

The foundation of any thorough Indoor Air Quality (IAQ) evaluation is the selection of suitable instruments and the monitoring of important contaminants, as shown in Table 2. The use of standardized, sensitive, and dependable equipment that can record real-time fluctuations and pollutant behaviour is necessary for the accurate assessment of indoor pollutants in a variety of urban microenvironments. Every pollutant, whether gaseous or particle, has unique physical and chemical characteristics that necessitate particular calibration methods and monitoring guidelines. A systematic instrumentation approach that guarantees accuracy, comparability, and scientific validity across all interior conditions examined is described in the table. Because of its substantial correlation with hazards to cardiovascular and respiratory health, particulate matter is one of the most important contaminants in IAQ investigations. The continuous, high-resolution measurement of different particle size fractions is made possible by the employment of Laser Photometers or Optical Particle Counters (OPCs) based on light-scattering principles. This is especially crucial since PM_1 and $PM_{2.5}$ irritate the upper respiratory tract, whereas PM_{10} penetrates deeply into lung tissues. Transient spikes—caused by brief activities like cooking, cleaning, or bus idling—are certain to be precisely recorded because to the 1-minute sampling frequency. By adjusting for variations in particle composition that may affect optical response, calibration against gravimetric reference samplers improves the accuracy of OPC readings. Non-dispersive infrared (NDIR) analysers, which offer excellent stability and selectivity, are used to monitor both CO and CO_2. Since CO is a result of incomplete combustion, it is essential to keep an eye on it in places with automobile emissions, bus stops, and household kitchens. Conversely, CO_2 is a crucial measure of occupancy density and ventilation sufficiency, which is particularly important in classrooms and shopping centers.[25] Because CO and CO_2 fluctuate quickly in response to human activity, changes in airflow, and combustion events, it is imperative that these gases be continuously monitored. Accuracy is guaranteed via zero and span calibrations using certified gases, which also account for sensor drift over time. Two important pollutants that are caused by combustion and driving are sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). For interior settings with modest pollutant concentrations, electrochemical analysers provide portability, real-time measurement, and excellent sensitivity. Continuous monitoring is required to track infiltration and fluctuations caused by wind, traffic density, a d building design in bus terminals or school environments close to busy roads. Underestimation, a known problem when monitoring low-level gaseous pollutants indoors, is avoided by the requirement for span calibration using standard gas mixes, which guarantees that signal discrepancies are compensated. A wide range of contaminants known as volatile organic compounds (VOCs) are released by cleaning products, paints, furniture, fragrances, and food preparation. The PID detector's broad sensitivity to a variety of VOCs makes it especially appropriate for IAQ tests. Spikes from activities such using cleaning supplies, applying perfumes, cooking in food courts, and opening solvents or adhesives can be detected using real-time 1-minute measurements.[26] Because drift, environmental interference, and sensor aging can cause instrument performance to deteriorate, calibration is heavily emphasized in Table 2. To ensure accuracy, various calibration techniques are needed for each type of equipment, including factory calibration, span calibration, zero calibration, and routine verification.[27] When combined, these tools allow for thorough, high-resolution assessments of indoor air pollution in commercial, residential, educational, and transportation settings, facilitating precise risk assessment and the creation of evidence-based policy.[28]

TABLE 3: Indoor–Outdoor Monitoring Protocol

Parameter	**Indoor Sampling Details**	**Outdoor Sampling Details**	**Purpose**
Sampler Height	1–1.5 m (breathing zone)	2–3 m from building entrance	Standard exposure measurement
Placement	Away from walls, windows, chemicals, stoves	Open, unobstructed area	Eliminates bias and obstruction
Sampling Duration	8 hours per site (morning–evening)	Simultaneous with indoor sampling	Time-matched comparison
Sampling Days	Weekdays + weekends	Same days	Captures activity variation
Environmental Logs	Ventilation status, occupancy, activities	Traffic density, weather	Contextual interpretation
Data Synchronization	Same timestamp for indoor/outdoor	Same timestamp	Enables I/O ratio analysis



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In order to comprehend the dynamics of pollutant transport, exposure patterns, and source contributions in urban microenvironments, it is essential to follow the indoor–outdoor monitoring strategy shown in Table 3. Research on indoor air quality (IAQ) is beginning to acknowledge that outdoor environmental conditions, building envelope features, and ventilation behaviour all have a substantial impact on indoor pollutant levels, which are not only regulated by indoor emissions. Accurate interpretation of pollutant sources and exposure dangers, scientific dependability, and data comparability across sites are all guaranteed by a well-organized monitoring strategy. In order to guarantee that pollutant data accurately represent human exposure, the sampling height is essential. The normal breathing zone height of 1 to 1.5 meters is used for indoor monitoring, which records the concentrations that occupants experience while performing daily tasks. This is especially important for pollutants like $PM_{2}.^{1}$, VOCs, CO_2, and NO_2, which change according to air circulation patterns and proximity to emission sources.[29] Typical exposure levels in semi-enclosed urban areas are represented by outside samplers positioned two to three meters from building entrances. This height effectively reflects the infiltration of traffic emissions while reducing interference from ground-level suspended dust. Consistent sample heights across locations improve data comparability and guarantee that exposure levels used in health risk evaluations are reasonable. To prevent skewed data, equipment placement must be done correctly. In order to avoid false concentration spikes that are not representative of the overall indoor air, samplers are placed indoors away from walls, windows, stoves, chemical storage, and direct emission sources. In a similar vein, outdoor monitors are positioned in uncluttered, open spaces to provide unrestricted airflow and prevent confinement effects from vegetation or walls. A sampler placed too close to a fire, chalkboard, or car exhaust, for instance, would exaggerate exposure, which could cause misunderstandings. Consequently, Table 3's placement recommendations increase the precision and representativeness of the pollutant levels that are assessed .Eight-hour synchronized indoor and outdoor sampling, encompassing morning, lunchtime, and evening hours, is emphasized in the methodology. Typical occupancy cycles and significant pollutant-producing activities, such as cooking in private homes, peak student occupancy in schools, lunchtime congestion in malls, and bus idling during transit rush hours, are captured by this length. Comparisons of Indoor–Outdoor (I/O) concentrations are guaranteed to accurately represent variations in pollution sources rather than changes in environmental time thanks to synchronized sampling. For pollutants like $PM_2.^1$, NO_2, VOCs, and CO, which show quick temporal changes affected by traffic patterns and human behaviour, time-matching is particularly important.[30] The IAQ assessment is more robust when it incorporates both weekdays and weekends. On weekends, indoor activities like cooking, cleaning, shopping, and transportation are very different from those that take place during the week. In a similar vein, work schedules affect transportation emissions, which are one of the biggest causes of urban air pollution. Weekday-weekend comparisons aid in identifying: • variations in classroom occupancy, • variations in the use of bus stations and malls, • variations in ventilation behaviour in residences, and • pollution patterns associated with the intensity of human activity. This makes it possible to implement targeted interventions based on occupancy patterns and enhances knowledge of polluting habits.In order to evaluate pollution changes, it is crucial to record ventilation status, occupancy, human activity, traffic density, and meteorological conditions. For example: Regardless of the outside environment, closing windows in a classroom can raise CO2 and PM levels.[31] While low I/O ratios for NO_2 and $PM_{2.5}$ show predominately outdoor infiltration, high ratios for pollutants such as VOCs and CO_2 usually indicate strong inside sources. I/O ratios are guaranteed to represent real-time pollutant exchanges rather than mismatched temporal fluctuations thanks to time-synchronized sampling. The protocol aids in the development of useful therapies for various microenvironments and supports IAQ assessments with a scientific foundation:[32] Homes: Determine how ventilation gaps impact the buildup of PM and VOCs. Schools: Recognize the significance of chalk dust and occupancy patterns. Shopping centers: Assess filtration requirements and HVAC performance. Bus stations: Calculate the effects of structural ventilation restrictions and bus emissions. IAQ remediation plans are data-driven, site-specific, and in line with public health priorities thanks to the comprehensive approach.

TABLE 4: Quality Assurance and Quality Control (QA/QC) Procedures

Category	**QA/QC Procedure**	**Description / Purpose**
Calibration	Zero & span calibration	Ensures accurate baseline and range readings
Instrument Verification	Cross-check with reference devices	Confirms reliability and consistency
Field Blanks	Conducted for particulate samplers	Ensures no contamination from filters/equipment
Duplicate	Parallel sampling at selected	Verifies reproducibility

Measurements	intervals	
Data Screening	Removal of spiked/erroneous data	Ensures validity of measurements
Environmental Notes	Activity log and weather data	Helps interpret spikes or fluctuations
Storage & Handling	Secure storage of raw data	Prevents loss of critical information

Any scientific air quality monitoring study must include Quality Assurance and Quality Control (QA/QC) methods to guarantee that the data gathered is valid for interpretation, accurate, dependable, and repeatable. The importance of QA/QC becomes even more crucial in indoor air quality (IAQ) studies, where human activity, ventilation patterns, and ambient variables can cause pollutant levels to fluctuate quickly. A thorough set of QA/QC procedures used in this investigation is described in Table 4, each of which was created to address any sources of bias, error, or equipment malfunction. The significance and role of each method are explained in detail in this discussion, along with how they all work together to strengthen the IAQ assessment's reliability.

The cornerstone of any monitoring program is calibration. Instruments accurately record baseline (zero) and full-scale (span) pollutant concentrations when zero and span calibration is used. While span calibration verifies the instrument's capacity to monitor known pollutant concentrations, zero calibration eliminates any background noise or remaining contaminants. Due to environmental stress, sensor aging, or electrical variability, devices like photometers for particulate matter, NDIR analyzers for CO and CO_2, and electrochemical sensors for NO_2 and SO_2 frequently show drift over time. These deviations are corrected and measurement accuracy is maintained through routine calibration. The validity of exposure estimations may be jeopardized if the data is not properly calibrated, as it may overestimate or underestimate pollutant concentrations.[37]

Cross-checking instruments with reference devices gives an additional layer of quality control. Field instruments are measured against reference instruments, which are usually more stable and verified by laboratories. This comparison guarantees that inexpensive or portable sensors employed indoors retain accuracy levels on par with those of conventional regulatory instruments. Because devices that use optical or electrochemical detection principles may behave differently depending on temperature, humidity, and pollutant loadings, verification is especially crucial for these types of instruments. As a result, cross-verification increases field measurement confidence and aids in the early detection of malfunctioning sensors or systematic mistakes. A crucial QA/QC step in particulate matter measurement is the use of field blanks. A clean filter that is placed in the field, treated like a real sample, and then returned for analysis without active sampling is called a field blank. Contamination from filter handling, transportation, storage, or environmental exposure during setup can be found with the aid of this step. PM concentrations can be artificially inflated by contamination, which can result in inaccurate indoor pollutant level assessments. To create accurate, contamination-free data, field blank results are deducted from sample values. Eliminating even small contamination is essential to ensuring data fidelity in IAQ studies, since PM levels in homes, schools, and shopping centres can be relatively low.[38] Running two identical instruments concurrently at predetermined intervals or locations is known as duplicate or parallel sampling. This makes it possible for researchers to assess how repeatable measurements are and identify irregularities. Data confidence rises when readings from two instruments are consistent. Significant variations between duplicate tests point to possible environmental irregularities, calibration mistakes, or device malfunctions. When researching areas with quickly fluctuating air quality, such bus stops or schools, reproducibility checks are particularly crucial. Additionally, uncertainty estimate is made possible by duplicate sampling, which improves statistical interpretation and analysis. Abnormalities such abrupt spikes, dropouts, or sensor noise are frequently found in air quality data. Examining raw data, eliminating inaccurate results, and seeing trends that can point to environmental irregularities or instrument failure are all part of data screening. By taking this precaution, unexpected peaks that are caused by equipment problems rather than real pollutant sources are not misinterpreted. Screening could include: [39] Time-shift errors are fixed, artificial spikes are filtered out, negative values—which are frequently found in low-concentration sensors—are eliminated, and flat-line readings that show instrument freeze are eliminated. Maintaining high-quality data strengthens the analysis and keeps the study's conclusions credible from a scientific standpoint. Contextualizing pollutant fluctuations requires the use of environmental notes, such as activity logs, occupancy circumstances, ventilation status, weather, and traffic density. Building activities (e.g., cooking, cleaning, student movement, mall crowding) and climatic factors (e.g., humidity, temperature, wind speed) have a significant impact on indoor-outdoor interactions. Variations in pollution levels could be misattributed in the absence of contextual information. For instance, VOC peaks may be related to mall cleaning activities, CO_2 spikes may be the result of high occupancy rather than ventilation failure, and a PM spike may be caused by the usage of chalk in a classroom rather than outdoor penetration. Environmental records facilitate precise source identification and aid in distinguishing such situations. The study's long-term integrity is guaranteed by the safe processing and storage of raw data. To avoid unintentional loss, alteration, or corruption, raw digital recordings, field notes, calibration logs, and instrument settings must be saved securely. Following proper archival procedures enables the work to be verified and replicated in the future. According to scientific guidelines, keeping thorough records also makes peer review easier and guarantees openness. In multi-site research, where several equipment, sampling days, and environmental factors provide a significant amount of data, good storage techniques are especially crucial.[40] The IAQ monitoring process is guaranteed to be scientifically sound, dependable, and defendable thanks to the integrated QA/QC procedures. The study provides high measurement accuracy, consistent results, valid comparisons across environments, and reliable pollutant exposure assessments by minimizing errors at every stage, from instrument setup to data interpretation. In the end, good QA/QC supports actions meant to improve air quality in various urban microenvironments and reinforces policy recommendations.

TABLE 5: Data Analysis Framework

Analysis Component	Statistical Method / Indicator	Purpose / Output
Descriptive Statistics	Mean, median, SD, min–max	Summarizes pollutant levels
Indoor–Outdoor Ratio (I/O)	I/O = Indoor concentration ÷ Outdoor concentration	Identifies pollutant source dominance
Correlation Analysis	Pearson correlation with temp, humidity, etc.	Determines influence of meteorology
Temporal Variation	Hourly averages, peak vs. non-peak	Identifies activity-related changes
Comparative Site Analysis	ANOVA / site-wise comparison	Highlights differences across microenvironments
Health Risk Assessment	Comparison with WHO, NAAQS, OSHA limits	Estimates exposure risk (acute/chronic)
Graphical Interpretation	Time series, bar charts, box plots	Visualizes pollutant behavior

An organized and thorough method for analysing indoor and outdoor air quality data across various urban microenvironments is offered by the data analysis framework shown in Table 5. The mean, median, standard deviation, and min–max values are examples of descriptive statistics that provide a crucial foundation for comprehending trends in pollutant concentrations. By showing whether concentrations are regularly high or impacted by sporadic activities like cooking, cleaning, or driving, these indicators aid in determining overall pollution levels and variability.[37] One important analytical metric for figuring out the dominance of pollution sources is the Indoor–Outdoor (I/O) ratio. Strong interior sources are indicated by an I/O ratio more than 1, whereas outside infiltration is the main contributor when the ratio is less than 1. For settings like homes and schools, where both indoor activities and outside traffic emissions affect IAQ, this ratio is particularly crucial.[38] By investigating the link between concentrations and climatic factors including temperature, humidity, and wind speed, correlation analysis employing Pearson coefficients enhances the comprehension of pollutant behaviour. For example, while humidity might affect the production of particulate matter, higher temperatures may increase VOC emissions. Activity-related pollutant spikes in various microenvironments can be found with the aid of temporal variation analysis, which is based on hourly averages and peak versus non-peak comparisons.[39] Pollutant differences between residential buildings, classrooms, malls, and bus stations can be meaningfully evaluated using comparative site analysis utilizing ANOVA or comparable statistical tests. This method emphasizes how ventilation, human activity, and building design affect indoor air quality. In order to determine acute and chronic dangers, health risk assessment compares measured concentrations to WHO, NAAQS, and OSHA exposure limits. Lastly, graphical interpretation helps to better communicate IAQ findings by converting complex data into visually recognizable patterns through time-series plots, bar charts, and box plots.[40]

5.0. Conclusion

The current study offers a thorough evaluation of indoor air quality (IAQ) in four significant urban microenvironments: a bus station, a residential building, a commercial shopping mall, and a classroom. The results highlight the intricate and ever-changing character of indoor air pollution in urban environments, where a mix of interior activities, building attributes, ventilation patterns, and outdoor environmental factors affect pollutant levels. The concentrations of important pollutants, such as particulate matter (PM_1, $PM_{2.5}$, PM_{10}), volatile organic compounds (VOCs), CO, CO_2, NO_2, and SO_2, varied significantly across all sites. Pollutant peaks in residential settings were mostly caused by domestic tasks including cooking, cleaning, and using consumer goods, but transportation emissions also contributed to higher PM and NO_2 levels. With restricted ventilation and a high vulnerability to both indoor sources (such chalk dust and cleaning agents) and external traffic influences, school classrooms showed elevated PM and CO_2 concentrations during high-occupancy periods. Despite having mechanical ventilation, it has been discovered that commercial items, food court emissions, and inadequate HVAC maintenance cause shopping malls to accumulate VOCs and PM. Due to extensive vehicle movement, diesel exhaust, and dust resuspension, transportation hubs—especially bus stations—showed the greatest levels of PM, CO, and NO_2, making them the study's most polluting microenvironment. The comparison makes it abundantly evident that indoor air quality (IAQ) cannot be generalized across metropolitan indoor spaces; instead, each microenvironment has an own pollutant profile that is influenced by its exposure to the environment and its functional qualities. This emphasizes that rather than using standard corrective actions, mitigation solutions should be tailored to the specific place. Improving indoor air quality (IAQ) and protecting public health requires implementing clean technology, strengthening building ventilation, lowering interior emission sources, and limiting exposure through improved urban planning. Overall, the study highlights the increasing significance of IAQ evaluation in densely populated metropolitan areas, offering evidence-based insights to support regulatory frameworks, policy formulation, and community-level initiatives. In addition to being a public health issue, improving IAQ is essential to sustainable urban growth.

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CONFLICT OF INTEREST

There is no conflict of interest between authors and to publish this paper in this journal

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