"AUREL VLAICU" UNIVERSITY OF ARAD
INTERDISCIPLINARY DOCTORAL SCHOOL
FIELD: ENVIRONMENTAL ENGINEERING

SUMMARY

Contributions regarding the determination of pollutants in indoor spaces

Maria Andreea POPA (married ŢEPENEU)

SCIENTIFIC COORDINATOR:

Prof. univ. Dr. habil. Lucian COPOLOVICI

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SUMMARY

INTRODUCTION

Urbanization has grown exponentially, and about half of the world's population lives in urban areas today. This phenomenon has drawn attention to the environmental, natural resources, and public health risks. In recent decades, cities have increasingly become a source of environmental degradation and resource depletion [1].

Air pollution is recognized by the World Health Organization (WHO) as a global public health problem, defined as the presence of harmful particles in the atmosphere from various sources [2].

Research on indoor air quality has seen a significant expansion since the 1970s with the awareness of air exchanges with the outdoor environment [3]. IAQ is affected by outdoor sources, building characteristics, especially ventilation, and physical parameters (such as relative humidity and temperature). Still, internal emission sources and indoor parameter variability should not be ignored [4].

Indoor pollutants may originate from external sources and be transported indoors via open windows or ventilation or indoors [5, 6]. Thus, ambient (outdoor) air quality directly influences indoor air quality [7], which is about 5-10% poorer than that of the outdoor environment [8, 9]. Among the compounds used for IAQ assessment, WHO lists radon, nitrogen dioxide, polycyclic aromatic hydrocarbons, formaldehyde, volatile organic compounds, particulate matter, carbon dioxide, sulfur dioxide, nitrous oxide, semi-volatile organic compounds, and biological contaminants [4, 10].

Indoor environments such as homes, offices, and other enclosed spaces can often become reservoirs for various chemical and biological pollutants. These pollutants come from a wide range of sources, including building materials (such as paints, adhesives, and insulation), furniture (which can emit formaldehyde and other volatile organic compounds), combustion processes (e.g., cooking, heating, and smoking indoors), cleaning activities (through the use of cleaning chemicals), and from outdoor air that enters enclosed spaces and can bring with it pollutants such as ozone and particulate matter. In addition, specific secondary chemical reactions indoors can create new pollutants from existing ones. Exposure to this complex mix of pollutants in indoor environments is a significant public health concern. Indoor pollutants can cause various health problems, from minor eye, nose, and throat irritations to more serious effects such as asthma exacerbation, respiratory issues, allergic reactions, and even long-term effects such as cardiovascular disease and cancer. Recognition of the importance of indoor air quality has prompted international and national institutions, such as the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA), to address this issue by developing guidelines and standards for assessing the risks associated with indoor pollutants. These organizations emphasize the need to improve indoor air quality through proper ventilation, using less toxic materials and products, and implementing effective cleaning and maintenance practices [11].

OBJECTIVES

The objectives proposed in this PhD thesis are:

1. To determine the concentrations of formaldehyde, volatile organic compounds (VOCs), particulate matter (PM_1, $PM_{2.5}$, PM_{10}), and carbon dioxide (CO_2) in different areas of a general store and an office building to assess indoor air quality.
2. Identify and characterize the primary sources of air pollutants in the general store and office building, including building materials, furniture, human activities, and ventilation systems.
3. Compare collected data with existing indoor air quality standards and guidelines to assess compliance with Environmental Protection Agency or World Health Organization standards and procedures.
4. Analyze the chemical composition of accumulated dust in the shop and offices, using analytical techniques such as FTIR spectrometry to reveal the presence of possible irritants or allergens. Assess the impact of exposure to identified pollutants on the health of general store employees, customers, and office workers by administering a questionnaire to recognize symptoms of sick building syndrome (SBS). Based on the study results, propose specific and compelling measures to improve indoor air quality, reduce exposure to pollutants, and improve occupant health and comfort.
5. Assess seasonal and daily variations in indoor air pollutant levels to understand air quality dynamics concerning environmental changes and human activity.

EXPERIMENTAL PART

DETERMINATION OF AIR QUALITY IN A GENERAL STORE

Introduction

Shops and shopping centers have a specific spatial design characterized by variety and complexity. This peculiarity of their physical environment influences the behavior and comfort of visitors. Differences between residential and office buildings are important and are due to the specific nature of these commercial spaces.

Determination of formaldehyde concentration

Our study aimed to investigate formaldehyde concentrations in different areas of a shopping center during opening hours (Figure 1) [12].

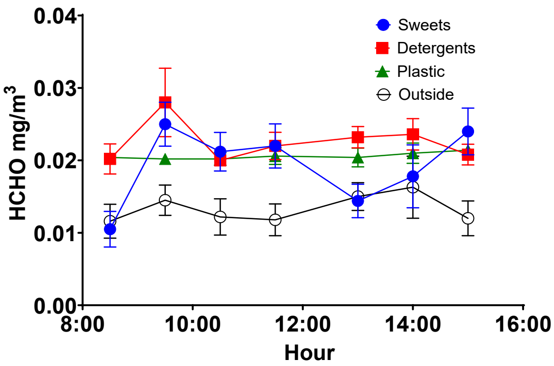


Figure 1. Variations in formaldehyde concentration during working hours in 3 different departments and outdoors.

Formaldehyde concentrations were not significantly different for the different departments (One-way ANNOVA., p=0.67) but considerably higher than outdoor concentrations ($p<0.05$) (Figure 2).

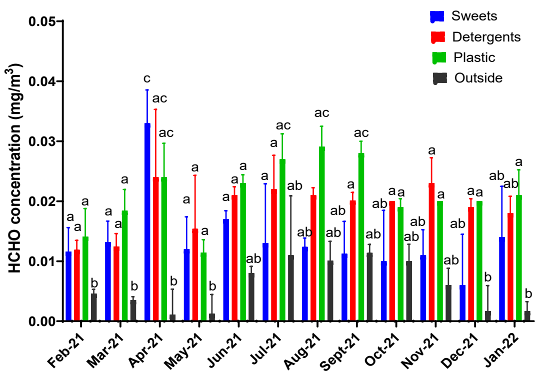


Figure 2.Monthly variations of formaldehyde concentration during one year of measurements in 3 different departments and outdoors. Data with different letters are significantly different ($p < 0.05$), while data with the same letters are not significantly different ($p > 0.05$). Values represent the means of three independent measurements.

The concentration of formaldehyde inside the store varies over a year between 6 and 33 $\mu g/m^3$, which is below 100 $\mu g/m^3$ (the threshold for public-use facilities) and in the same range as reported in a previous study in Hong Kong (range 15 to 60 $\mu g/m^3$) [13].

Determination of the concentration of volatile organic compounds in the store

Concentrations of total volatile organic compounds do not vary during working hours (Figure 3).

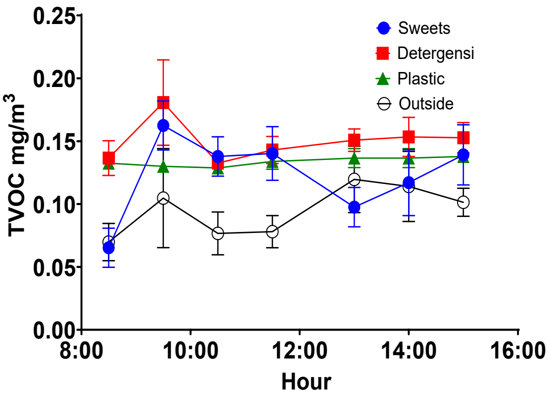


Figure 3. Total volatile organic compounds concentration variations during working hours in 3 different departments and outdoors.

Our results indicate that VOC levels inside the store remain relatively constant during working hours, around 0.15 mg/m³.

The total concentration of volatile organic compounds was not significantly different for the departments ($p = 0.107$) (Figure 3). The annual mean values were substantially higher for the detergents and plastics departments (compared to outside 0.14 ± 0.03 mg/m^3 and 0.16 ± 0.07 mg/m^{3,} respectively) compared to the value outside (0.07 ± 0.03 mg/m^3). In the case of the confectionery department, the VOC concentration during the year was not significantly different from the value outside ($p > 0.05$).

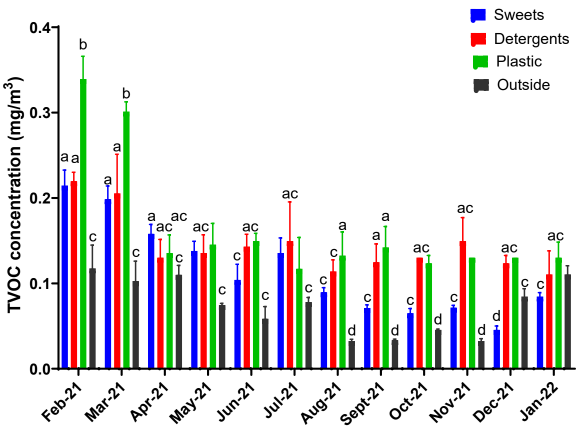


Figure 4. Monthly changes in total volatile organic compounds concentration over a year of measurements in 3 different departments and outdoors. Data sharing different letters are significantly different ($p < 0.05$), while data sharing the same letters are not significantly different ($p > 0.05$). Values represent the means of three independent measurements.

The mean values of lactic acid concentration during the year for the sweets, detergents, and plastics department were 44 ± 11 µg/m^3, 43 ± 7 µg/m^3, and 38 ± 5 µg/m^3, respectively, while the mean outdoor value was 3.5 ± 1.7 µg/m^3 (Figure 5).

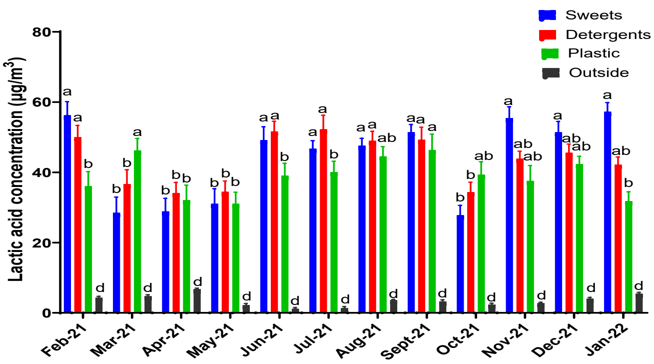
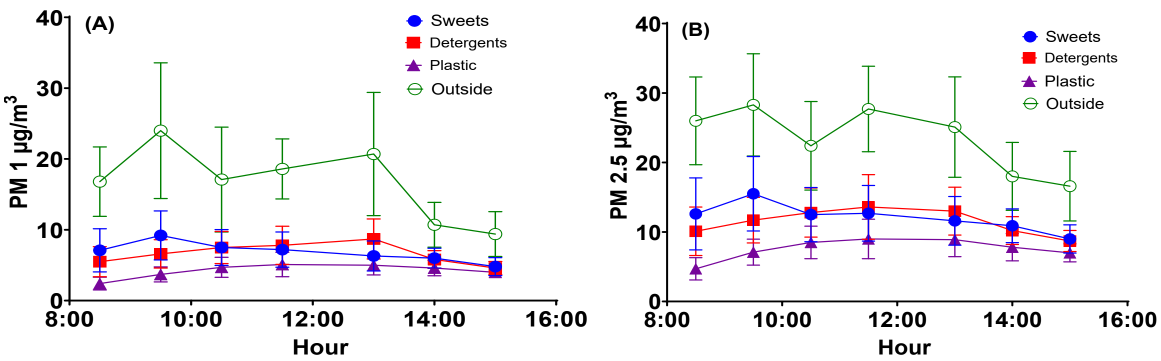


Figure 5. Monthly variations in lactic acid concentration over a year of measurements in 3 different departments and outdoors. Data with different letters are significantly different ($p < 0.05$), while data with the same letters are not significantly different ($p > 0.05$). Values represent the means of three independent measurements.

The concentration of BTEX and monoterpenes over a year is shown in Figure 6. The average toluene concentration in the confectionery department was 3.43 ± 0.28 µg/m^3, in the detergent department 3.43 ± 0.24 µg/m^3, in the plastic department 3.56 ± 0.32 µg/m^3, with no statistical difference between the annual average values for the departments ($p=0.495$). Outside the store, the toluene concentration was 1.50 ± 0.92 µg/m^3 significantly lower than inside the store ($p<0.05$). Toluene concentrations outside the store in the cold months (December-March; 2.72 ± 0.20 µg/m^3) were higher than in the warm period (0.89 ± 0.19 µg/m^3).

Determination of suspended particulate matter concentrations in the store

The study assessed the levels of particulate matter, specific to PM_1, $PM_{2.5}$, and PM_{10}, inside a commercial store by comparing them to the variations recorded in outdoor air over a working day and a calendar year. Our analysis indicates that indoor PM_1, $PM_{2.5}$, and PM_{10} concentrations remain relatively constant throughout the day, showing a stability of indoor air quality in contrast to the significant variations observed outdoors. Outside, these particles' levels show notable fluctuations between different times of the day and in comparison to the same time on different days, as illustrated in Figure 7.



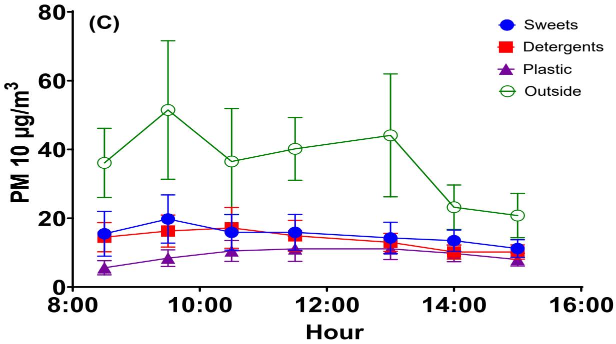


Figure 7. Variations in PM_1 (A), $PM_{2.5}$ (B), and PM_{10} (C) concentrations during working hours in 3 different departments and outdoors.

PM_1, $PM_{2.5}$, and PM_{10} concentrations are higher outside than inside the shop. There is no clear trend in PM concentrations in different departments. Moreover, the PM concentration in the sweets departments is higher in February and March, but it does not differ significantly from the other departments in the rest of the year. The annual average outdoor PM_1 concentration was 10.4 ± 3.4 µg/m^3, the $PM_{2.5}$ concentration was 19.0 ± 4.7 µg/m^3 and the PM_{10} concentration was 25.4 ± 5.2 µg/m^3. The highest $PM_{2.5}$ concentration was found in October at 24.0 ± 0.8 µg/m^3. The lowest concentrations of airborne particles were found within the store in October and November. These findings also suggest that the main sources of particulate matter inside the store come from outside, given the low indoor and outdoor concentrations.

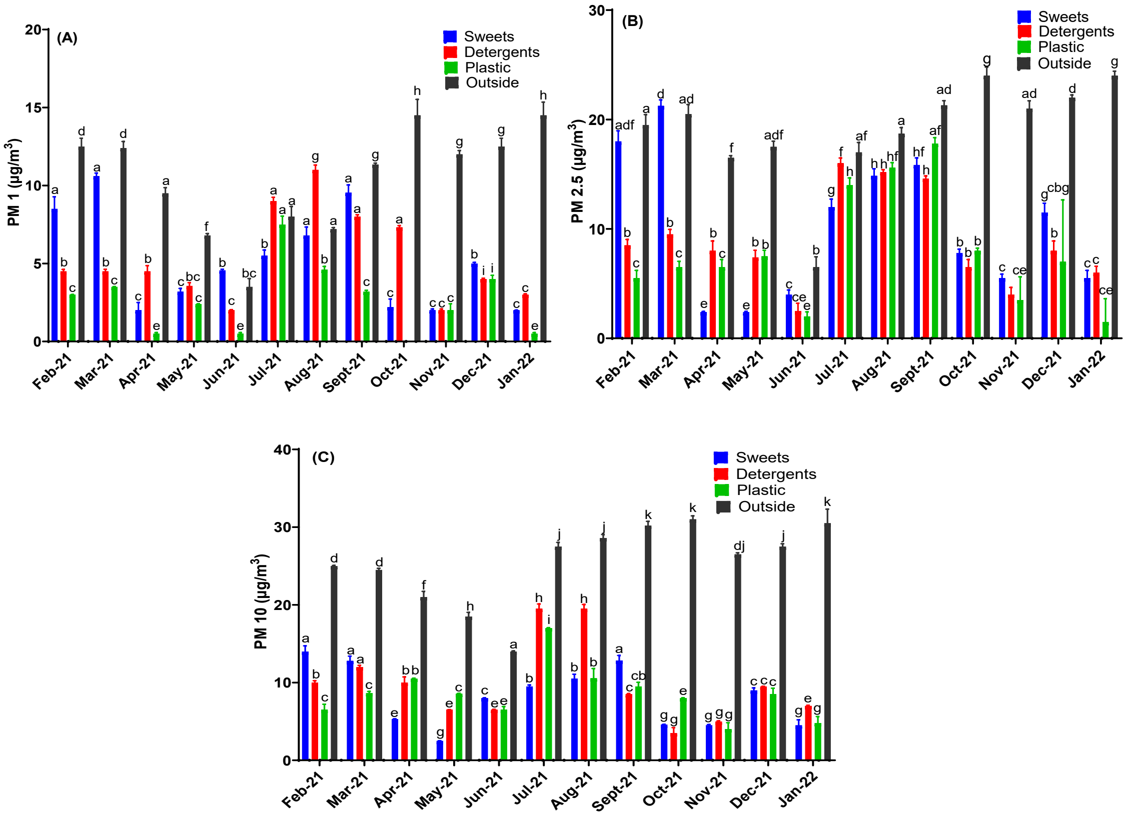


Figure 8. Monthly variations of PM_1 (A), $PM_{2.5}$ (B), and PM_{10} (C) concentrations during one year of measurements in 3 different departments and outdoors.

A much lower concentration of $PM_{2.5}$ was found in the store than in other studies [13-15], which could be clarified by a better cleaning strategy implemented during the COVID-19 pandemic.

Determination of the chemical composition of accumulated dust in the shop

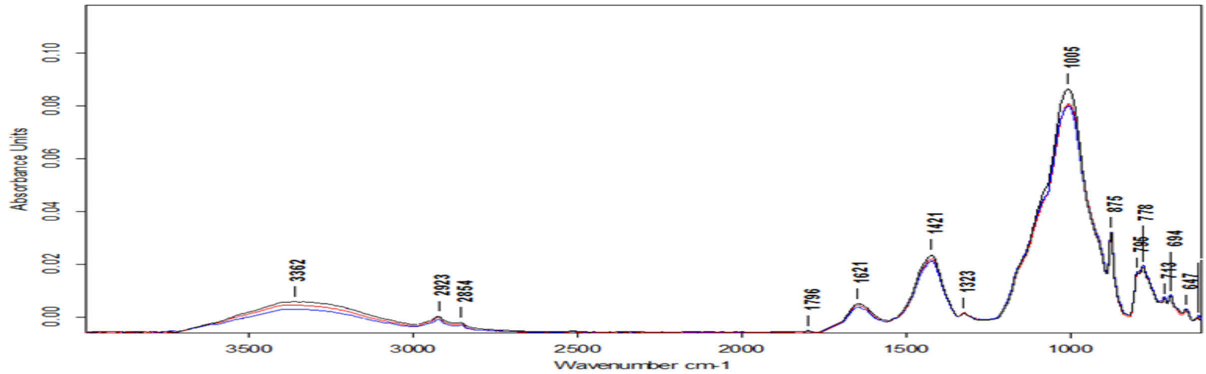
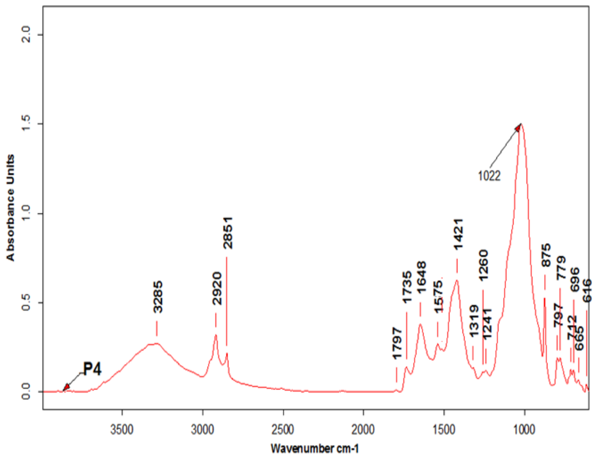
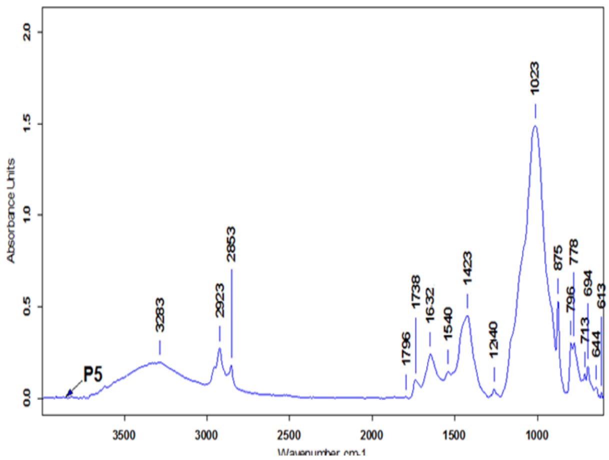


Figure 9. FTIR-ATR spectra of dust samples collected outside the shop.

The presence of silicate and carbonaceous minerals in the constitution of the sediment dust samples taken from the atmosphere outside the shop is mainly due to natural soil erosion phenomena or even Saharan dust events. Literature studies mention that the main constituents of atmospheric dust are silicate (quartz, phyllosilicate, and clays) and carbonaceous in nature and originate from natural soil constituents and that the presence of palygorskite in the constitution of atmospheric PM is due to Saharan dust events, which are becoming more and more frequent over Europe. [16-22].

Along with these major compounds, the FTIR-ATR spectra of the dust samples collected from the shop's outdoor atmosphere also contain bands specific to minor compounds such as hydrocarbons (~2923 cm^{-1} and ~2854 cm^{-1}) or ammonium nitrate (~1418 cm^{-1} and ~1323 cm^{-1}) [23]. Studies have shown that these compounds occur in the atmosphere as anthropogenic pollutants resulting from fuel combustion processes or reactions between acid precipitation and soil organic matter [17, 22-24].





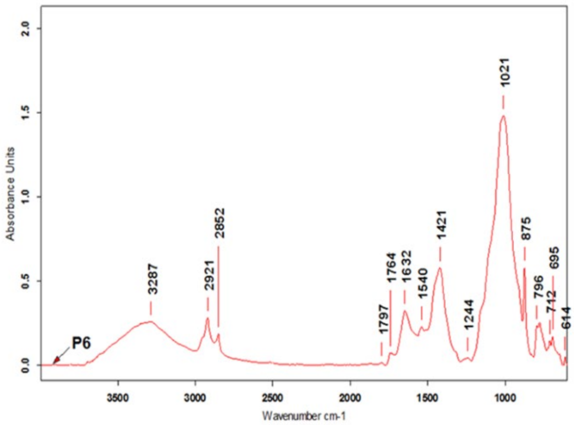


Figure 10. FTIR spectra of samples collected from inside the shop.

The FTIR-ATR spectra of the samples collected from inside the shop are much more complex than those of the samples from outside and contain several bands specific to organic and bio-organic compounds, in addition to the vibrational bands of silicate and carbonate minerals. The FTIR-ATR spectra of the interior samples also contain bands specific to $(CO_3)^{2-}$ion in carbonates such as calcite. Carbonates are either due to the external environment or the construction materials used for the interior finishes. Gypsum ($CaSO_4.2H_2O$) was identified only in sample P4 by the vibrational band located in the FTIR-ATR spectrum and probably originates from the gypsum used for the walls [25-27].

Ammonium nitrates were identified in samples P4 and P6. As for the organic compounds in the dust samples taken from inside the shop, the FTIR-ATR spectra show bands specific to carbonyl, ether, and aromatic groups (e.g., benzene, toluene, xylene, polyaromatic nitrates). Chronic daily dose (CDD) values were assessed for all departments to estimate the health effects on residents exposed to formaldehyde. The average CDI value for formaldehyde over the year is in store at 3.60 mg/day kg, with a maximum of 6.60 mg/day kg in the Sweets department and a minimum of 1.2 mg/day kg in the same department. The average intake is three times higher than the average concentration outside the store (1.17 mg/day kg). The average CSF in the store was 6.7 x 10^{-6}, which means that 6.7 people per 1,000,000 have a high risk of cancer from formaldehyde.

Thirty-one employees responded to our questionnaire, of which 22 (70.9%) were female. The average age of the group was 37.3±10.4 years (between 19 and 55 years). One subject was previously known for allergies, none of the subjects had an upper or lower respiratory tract infection in the previous week, and 4 reported concomitant illnesses. Two of the four subjects with concurrent illnesses reported 6 and 8 symptoms, respectively, while the other two reported having only one symptom from the BSS list. Twenty-three (74%) subjects had at least one symptom, 25.8% had between 2 and 3 symptoms, and 4 (12.9%) subjects had four or more symptoms. The median number of symptoms per patient was 1 (range IQ = 0.5-2.5, range: 0-8) (Figure 11 A). In terms of gender distribution, a similar proportion of male subjects (77.7%) had symptoms compared to female subjects (72.7%) (p=0.77).

Regarding symptom assessment, our study showed that, in a relatively young group of workers, most workers experienced at least one symptom that could be attributed to the work environment. Fatigue, nose, throat, and skin symptoms were the most common, similar to other studies [28].

Conclusions

The present study focuses on assessing indoor air quality in a shop and identifying associated health symptoms. Formaldehyde, a group B carcinogen, was detected, but concentrations remained within safe limits, the main sources being surface coverings, floor cleaners, textiles, and furniture. The study also examined monoterpenes, lactic acid, and particulate matter concentrations, with differences observed between indoor and outdoor conditions. Relatively low PM2.5 concentrations were found, possibly influenced by improved cleaning practices adopted during the COVID-19 pandemic. Assessment of symptoms indicated their occurrence in many of the younger workers, including fatigue, nasal, throat, and skin problems, without establishing a direct link between these and sick building syndrome or formaldehyde exposure, suggesting the need for further investigation. No significant gender differences in symptom prevalence were observed, but the limited size of the study calls for caution in generalizing the results. In conclusion, the study highlights the importance of further investigation of indoor air quality and its potential impact on workers' health in a relevant economic sector.

VARIABILITY OF INDOOR AIR POLLUTANTS IN OFFICES AND THEIR IMPACT ON WORKERS' HEALTH

Introduction

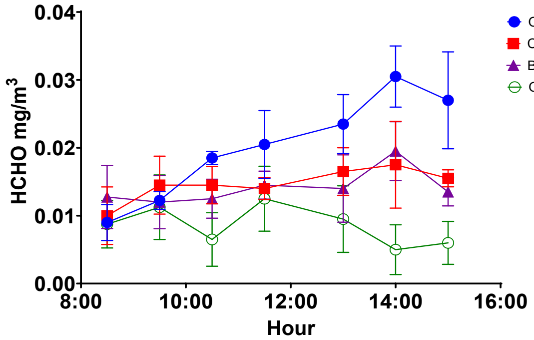
Globally, an increasing proportion of the modern workforce works in office premises [29]. Still, the well-being and health of people working in enclosed spaces have become a significant concern because of the impact of indoor air quality on their general condition [30, 31].

Office workers spend much of their time in enclosed spaces where they are constantly exposed to various contaminants. The main objective of this study was to assess the concentration of pollutants inside an office building over a year and to analyze the composition of the accumulated dust using FTIR. Our secondary objective was to investigate the prevalence of typical SBS symptoms among the building's employees [32].

Between March 2022 and March 2023, three separate rooms were sampled intermittently: office, corridor, and bathroom, from the office space and the outside air. The building is located in the city of Reșița, in western Romania, the monthly assessments were performed consistently on the same day (Wednesday) and at the same time (noon), totaling four measurements per month. Parameters assessed included total volatile organic compounds, PM_1, $PM_{2.5}$, PM_{10}, and formaldehyde.

Determination of formaldehyde concentration in offices

The formaldehyde concentration remains constant outside the building at a 13 μg/m^3 level. In contrast, it increased almost threefold inside the building within 8 hours (Figure 20). Between 2011 and 2015, average indoor formaldehyde concentrations in newly renovated offices in China were 94 μg/m^3 [33]. There are significant differences between the concentration inside the office (0.021 μg/m^3) and outside (0.012 μg/m^3) after 3.5 hours ($p<0.05$). The same trend was found for air in corridors and bathrooms, which could be explained by formaldehyde emission from the surface of materials (wood products, carpeting, and insulation) [34, 35]. Interestingly, at the end of the program, the concentration of formaldehyde became significantly higher than in the corridor due to emissions from various pieces of furniture and electronic devices presented in the office [36].



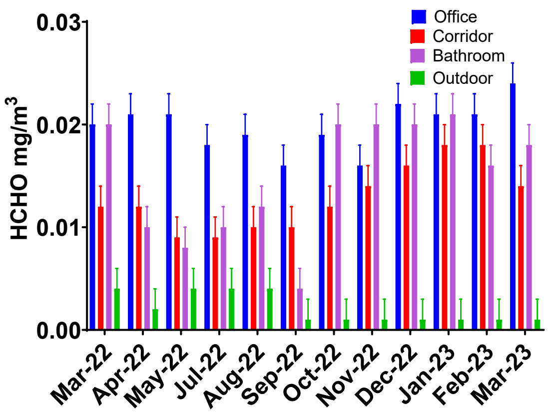


Figure 12. Variation of formaldehyde concentrations during working hours, and over a year.

The concentration of formaldehyde in the office did not vary dramatically throughout the year, but the concentration was lower in September and higher in March 2023 than in the other months. Interestingly, formaldehyde concentrations in the corridor and bathroom showed a notable decrease during the summer, measuring 9.7 µg/m^3 for the corridor and 8.7 µg/m^3 for the bathroom.

Variation in concentration of volatile organic compounds

The total concentration of volatile organic compounds (TVOC) increased indoors while the concentration remained constant outdoors (Figure 13).

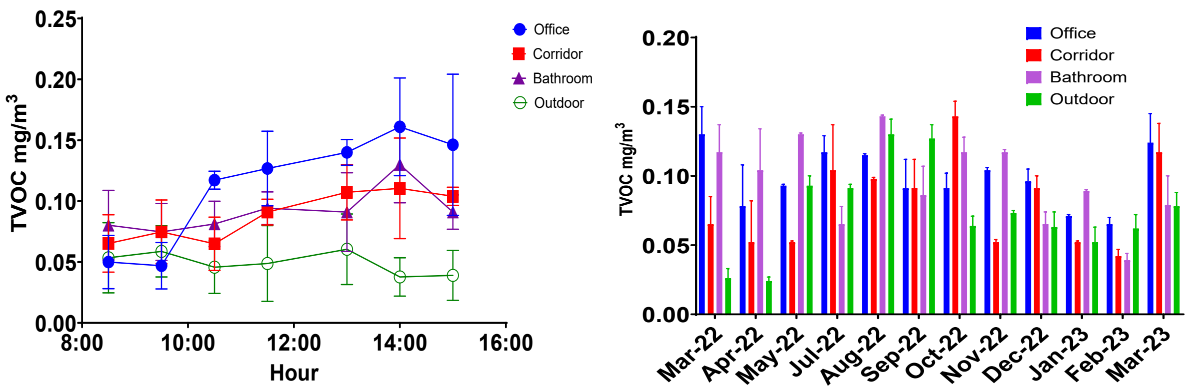


Figure 13. Variation of total volatile organic compound (TCOV) concentrations during working hours.

After the first hour of work, the concentration of TCOV rises sharply in the office, while the trend is not so evident in the corridor and bathroom. Such a trend has been found in offices and ordinary homes [37, 38]. Sources of TCOV in the office could be attributed to plastics, paints, and mainly consumer products such as perfumes and body sprays. Concentrations of volatile organic compounds (VOCs) in the ambient environment showed a noticeable seasonal variation, with considerably higher levels in summer compared to winter. Our data indicate that the average concentration reached 110 ± 21 µg/m³ in May-September. In contrast, a distinct reduction was observed in the October-April period with an average concentration of 55 ± 20 µg/m³. This observed disparity in VOC concentrations between seasons highlights the influence of meteorological and environmental factors on atmospheric composition, thus requiring a comprehensive understanding of the mechanisms underlying these seasonal variations.

Variation of suspended particulate concentrations

PM1, PM2.5, and PM10 concentrations did not vary significantly during working hours (Figure 14). The concentration of particulate matter did not decrease considerably in the office compared to outdoor air. The same trend was observed for all particle sizes. The ratio of $PM_{2.5}$ to PM_{10} for outdoor air was 0.83 ± 0.08 µg/m^3. Such a high ratio of fine particles indicates that air pollution comes more from [39, 40].

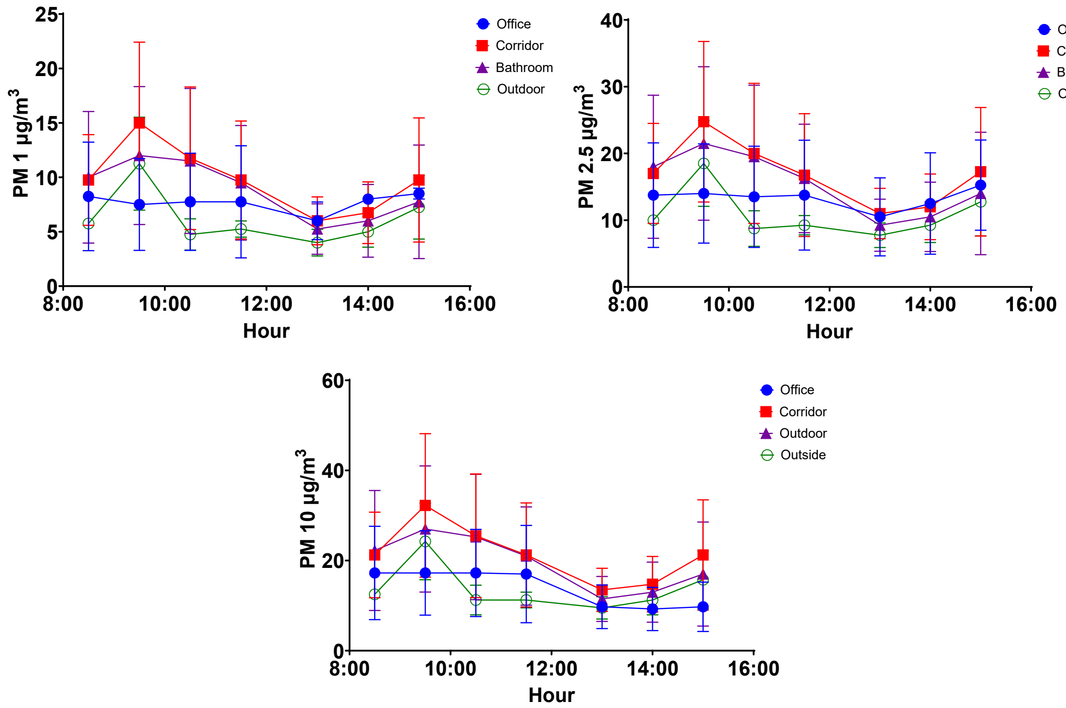


Figure 14. Variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations during working hours.

The concentrations of particulate matter over a year are shown in Figure 15. The variation in PM_1, $PM_{2.5}$, and PM_{10} concentrations is significant over the year, with a maximum of 45 µg/m^3, 75 µg/m^3 and 96 µg/m^3 respectively.

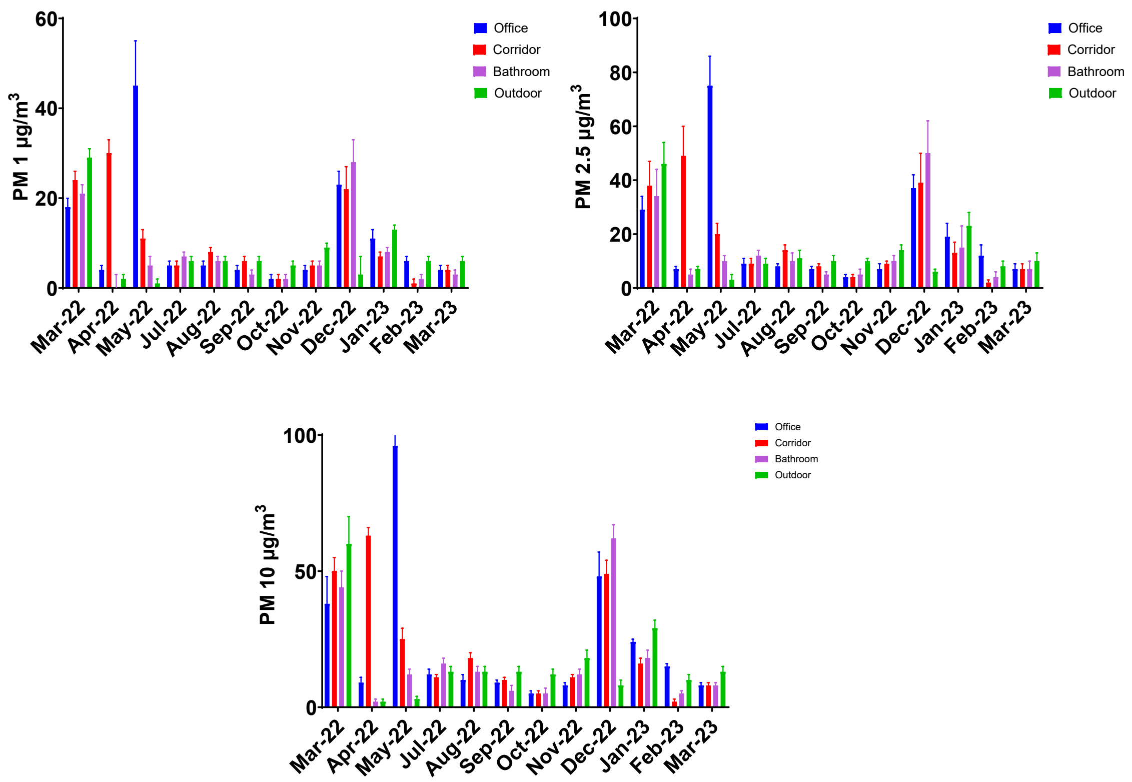


Figure 15. Variation of PM_1, $PM_{2.5}$, and PM_{10} concentrations over one year.

The findings suggest that daily average indoor PM_{10} and $PM_{2.5}$ concentrations were within the WHO recommended limits. However, there are three months with high PM concentrations: March, May, and December. The highest office concentrations exceed 90 $\mu g/m^3$, the same range as in the 25 naturally ventilated urban residences in Alexandria, Egypt [41]. The lower concentration for corridors and bathrooms could be explained by the higher ventilation of these rooms than for offices. Sources of PM in offices could be an accumulation of dust and dirt on surfaces, furniture, and office equipment.

Determination of indoor dust composition using the FTIR technique

The identification of organic and inorganic groups present in sediment dust samples collected both inside and outside the environment was performed by attenuated total reflection Fourier transform infrared spectrometry (ATR-FTIR).

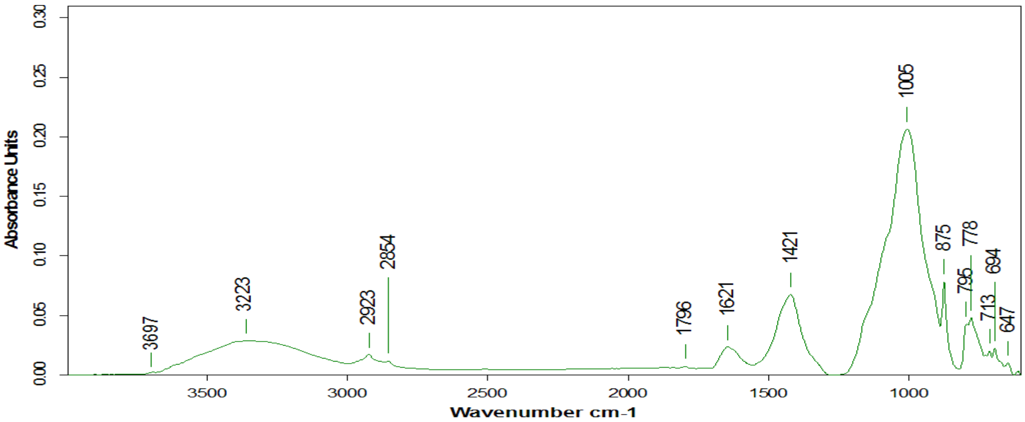
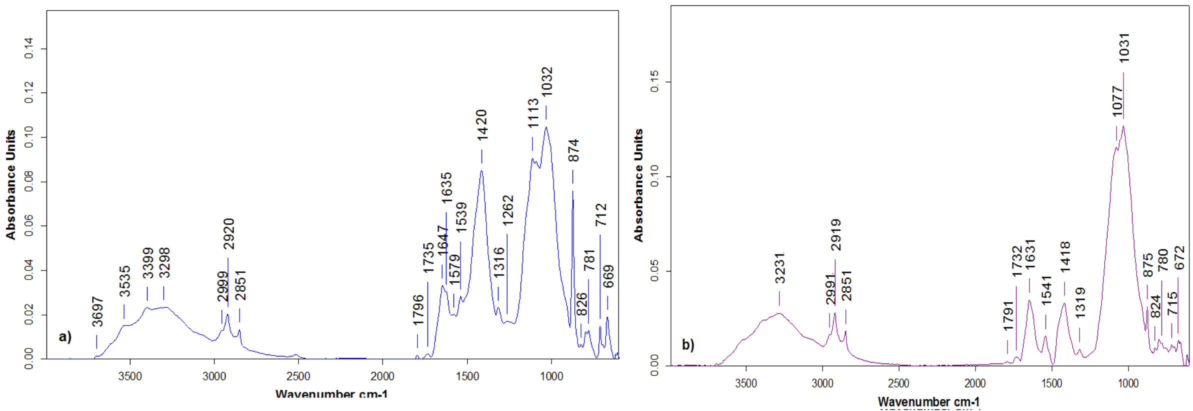


Figure 16. FTIR-ATR spectrum of the outdoor dust sample.

The FTIR-ATR spectrum of the sedimented dust sample taken from the outdoor environment is dominated by the vibration bands of phyllosilicates, clay minerals, and quartz located at 3697 cm^{-1}, 1621 cm^{-1}, 1005 cm^{-1}, 795 cm^{-1}, 778 cm^{-1}, 694 cm^{-1} and 647 cm^{-1} [42]. The presence of calcite-type carbonates can also be identified. The presence of silicates, aluminosilicates, and carbonates in the chemical composition of the sediment dust extracted from the atmosphere has been observed and reported in the literature by several authors. It has been attributed mainly to soil erosion, Saharan dust events, and layered building materials [16-18, 20-22, 43]. Organic compounds of the aliphatic hydrocarbon type were identified in the sample investigated in the open air by the bands located in the FTIR spectrum at 2923 cm^{-1} and 2854 cm^{-1} [23]. Studies have shown that hydrocarbons in dust particles come mainly from fuel combustion processes [17, 22, 24, 44]



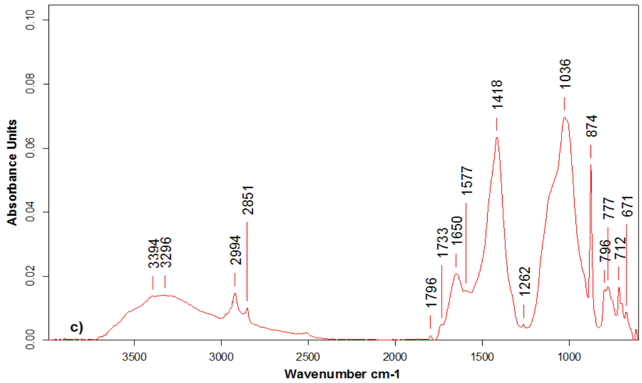


Figure 17. FTIR-ATR spectra of indoor dust samples: (a) - office; (b) - bathroom; (c) - corridor.

Compared to the outdoor sample, the FTIR-ATR spectra (Figure 17) of the settled dust samples collected from the office, bathroom, and corridor are more complex and contain, in addition to the bands identified in Figure 6, several new bands specific to inorganic, organic or bio-organic compounds generated by indoor sources (e.g. wall building materials, wall covering materials, insulation materials, carpets, electronic devices, furniture, human activities, human body, hygiene and personal care products, etc.). Thus, the presence of gypsum ($CaSO_4 \cdot 2H_2O$) from interior plaster walls was observed in all three interior samples (~3535 cm^{-1}, ~3399 cm^{-1}, ~1113 cm^{-1} and ~670 cm^{-1} [25-27, 45]), together with calcite, quartz, phyllosilicate and clay minerals (minerals from both wall finishing materials and the outside atmosphere due to ventilation).

Impact on human health

Health indices associated with formaldehyde concentrations present in the office, hallway, and bathroom as well as outdoors were calculated. The HQ value, which is below the threshold of 1, indicates that the levels of formaldehyde identified, whether in indoor spaces such as the office, hallway, and bathroom or in the outdoor environment, do not reach the limits set as hazardous to public health. This suggests that there is currently no significant risk to general health caused by the presence of formaldehyde in these locations. However, the finding that there is a 1 in 100,000 risk of developing cancer from exposure to formaldehyde in office spaces, based on a CSF of approximately 10^{-5}, highlights a specific concern for people who spend significant time in these environments. Although this level of risk is considered manageable under standard public health risk assessments, it signals the need for close monitoring of indoor air quality and the implementation of effective strategies to reduce exposure to harmful substances.

Conclusions

Office occupants are exposed to a variety of indoor air pollutants such as particulate matter (PM), volatile organic compounds (VOCs), and formaldehyde. The study observed that VOC levels in the office under study increased significantly throughout the day, from an initial value of 0.050 ± 0.044 µg/m^3 at 8:00 in the morning to 0.14 ± 0.11 µg/m^3 by 15:00. Similarly, formaldehyde concentrations increased significantly over 8 hours, from an average of 9 ± 5 µg/m^3 to 27 ± 14 µg/m^3. These pollutants come from a variety of sources, including building materials, office equipment, and daily activities, making it difficult to maintain good indoor air quality. Levels of these pollutants can vary with the seasons, with higher levels of particulate matter observed in the cooler months. There is a strong correlation between exposure to higher levels of indoor air pollutants and the experience of symptoms of Sick Building Syndrome (SBS), such as eye irritation, shortness of breath, and cognitive problems. The study highlights the importance of improving indoor air quality to prevent health problems for office workers and highlights the need to take steps to clean the air in office spaces to maintain the health and well-being of occupants.

GENERAL CONCLUSIONS

Our research highlights the importance of ongoing assessment of pollutants specific to office and commercial environments, such as particulate matter (PM), volatile organic compounds (VOCs), and formaldehyde, which originate from a wide range of sources including building materials, furniture, electronics, and everyday human activities.

Analysis of diurnal and seasonal variations in VOC levels shows constant internal emissions, emphasizing the need for rigorous control of emission sources in enclosed spaces. Furthermore, the increases observed in formaldehyde levels during the working day suggest the existence of continuous emission sources, highlighting the potential health risks for occupants.

There is a clear correlation between exposure to pollutants and the prevalence of symptoms associated with Sick Building Syndrome (SBS), such as eye irritation, breathing difficulties, and cognitive problems, revealing a direct negative impact of indoor air quality on occupant health. It is recommended that efficient ventilation and purification systems be implemented, materials with low emission profiles be used, and strict maintenance and cleaning protocols be adopted. Adequate indoor air quality (IAQ) management requires an integrated approach, including careful monitoring of pollutants, reducing emission sources, and implementing proactive air quality improvement strategies. Focusing on improving IAQ in office and commercial spaces contributes significantly to preventing health problems and improving the quality of life of occupants, ensuring a safe and healthy working and commercial environment.

These conclusions underline the need for increased attention to indoor air quality and the adoption of effective measures to protect the health of occupants in enclosed spaces, thereby contributing to safer and healthier working and business environments.

LIMITS AND PERSPECTIVE

The study may be limited by the number and diversity of office and commercial premises assessed, and limited sampling may influence the generalisability of the results to a broader range of office and commercial environments. Accurate identification of all sources of air pollutants can be challenging given the many materials, products, and activities in enclosed spaces that can contribute to indoor air quality. This includes variations in space use and occupant behavior.

Limitations related to pollutant measurement methodologies, including sensitivity, specificity, and potential errors of measuring instruments, can affect the accuracy and reliability of the data collected. The study may not adequately cover temporal and seasonal variations in pollutant levels. Important fluctuations that could significantly impact indoor air quality (IAQ) may be missed without long-term monitoring. Assessment of the impact of pollutants on occupant health may be limited by the absence of longitudinal data or a study design that allows direct causal inferences between pollutant exposure and health manifestations. There is a risk that the study may not be able to fully control all variables that could influence both pollutant levels and occupant health, including factors such as building age, ventilation systems, and individual occupant behaviors. For assessments based on occupants' reported symptoms or their perceptions of air quality, there is a risk of subjectivity and individual variability that could affect the interpretation of the data. The study may not include a detailed assessment of the effectiveness of various air quality improvement interventions, thus limiting the ability to provide specific recommendations for improvement practices or policies.

Given the limitations identified, there are several promising directions for future research in indoor air quality, particularly in offices and commercial spaces. First, it would be beneficial to expand studies to encompass a wider variety of environments from different geographic regions and with varying types of design and use. This would improve representativeness and facilitate the generalisability of results. Also, implementing longitudinal studies assessing seasonal and long-term variations in air quality and their impact on occupant health would provide a deeper insight into the dynamics of pollutants and their effects.

It is essential to develop and implement more accurate and sensitive measurement methodologies, and the use of advanced technologies and extensive data analysis could significantly improve the accuracy and reliability of these measurements. Approaching the issue of indoor air quality (IAQ) from a multidisciplinary perspective, integrating expertise from medicine, environmental engineering, psychology, and architecture, is crucial to understanding the complexity of factors influencing IAQ and their impact on health.

Evaluation of the effectiveness of various IAQ improvement strategies, including optimizing ventilation systems and introducing low-emission building and finishing materials, is also needed. Studies could explore the cost-benefit relationship of different interventions to determine the most effective measures. Using modeling and simulation to predict the impact of building design changes, occupant behavior, and IAQ management strategies can facilitate the preventive design and optimization of office and commercial spaces.

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