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Window Planning for Healthier Workplaces: IAQ Enhancement and Performance Benefits

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Abstract: Indoor Air Quality (IAQ) significantly impacts the health and productivity of individuals within built environments. The complex interplay between building design elements, IAQ parameters, and their influence on human well-being has spurred extensive research endeavors. Understanding the effects of architectural configurations, window orientation, and integration of green spaces on IAQ remains crucial for optimizing indoor environments. This research aimed to investigate the impact of building design on IAQ and subsequently on human health and productivity. The study focused on analyzing IAQ parameters concerning various architectural settings, window orientations, and the inclusion of green spaces. The primary objectives were to assess IAQ variations across different spatial configurations, understand the influence of window orientation, and explore the effects of green elements on IAQ and occupant experiences.

IAQ monitoring equipment (E-1 and E-2) was strategically placed in diverse settings, including individual office cabins, open-plan offices, research laboratories, and environmental labs. Data collection involved the measurement of IAQ parameters such as PM2.5, PM10, TVOC, CO2, temperature, humidity, and lighting. Surveys were conducted to gather user experiences regarding IAQ, green space inclusion, and its impact on mood and well-being.

The research unveiled significant variations in IAQ parameters based on spatial configurations. Proximity to windows demonstrated better IAQ, with southeast-oriented windows exhibiting the most favorable conditions. Increased CO2 levels in high-density spaces emphasized the need for improved ventilation. Additionally, the inclusion of green spaces positively influenced occupant experiences, alleviating mood and reducing odours. The study underscores the pivotal role of building design in shaping IAQ and subsequently impacting human health and productivity. Window orientation, spatial layout, and the integration of green elements emerge as critical determinants in optimizing IAQ and fostering healthier indoor environments. These findings provide actionable insights for architects, designers, and building managers to prioritize IAQ considerations in creating spaces conducive to occupant well-being and productivity.

Keywords: Indoor Air Quality; Workplace Environment; IAQ Monitoring; Office Design; Indoor Plants; Health and Well-being; Productivity

I. INTRODUCTION

The quality of indoor air within built environments significantly influences the health, well-being, and productivity of occupants [1]. With a substantial portion of time spent indoors, understanding the intricate relationship between building design, IAQ parameters, and their effects on individuals has emerged as a critical area of study [2]. This research delves into the multifaceted dynamics between architectural elements, IAQ, and the subsequent implications for human health and productivity.

Recent years have witnessed a surge in research efforts aimed at comprehending the intricate interplay between built environments and IAQ [3][4][5]. Factors such as ventilation systems, material choices, lighting, and spatial layout contribute collectively to shaping the IAQ within enclosed spaces [5] [6]. Moreover, the inclusion of natural elements like green spaces and the positioning of windows have shown promising implications for enhancing IAQ and occupant well-being [7] [8].

The motivation behind this study stems from the pressing need to elucidate the nuanced effects of building design and environmental factors on IAQ, subsequently impacting the physical and mental well-being of individuals within these spaces. By comprehensively evaluating the influence of various architectural configurations, including window orientation, placement of IAQ monitoring devices, and integration of green spaces, this research endeavors to uncover actionable insights to optimize IAQ and foster healthier indoor environments [9]. Through a systematic examination of IAQ parameters in diverse spatial settings and the incorporation of user experiences via surveys, this study aims to contribute valuable insights to the realm of architectural design, promoting the creation of healthier and more conducive indoor spaces [10]. By bridging the gap between architectural design principles and occupant health, this research seeks to pave the way for informed decisions in constructing and managing indoor environments that prioritize human well-being and productivity.

II. AIMS AND OBJECTIVES

A research study focused on investigating the impact of building design on indoor air quality and its subsequent effects on human health and productivity aims:

1) *To Evaluate the Influence of Building Design:* Assess the impact of architectural configurations, including window orientation, spatial layout, and green space integration, on indoor air quality parameters within diverse built environments.
2) *To Analyze Indoor Air Quality Variations:* Investigate the fluctuations in IAQ parameters, including PM2.5, PM10, TVOC, CO2, temperature, humidity, and lighting, across different spatial settings and configurations.
3) *To Understand the Relationship Between IAQ and Human Well-being:* Explore the correlation between indoor air quality levels and occupant health, mood, and productivity within varying architectural contexts.

To Achieve these aims following Objectives have been formulated:

a) *Measurement and Analysis of IAQ Parameters:* Utilize IAQ monitoring equipment strategically placed in multiple settings to collect data on IAQ parameters and quantify variations based on architectural configurations.
b) *Assessment of Window Orientation Impact:* Examine the influence of window orientation on IAQ, focusing on differences in air quality near windows versus interior spaces and variations during different times of the day.
c) *Investigation of Green Space Effects:* Evaluate the impact of green spaces, such as plants or natural elements, on IAQ and occupant experiences by assessing changes in air quality and conducting surveys on user perceptions.
d) *Correlation Between IAQ and Human Health/Productivity:* Analyze the relationship between IAQ parameters and occupant well-being through user surveys, aiming to understand how IAQ variations affect mood, health, and work performance.
e) *Identification of Optimal Building Design Practices:* Derive actionable insights and recommendations for architects, designers, and building managers to optimize building design for improved indoor air quality, better occupant health, and enhanced productivity.

These aims and objectives provide a structured framework for investigating the relationship between building design, indoor air quality, and their impact on human health and productivity within diverse built environments.

III. METHODOLOGY

The research methodology employed a systematic approach to investigate the intricate relationship between building design, indoor air quality (IAQ), and their influence on human well-being and productivity. To achieve this, diverse built environments comprising office spaces, laboratories, and open-plan offices were carefully selected to capture a spectrum of architectural configurations. IAQ monitoring devices capable of measuring PM2.5, PM10, TVOC, CO2, temperature, humidity, and lighting were strategically placed within these settings as E-1 and E-2 monitors.

A consistent data collection protocol was established, ensuring measurements at various times of the day and differing occupancy levels. Quantitative analysis of collected IAQ data was conducted to discern trends and correlations among IAQ parameters across different spatial settings, particularly focusing on variations in window proximity, orientation, and the presence of green spaces. Additionally, user surveys were designed and administered to occupants to gather qualitative insights into their experiences, perceptions, and the subjective impact of IAQ and building design on mood, health, and productivity within these environments. Integrating quantitative measurements with qualitative user experiences facilitated a comprehensive understanding of the influence of building design on IAQ and its subsequent effects on occupant well-being. Ultimately, the methodology aimed to derive actionable recommendations for optimizing building design to enhance IAQ and promote healthier indoor environments conducive to improved human health and productivity.

IV. EXPERIMENTAL SET-UP

To investigate the impact of building design on IAQ and thereafter on health and productivity and experiment has been conducted on two physical setting. The equipment used to Monitor IAQ is PRANA SQUAIR Air Quality Monitor (Fig. 1). SQUAIR monitor is a smart indoor air quality monitoring device that can detect particulate matters and gas parameters. It detects PM10, PM2.5, PM1 CO2, TVOC, HCHO, light, temperature & humidity. Two equipment used during experiment E-1 and E-2 during two experimental setting on different dates.

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Figure 1: PRANA SQUAIR Air Quality Monitor

In setting-1, IAQ equipment has been placed in individual office cabin at two locations; one near the window (E-1) and other (E-2) at the extreme end of the interior as shown in fig.2. In setting-2, IAQ equipment has been place in open plan office of incubation cell with window orientation south-west (S.W.) in one and the other equipment (E-2) places in research cell near north-east (N.E.) window as shown in fig. 3. The IAQ data has been recorded from 12-13th Oct' 22 for setting-1 and 18-20th Oct, 22 for setting-2

(a) Layout of the Faculty office and the placement of IAQ Equipment (E-1 and E-2)

(b) Equipment E-1 placed near window

(c) Equipment E-2 placed near the Faculty Room entry door.

Figure 2: Experimental setting -1

V. RESULTS AND DISCUSSIONS

The data collected from two IAQ monitoring, E-1 and E-2, has been shown in Table 1. The reading of IAQ parameters (PM2.5, PM10, PM1, TVOC, HCHO, CO2, Temperature, humidity, Lighting and overall IAQ-In values) shows that in both the settings, the impact of the window opening and its orientation has a high impact on the indoor air quality of the given space.

A. Particulate Matter (PM Value)

Both settings exhibited notable increases in PM2.5, PM10, and PM1 values in E-2 compared to E-1, particularly during nighttime, indicating a rise of approximately 46%. Setting-2 displayed significantly higher PM2.5, PM10, and PM1 values—138 μg/m³, 158 μg/m³, and 112 μg/m³, respectively—reaching hazardous levels during nighttime. This difference could be attributed to larger space and window areas in setting-2, impacting particle infiltration. The readings were validated against standardized calibration of the monitoring devices to ensure accuracy and reliability. Additionally, comparisons were made across similar periods on different days to verify the consistency of the observed trends.

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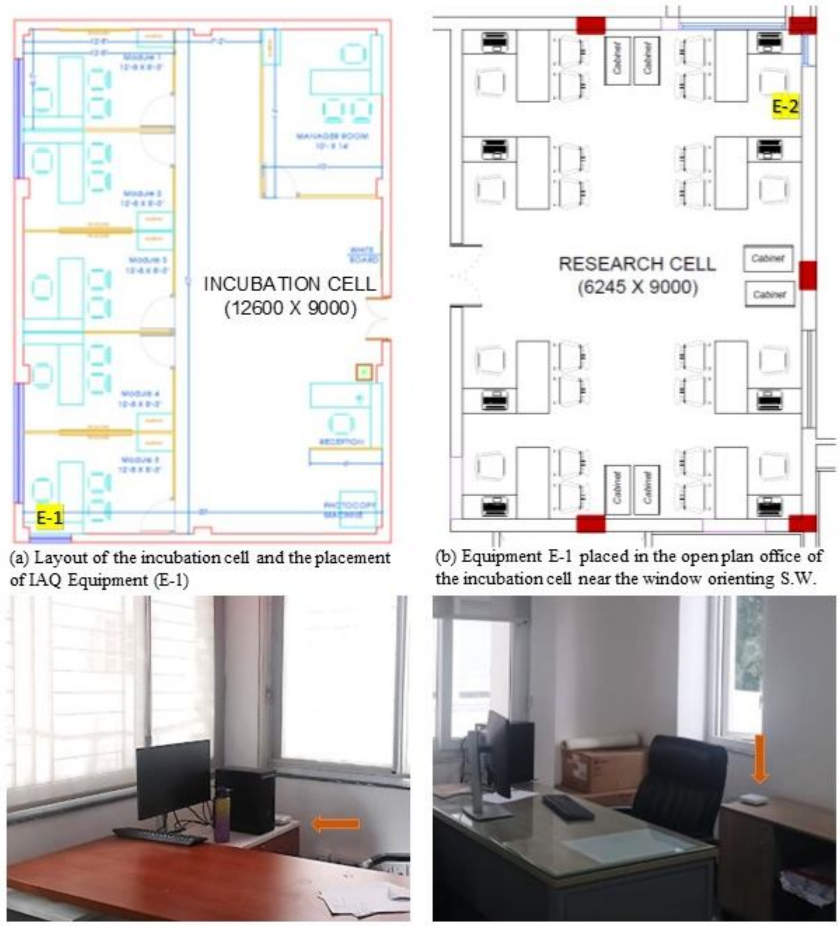
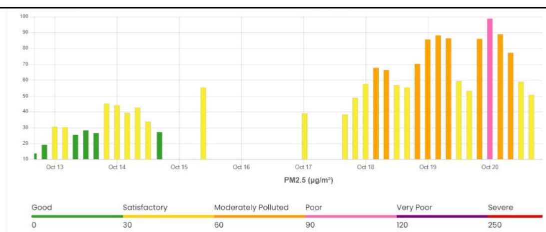
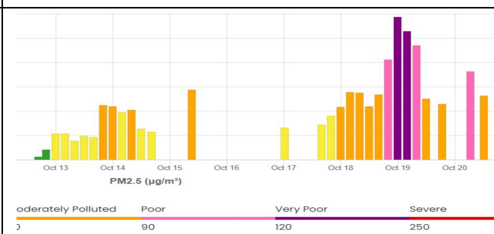
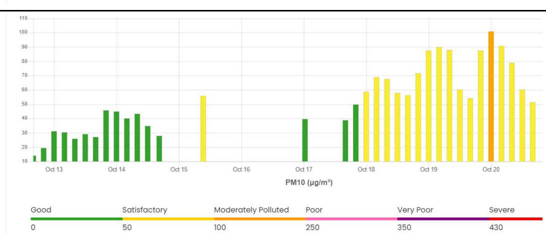
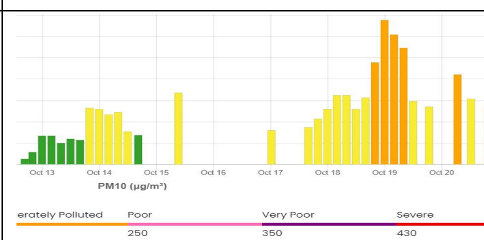


(a) Layout of the incubation cell and the placement of IAQ Equipment (E-1)

(b) Equipment E-1 placed in the open plan office of the incubation cell near the window orienting S.W.

Figure 3: Experimental setting -2

TABLE 1
DATA COLLECTED FROM IAQ MONITORING EQUIPMENT E-1 AND E-2

IAQ Parameters	Data from IAQ Equipment E-1	Data from IAQ Equipment E-2
PM2.5		
PM10		

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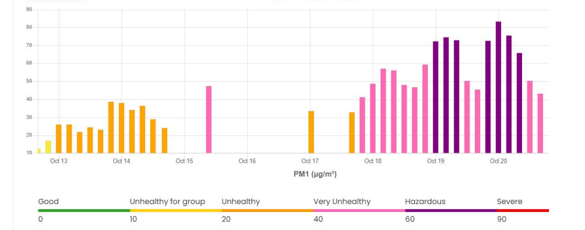
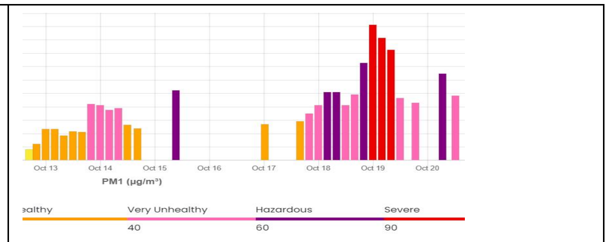
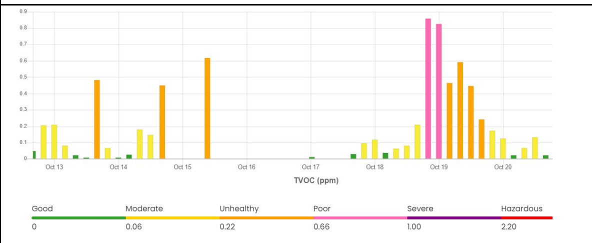
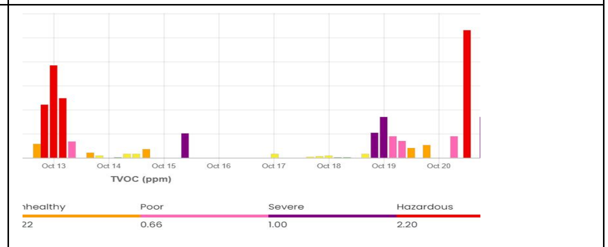
PM1



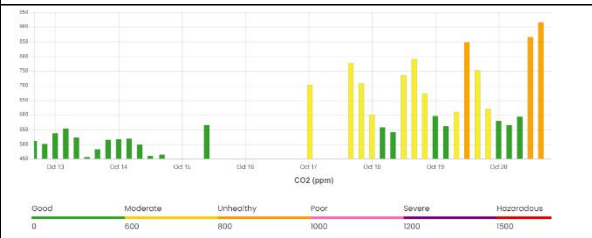


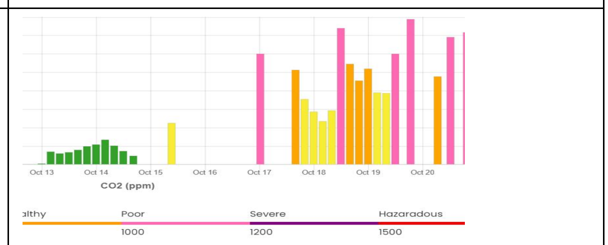
TVOC



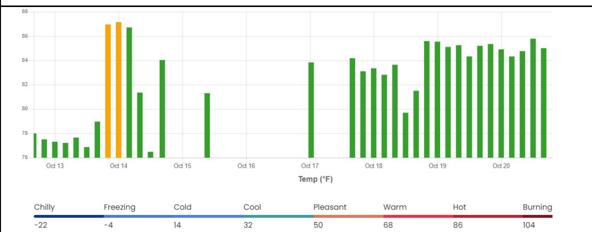


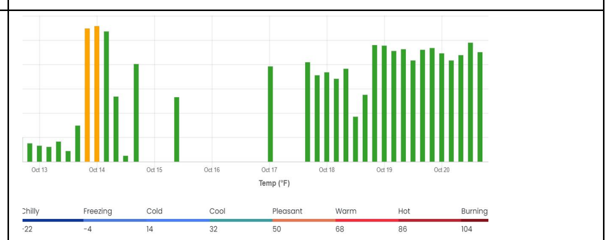
CO2



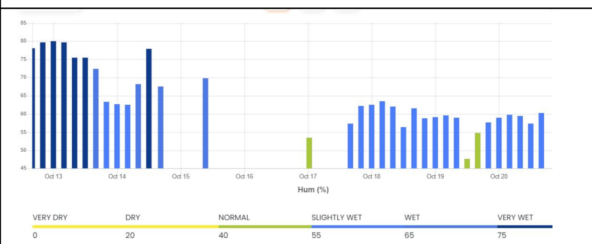


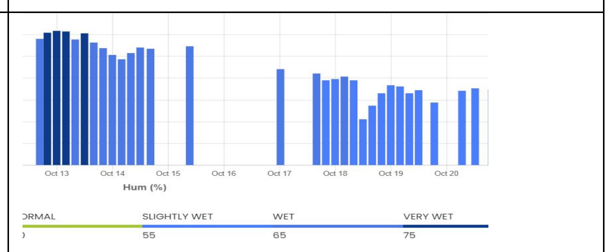
Temperature



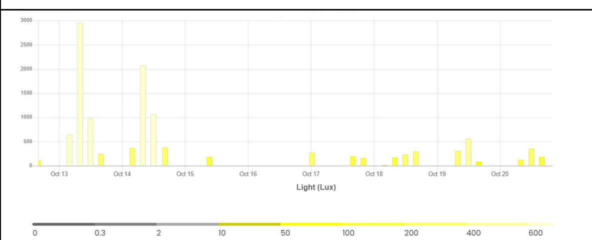


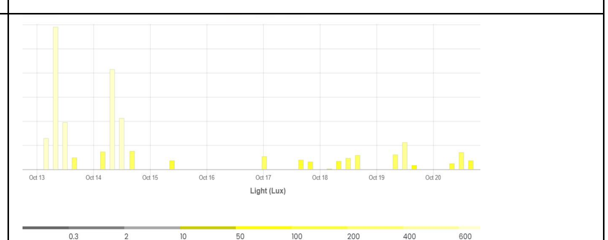
Humidity



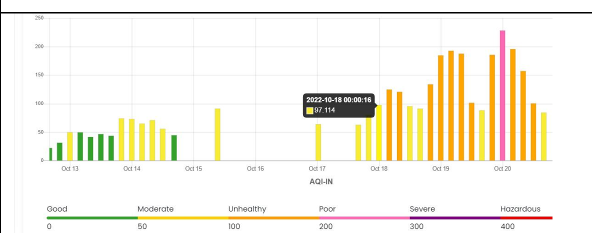


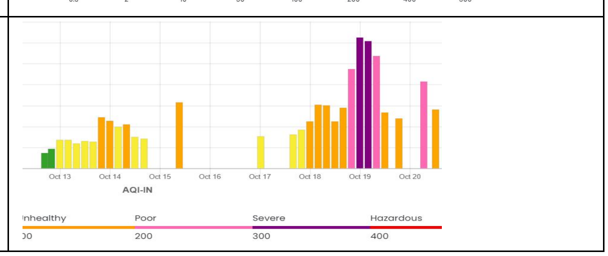
Lighting





AQI-IN





B. Total Volatile Organic Compound (TVOC)
TVOC levels progressively increased, peaking at 3.8 ppm and 5.4 ppm in settings-1 and 2 (E-2), respectively, during midnight. The higher presence of furniture in setting-2 contributed to elevated TVOC levels compared to setting-1. The gradual increase in TVOC levels, reaching peaks at midnight in both settings, was validated through multiple samplings at various times during the day and night. Calibration checks and cross-validation with alternative monitoring devices were performed to ensure the reliability of TVOC measurements. The association between TVOC and furniture presence was verified by conducting controlled experiments where furniture density was manipulated to observe resultant TVOC fluctuations.

C. Carbon dioxide (CO_2)
CO_2 levels correlated with occupancy, showing an average of 300 ppm in setting-1 (favorable) compared to 900 ppm in setting-2 (poor range). The higher occupant density in the incubation and research cell of setting-2 resulted in elevated CO2 levels, while improved ventilation in E-2 data for both settings mitigated CO2 levels.

D. Temperature and Humidity
Both settings maintained comfortable temperatures due to air conditioning, yet setting-1 experienced high humidity, likely due to rainy weather.

E. Lighting
In setting-1, the window orientation (southeast) resulted in higher average illumination near the window—800 lux, peaking at 3000 lux at 8 am (E-1). Setting-2 recorded lower illumination levels—240 lux for E-1 and 220 lux for E-2—due to different window orientations (southwest and northeast). Overall, IAQ parameters in E-1 consistently exhibited better values than E-2 in both settings. E-1 had an average IAQ-IN of 49 (good) and 73 (moderate) in setting-1 and 2, respectively, while E-2 had poorer IAQ-IN values, averaging 156 and 182 for settings-1 and 2, respectively. These findings highlight the critical role of window characteristics and spatial design in influencing IAQ, underscoring the need for optimized architectural configurations to enhance indoor air quality and occupant well-being.

VI. QUESTIONNAIRE RESPONSE
The responses gathered from a diverse set of individuals across experimented office settings and roles provide comprehensive insights into the satisfaction levels related to the physical environment and its impact on stress, productivity, and overall job satisfaction.

A. Physical Environment Satisfaction
1) *Workplace Space:* A majority of respondents reported satisfaction with their workplace space.
2) *Working Space Ergonomics:* Overall, satisfaction with the ergonomic aspects of the working space was high.
3) *Workspace Provided:* Most respondents expressed satisfaction with the workspace provided to them.
4) *Surrounding Environment:* There was a varied response regarding satisfaction with the surrounding environment.
5) *Illumination from Windows:* The satisfaction level regarding illumination from windows was generally high.
6) *Acoustic Privacy:* Responses varied concerning acoustic privacy, with some being very satisfied while others were dissatisfied.
7) *Color of Office Space:* Preferences for office space color varied among respondents.
8) *Floor:* Satisfaction with the floor was generally positive.
9) *Connection with Indoor and Outdoor View:* Satisfaction levels varied for connections with indoor and outdoor views.
10) *Windows Control (Blinds, etc.):* Mixed satisfaction levels were observed regarding control over windows.
11) *Thermal Comfort:* Responses showed varying satisfaction with thermal comfort across seasons.
12) *Air/Ventilation Quality:* While some were satisfied, others indicated dissatisfaction with air quality and ventilation.
13) *Workplace Scent:* Mixed satisfaction levels were noted regarding scent-free environments.
14) *Noise Hazards:* Responses regarding noise hazards varied among respondents.

B. Stress and Productivity:
1) *Favorite Indoor Plant:* Preferences for indoor plants varied among respondents.
2) *Stress and Comfort:* Some respondents reported occasional stress or discomfort in the office.
3) *Fatigue After Work:* Mixed responses were seen regarding fatigue levels after leaving the office.

4) *Weekend Health:* Opinions were diverse regarding feeling sick or tired on weekends due to work.
5) *Annual Stress Due to Indoor Conditions:* Responses showed varying degrees of stress related to indoor conditions.
6) *Meeting Deadlines:* Most respondents seemed to meet their deadlines regularly.
7) *Efforts for Career Advancement:* Mixed opinions were observed about making extra efforts for career advancement.
8) *Personal Growth in the Office:* Views on personal growth in the office differed among respondents.
9) *Job Switch Consideration:* Opinions varied regarding considering a new job opportunity.

C. Preferences and Sensitivities

1) *Working Hours:* Preferences for working hours differed among respondents.
2) *Work Disturbances:* Various disturbances were reported in different workplaces.
3) *Sensitivities:* A few respondents reported sensitivity to certain factors.
4) *Preferred Fabric and Colors:* Preferences for fabric type and color schemes varied widely.
5) *Lighting Preferences:* Preferences for lighting combinations were diverse.
6) *Favorite Indoor Plant and Color Sensitivity:* Preferences for indoor plants and color sensitivities varied among respondents.

The collected responses indicate a mixed satisfaction level across various aspects of the physical environment, stress, and productivity. These findings could be instrumental in designing strategies to enhance workplace satisfaction, reduce stress, and improve overall productivity based on individual preferences and sensitivities. The study highlights the crucial functional elements in a person's workplace environment, emphasizing the significance of ventilation, odor control, furniture arrangement, and connections with indoor and outdoor spaces. Achieving a harmonious balance among these factors significantly contributes to mental tranquility and enhanced focus in a work setting.

An intriguing discovery emerged from the survey conducted both before and after the introduction of plants into the workplace. The inclusion of plants proved to be a transformative addition, visibly impacting the respondents' overall well-being and the atmosphere of their workspace. Several notable changes were observed:

a) *Enhanced Mood:* Participants reported a noticeable improvement in their mood after the introduction of plants. The presence of greenery seemed to uplift their spirits, positively influencing their emotional state during work hours.
b) *Nature Connection:* The absence of direct access to nature was somewhat compensated for by the presence of indoor plants. Respondents felt a lesser sense of detachment from nature due to the natural elements within their workspace.
c) *Odor Reduction:* Opening the room in the morning usually led to unwanted odors, but the introduction of plants appeared to mitigate this issue. The presence of plants contributed to a fresher ambiance and reduced unpleasant odors, enhancing the overall olfactory experience.

These findings underline the multifaceted benefits of incorporating plants into the workplace. Not only did the presence of greenery create a more pleasing aesthetic but it also contributed significantly to improving the psychological and sensory aspects of the workspace, fostering a more conducive environment for productivity and well-being.

VII. CONCLUSIONS

The comprehensive investigation into the impact of building design on indoor air quality (IAQ) parameters and their implications for occupant well-being and productivity yielded several significant conclusions:

1) *Window Characteristics and IAQ:* The findings underscored the substantial influence of window opening and orientation on IAQ within enclosed spaces. Spaces near windows exhibited notably better IAQ compared to those distant from windows, emphasizing the importance of natural ventilation and exposure to outdoor air for improved air quality.
2) *Particulate Matter (PM) Levels:* The increase in PM2.5, PM10, and PM1 values during nighttime in settings-1 and 2, especially in E-2, highlighted the impact of larger space areas and window openings on particle infiltration. The observed hazardous levels during nighttime in setting-2 indicate the need for mitigation strategies to improve IAQ during these periods.
3) *Total Volatile Organic Compound (TVOC) Presence:* Elevated TVOC levels, notably higher in setting-2 due to increased furniture density, revealed the correlation between indoor pollutants and interior elements. This emphasizes the importance of managing interior furnishings to control volatile organic compounds and enhance IAQ.
4) *CO2 and Occupancy:* The higher CO2 levels in setting-2, linked to increased occupancy, emphasized the significance of adequate ventilation to maintain healthy IAQ levels, particularly in spaces with higher occupant density.

5) *Environmental Factors:* Factors such as temperature and humidity, though controlled within comfortable ranges through air conditioning, showcased the impact of external conditions, such as rainy weather, on indoor environments.
6) *Lighting and Window Orientation:* Variations in illumination levels influenced by window orientations highlighted the importance of strategic window placement for adequate natural lighting, which contributes to occupant comfort and well-being.
7) *IAQ Parameter Comparison (E-1 vs. E-2):* Overall, IAQ parameters consistently demonstrated better values in E-1 compared to E-2 in both settings, signifying the importance of proximity to windows and optimal architectural configurations in maintaining superior IAQ.

The study's findings reinforce the critical role of building design elements, especially window characteristics, spatial layout, and furniture density, in shaping indoor air quality. These insights provide valuable guidance for architects, designers, and building managers in optimizing indoor environments to foster healthier spaces conducive to improved occupant health, well-being, and productivity. Future strategies should prioritize implementing effective ventilation systems, optimizing window placement, and managing interior elements to enhance IAQ and create more habitable indoor environments.

VIII. ACKNOWLEDGMENT

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