Effect of Heatwaves on $PM_{2.5}$ Levels in Apartments of Low-Income Elderly Population. A Case Study using Low-cost Air Quality Monitors

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Highlights

Indoor $PM_{2.5}$ levels increased in 24 tested apartments during heatwaves.

Median hourly I/O $PM_{2.5}$ ratios in most apartments tended to decrease with heatwaves.

The presence of smoking had a negative effect on $PM_{2.5}$ levels during heatwaves and regular days.

Abstract

Heatwaves are known to result in negative health effects in general and especially in vulnerable populations. At the same time, the effect of high outdoor temperatures on indoor air quality is largely unknown. To start filling this knowledge gap, we recruited 24 seniors from 3 low-income housing sites in Elizabeth, NJ, to participate in a study, during which we deployed consumer-grade sensors in their apartments to monitor airborne particulate matter ($PM_{2.5}$) and air temperature. Additionally, one empty apartment, used as a control, and an outdoor station were set up with the same type of sensors. Measurements were performed from July to September 2017. During this period, there were seven days when outdoor temperatures exceeded 90 °F (32 °C), our criterion for heatwave days.

First, we found that the average hourly indoor $PM_{2.5}$ levels varied among apartments and were greatly affected by the presence of smokers. During non-heatwave days, in apartments without smokers, the hourly median $PM_{2.5}$ concentrations ranged from 4 $\mu g/m^3$ to 12 $\mu g/m^3$, while in apartments with smokers, the hourly median $PM_{2.5}$ concentrations ranged from 14 $\mu g/m^3$ to 90 $\mu g/m^3$. More importantly, the indoor $PM_{2.5}$ levels were higher ($p<0.05$) during heatwave days. A statistically significant increase was observed for all apartments, regardless of the building site, presence of smokers, or type of air conditioning. Moreover, since human activity contributes to indoor $PM_{2.5}$, we separated the data into an active period (6:00 am to 10:00 pm) and the rest period (10:00 pm to the next day 6:00 am); the $PM_{2.5}$ increase during heatwaves was statistically significantly higher for both periods.

Overall, our data suggest that higher ambient temperatures could be an important factor for indoor $PM_{2.5}$ exposures. Future investigations should consider several exposure-modifying factors, such as the use of windows and AC, for a more accurate assessment of outdoor conditions affecting indoor exposures.

Keywords

Indoor $PM_{2.5}$, Consumer-grade Sensor, Heatwave, Low-income seniors, active and rest periods, Smoking.

1. Introduction

Climate change and the corresponding ambient temperature increase are urgent worldwide issues. The National Oceanic and Atmospheric Administration (NOAA) reported that the 2020 global surface temperature was 1.76° F (0.98 °C) higher than the average temperature of the twentieth century and that the temperature increase was accelerating (Lindsey and Dahlman 2021). In the United States, the annual average temperature in 2016 was 1.8°F (1.0°C) higher than at the beginning of the last century. Furthermore, it is expected to increase by 2.5°F (1.4°C) over the next few decades, with a projected increase of 3°F to 12°F (1.6°C to 6.6°C) by the end of this century (USGCRP 2018). Similar trends and projections apply to the authors' home state of New Jersey. The state's average annual temperature increased by 3.5°F (1.9°C) from 1895 to 2019 and is expected to increase from 1°F to 6°F (0.6°C to 3.3°C) by 2050 and from 3°F to 9°F (1.7°C to 5.0°C) by 2100 (NJDEP 2020).

The increasing temperature leads to an increasing number of heatwaves (Zografos et al. 2016). While the term "heatwave" does not have a universally accepted and firm definition, it usually means a certain duration of high ambient temperatures, typically above 30 °C (see discussion of definitions below, in 2.2). As warned by climate change experts, the world has experienced increasing heatwave intensity, frequency, and duration, and this trend is projected to increase in the future with climate change (Marcotullio et al.). In major cities across the United States, for example, from the 1960s to the 2020s, the frequency of heatwaves has increased from 2 per year to 6, and the average length of days for a heatwave has increased from about 3 days to about 4 days, and the intensity has increased from 2.0°F (1.1°C) to 2.3°F (1.3°C) above local thresholds (U.S. EPA 2022a).

Heatwaves, or prolonged high temperatures, are important because they negatively affect human well-being. They lead to higher hospital admissions for renal and respiratory diseases (Kovats et al. 2004); across the globe, mortality risk increases with increasing heatwave intensity (Tong et al. 2014; Xu et al. 2016). Heatwaves also lead to crop failures, wildfires, and higher air pollution (Xu et al. 2021). For example, during the 2003 heatwave in Europe, the peak temperature reached 101.3°F (38.5°C) in the UK, and there were estimated more than 50,000 excess deaths in Europe in August 2003 (Brücker 2005); most of the deceased were elderly persons (García-Herrera et al. 2010). During the 2010 heatwave in Russia, the daytime temperature in Moscow reached 100.8°F (38.2°C), and the excess deaths were close to 11,000 between July 6 and August 18, 2010. In addition, grain production in Russia dropped by 20–30 % compared to 2009 (Barriopedro et al. 2011; Loboda et al. 2017; Shaposhnikov et al. 2014). More recently, during June and July 2019, two record-breaking heatwaves occurred in Western Europe, and the temperature increase was associated with an increase in heat-related mortality in affected countries (Rustemeyer and Howells 2021; Vautard et al. 2020).

Overall, during heatwaves, excess deaths increase with age, and the excess mortality of women tends to be higher than that observed in men (Brücker 2005; Dhainaut et al. 2003). Other vulnerable populations include people with respiratory diseases and children (D'Ippoliti et al. 2010; Patel et al. 2019; Son et al. 2012). In addition, low-income populations with poor-quality housing, lack of air conditioning, and lack of access to health and social services face especially high risks of excess death during heatwaves (Michelozzi et al. 2005; Semenza et al. 1996).

The increase in both temperature and air pollution plays an important role in the increasing mortality and morbidity during heatwaves (Brücker 2005; Fischer et al. 2004). The extent of the temperature effect depends on both the daily ambient maximum temperature and the duration of the hot period (Basu 2009; Basu and Malig 2011; Hajat et al. 2006; Xu et al. 2018). While air pollution is associated with morbidity and mortality (Basu 2009), studies also suggest that concentrations of ambient ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter (PM) increase during heatwaves (Churkina et al. 2017; Mavrakis et al. 2021; Wu et al. 2019). This increase in ambient air pollution levels during heatwaves has been associated with increasing calls for ambulances, emergency room visits, hospital admissions, and even death rates (Patel et al. 2019; Stedman 2004). For example, Stedman (2004) estimated that during the first two weeks of the August 2003 heatwave, 21–38% of the total excess deaths in England and Wales were associated with elevated ambient ozone and PM_{10} concentrations. Fischer et al. (2004) suggested that the deaths attributed to heatwaves could have been caused by ambient ozone and PM_{10}.

Most of the existing heatwave studies have focused on outdoor air pollution using air quality data from local meteorological and air quality stations; however, there is a lack of data and studies exploring heatwaves' effect on indoor air quality (IAQ). Since people tend to spend more than 90% of their time indoors (U.S. EPA 1989), IAQ could be an important contributor to the negative health effects caused by heatwaves. However, few studies have investigated a relationship between heatwaves and IAQ. Both monitoring and modeling studies suggest that while natural ventilation systems can provide adequate thermal comfort in warm climates, they might not prevent outdoor pollutants from entering a building (Ahmed et al. 2021; Chen et al. 2019; Liu et al. 2018). For those studies that considered indoor air quality and temperature, they were likely to focus on indoor CO_2 only. For example, Fink et al. (2017) observed that the aggravation of symptoms of cardiovascular disease in the elderly is related to increased heat burden and high indoor CO_2 levels. Abdallah et al. (2014) simulated indoor CO_2 levels during summer using a solar chimney with a new cooling tower. However, these studies didn't present a relationship between the thermal environment and indoor air quality.

Given the rise in ambient temperatures and increasing frequency, intensity, and duration of heatwaves (Perkins-Kirkpatrick and Lewis 2020; Perkins et al. 2012), there is a need to better understand the effect of heatwaves on IAQ and potential negative health effects. Therefore, the presented study focused on the relationship between heatwaves and IAQ, particularly $PM_{2.5}$. Furthermore, the study focused on a vulnerable population – seniors in low-income housing – who are likely to have limited resources to adapt to high outdoor temperatures and the resulting high indoor temperatures and are at higher risks for negative health outcomes (Brücker 2005; Dhainaut et al. 2003; Michelozzi et al. 2005; Semenza et al. 1996). In terms of studied indoor air pollutants, we focused on the particulate matter with aerodynamic diameter below 2.5 µm ($PM_{2.5}$) because it can penetrate deep into the respiratory system as well as the bloodstream and cause various cardiovascular and respiratory diseases (Dominici et al. 2006; Feng et al. 2016; Kampa and Castanas 2008; Martins and Carrilho da Graça 2018; Pope and Dockery 2006; Seaton et al. 1995). $PM_{2.5}$, together with ozone, are criteria pollutants of pressing concern (U.S. EPA 2021; 2022b).

Another novel element of the study was the use of consumer-grade $PM_{2.5}$ monitors to monitor PM levels indoors. $PM_{2.5}$ monitors used to be expensive, but with technological advances, high-quality consumer-grade air quality monitors entered the market. Their low cost allows a wide application, and we were able to deploy air quality monitors in all 24 participating apartments.

Our study focused on the indoor $PM_{2.5}$ levels of the low-income elderly population during heatwave days, and the objectives of this study were:

(1) To examine the effect of heatwaves on indoor $PM_{2.5}$ levels and their indoor/outdoor ratio (I/O);
(2) Since the indoor pollution levels depend on residents' activity (Ferro et al. 2004; Huttunen 2018; Lin et al. 2017), we also examined the heatwave effects on the parameters above during an active period (6:00 am to 10:00 pm) and a rest period (10:00 pm to next day 6:00 am); and
(3) Lastly, since some study participants were smokers, we separately examined indoor $PM_{2.5}$ during heatwave days and non-heatwave days in smokers' and non-smokers' apartments.

2. Methods

2.1 Study sites and participants

The study was performed in the City of Elizabeth, NJ, which has elevated air pollution levels compared to the rest of the state of New Jersey (NJDEP 2017), in part due to the City's proximity to a major highway (I-95) and its connecting bridges, Port of Newark-Elizabeth Marine Terminal, which is the busiest port on the eastern seaboard of the US, and Newark Liberty Airport, a major international travel, and air freight hub.

Using flyers and community meetings, we recruited seniors from three multi-apartment buildings in different parts of the City of Elizabeth. Overall, 24 seniors volunteered to participate in the study. The three study sites were labeled as sites F, L, and M; their locations are shown in Figure 1. The demographic data and description of the apartments are shown in Table 1. All the recruited participants were seniors, 55 to 84 years old. Twenty (84%) were female, and 4 (16%) were male. There were 16 non-smokers and 8 smokers among the participants. There were no smokers in Site L.

Site F is an eleven-story building with 121 apartments. At least one window air conditioner (AC) was available in all participating apartments. A central AC was operating in common areas. Among the nine recruited participants, there were five smokers and four non-smokers. Site L is a four-story senior-only apartment building with 31 apartments. Central AC operated in all individual units and common areas. Four seniors, all non-smokers, were recruited. Site M is a collection of 15 three-story walk-up apartment buildings with 423 apartments. Window ACs were available in most participating apartments except one apartment (M105). Among the eleven participants, there were three smokers and eight non-smokers.

One empty apartment at site M was used as a control, and there was neither human activity nor AC in this apartment. In addition, an outdoor measurement station was also set up at site M in an open area, ~5 meters from the closest building. The outdoor station used the same air quality monitor type as used for indoor measurement, and it was installed in a Stevenson Screen to shield it from the elements (Figure S1). The Stevenson Screen is widely used in meteorological measurements, as it protects devices from rain and direct sunlight while allowing for air circulation.

The sensors were installed in June 2017, and all measurements were conducted simultaneously from July through September 2017.

2.2 Definition of a heatwave and hot days for this study

The definition of a heatwave is not universal due to different population acclimatization and adaptation across regions, and small changes in heatwave definition can lead to significant effects when evaluating heatwave health impact (Ramis and Amengual 2018; Xu et al. 2018; Xu et al. 2016; Yang et al. 2019). Xu et al. (2016) suggested that heatwave intensity plays a relatively more important role than its duration in determining heatwave-related deaths.

We have reviewed the definitions of heatwaves in other countries and by different organizations (Belmin et al. 2007; CMA 2021; Flammia 2021; Huynen et al. 2001; Itani et al. 2020; Kenny et al. 2010; Klenk et al. 2010; KNMI 2019; McCarty 2015; Melisurgo 2020; NOAA 2022; ONJSC 2022; Rey et al. 2007; Rocklöv and Forsberg 2010; U.S. EPA 2022a), and they are discussed in Supplemental Material. For the purpose of this study and following the discussion mentioned above on definitions of heatwaves, we considered all days that reached a temperature of 90°F (32°C) to be heatwave days. Therefore, this operational definition includes both heatwaves (e.g., at least two days with a daily maximum temperature of at least 90°F) and single hot days (e.g., single days with a maximum temperature of at least 90°F).

2.3 Air pollution monitors and their installation

The consumer-grade air pollution monitor AirVisual Node (IQAir, Goldach, Switzerland) was deployed in each recruited unit (apartment). The AirVisual Node uses a proprietary laser source and light scattering sensor AVPM25b to detect particles and report $PM_{2.5}$, PM_{10} concentrations, as well as temperature, relative humidity, and CO_2 concentrations (AirVisual 2016). An AirVisual Node collects data every 10 seconds and provides both internal and remote data storage. As tested in our previous study, the AirVisual Node is highly correlated with a research-grade instrument DustTrak DRX (Model 8534, TSI Inc., MN, USA); AirVisual Node tended to underestimate $PM_{2.5}$ concentrations for Arizona Road Dust and Polystyrene Latex (PSL) aerosol particles types but showed high precision among different AirVisual units (He et al. 2021). Temperature, relative humidity, and CO_2 concentrations measured by AirVisual showed high accuracy compared to an IAQ Meter (IAQ 7545, TSI Inc., MN, USA). Measurements also showed high precision among AirVisual units (He et al. 2021). Since all the indoor and outdoor measurements were performed with the same type of device and the data were used for relative comparisons, the AirVisual data were used as provided by the instruments, without adjustments.

In each participating unit and the empty unit, an AirVisual Node was usually placed on a table in the living room with a Wi-Fi hot spot to upload the data in near real-time. Figure S2 shows an example of the AirVisual placement in residence. Since residents arrange their furniture differently, each monitor's location, height above the floor, or proximity to windows differed from apartment to apartment. For the outdoor measurements, one AirVisual Node and one Wi-Fi hot spot were installed inside a Stevenson Screen (Figure S1) and placed at site M.

2.4 Factors affecting indoor $PM_{2.5}$ levels

Several factors were considered to identify the effects of heatwaves on indoor $PM_{2.5}$ levels.

First, we hypothesized that outdoor temperature affects indoor $PM_{2.5}$ levels. Therefore, all measurement days were separated into heatwave days and non-heatwave days based on the criterion above, i.e., the days when the temperature exceeded 90°F were considered heatwave days, and the rest of the days were considered non-heatwave, or regular, days. The ambient temperature data were obtained from our outdoor measurement station.

Second, $PM_{2.5}$ concentrations were analyzed separately for active and rest periods. Human activities, such as cooking, cleaning, and smoking, are known to contribute to indoor air pollution (Alberts 1994; Duflo et al. 2008; Sexton and Hayward 1987; Vrijheid et al. 2012). Since such activities are usually carried out during day time, we divided each day into active and rest periods. The recommended amount of sleep for the elderly is 7-8 hours (Chaput et al. 2018), and a large percentage of them go to bed by 10:00 pm or earlier (Gislason et al. (1993). Thus, this study defined the rest period from 10:00 pm to 6:00 am of the next day and the active period from 6:00 am to 10:00 pm. Since all recruited participants were seniors, the selected active and rest periods are justifiable and would apply to most of the participants. Since common indoor activities, such as cooking, smoking, cleaning, etc., are more likely to occur during the active period and less likely to occur during the passive period, separate investigation of the active and passive periods allows us to more directly observe the contribution of outdoor conditions to indoor PM during the rest period, when the contribution of indoor sources is typically diminished.

Third, smoking is a very important indoor pollution source, and the difference in PM concentrations between smokers' and non-smokers' units could be very significant. Therefore, we also stratified the $PM_{2.5}$ data by smoking status: eight apartment units housed smokers and sixteen apartments housed non-smokers.

2.5 Data analysis

All data collected by AirVisual Nodes were converted to hourly averages, including temperature, $PM_{2.5}$ concentrations, and the calculated indoor/outdoor ratios (I/O) of $PM_{2.5}$ levels.

The I/O ratio is widely used to show the relationship between indoor and outdoor air pollutant levels (Deng et al. 2017; Heydari et al. 2019; Lim et al. 2011; Pekey et al. 2010). Based on the average hourly indoor $PM_{2.5}$ concentration measured in each unit and the average outdoor $PM_{2.5}$ for the corresponding period, as measured by the outdoor station at site M, we calculated hourly I/O ratios for $PM_{2.5}$ levels as:

$$I/O_{(i)} = \frac{C_{indoor(i)}}{C_{outdoor(i)}} \quad [1]$$

C_{indoor}: average hourly indoor $PM_{2.5}$ concentration measured in each unit, $\mu g/m^3$

$C_{outdoor}$: average hourly outdoor $PM_{2.5}$ concentration measured by the outdoor station, $\mu g/m^3$

i: individual hour

Given the relative proximity of all three study sites (e.g., they were within 3 miles of each other), we assumed that the outdoor data from site M was representative of the other two sites as well.

Data normality was tested using the Shapiro-Wilk normality test (SPSS 2020). Since the $PM_{2.5}$ data and its I/O ratios were not normally distributed, a non-parametric Mann-Whitney test (SPSS 2016b) was used to compare $PM_{2.5}$ concentrations and I/O ratios between heatwave and non-heatwave days for each apartment as well as for each site. Moreover, to compare the $PM_{2.5}$ levels and I/O ratios among three sampling sites, a non-parametric Kruskal-Wallis test (SPSS 2016a) was applied separately for smokers' and non-smokers' units. All statistical tests were run using the Statistical Package for the Social Sciences (SPSS Statistics, International Business Machines Corporation, Armonk, New York, USA).

3. Results

3.1 $PM_{2.5}$ levels during the heatwave and non-heatwave days

The outdoor temperature during the study period is shown in Figure S3. Based on the heatwave definition and the design for this study, there were 7 heatwave days (7/13, 7/19 to 7/22, 8/1, and 9/24) and 85 non-heatwave days from July through September 2017 for all apartments.

The average hourly $PM_{2.5}$ levels for each unit during the heatwave and non-heatwave days are shown in box plots in Figure 2. It is clear that $PM_{2.5}$ levels varied substantially among different units during both heatwave and non-heatwave days. All units showed outlier concentrations, which were defined by the statistical analysis software as a value outside 1.5x of the interquartile range (IQR). Some outliers were as high as 2000 $\mu g/m^3$, indicating that the mean $PM_{2.5}$ concentrations could be substantially affected by the outlier values; the outlier effect on the median $PM_{2.5}$ concentrations should be much less pronounced.

The median hourly $PM_{2.5}$ concentrations ranged between 7 $\mu g/m^3$ to 172 $\mu g/m^3$ during the heatwave days and between 4 $\mu g/m^3$ to 90 $\mu g/m^3$ during non-heatwave days. Although the strongest outliers appeared for 21 units (87.5%) during non-heatwave days, the median hourly $PM_{2.5}$ levels didn't seem strongly affected by the outliers. As a result, according to the Mann-Whitney test, median hourly $PM_{2.5}$ concentrations in all apartments were statistically significantly higher during heatwave days than on non-heatwave days. The differences in median $PM_{2.5}$ values between heatwave and non-heatwave days ranged from 3 to 98 $\mu g/m^3$, depending on the apartment.

We also observed that during the heatwave days, outdoor $PM_{2.5}$ concentrations increased, and that led to the increase in indoor $PM_{2.5}$ concentrations, as shown by the $PM_{2.5}$ levels in the empty apartment, due to the penetration of particles through the building envelope. Another factor contributing to higher indoor $PM_{2.5}$ during heatwave days could be indoor sources. During heatwave days, residents likely limited the use of windows to ventilate their rooms, and airborne particles released from indoor sources remained trapped indoors, thus increasing the $PM_{2.5}$ concentrations.

3.2 I/O ratios of $PM_{2.5}$ concentrations during the heatwave and non-heatwave days

Figure 3 shows the hourly I/O ratios for each unit during heatwave days and non-heatwave days. As could be seen, the I/O varied substantially among different units. Similar to $PM_{2.5}$ levels, the I/O ratios exhibited a high number of outliers. Some individual I/O values were as high as 800-900, while the lowest values were as low as 0.2. Obviously, such a wide range of rates affected the mean I/O values. Thus, median I/O ratios were used to compare the I/Os between heatwave and non-heatwave days, as well as among units and buildings.

The median I/O in the empty apartment (e.g., control) was close to 1 during both heatwave and non-heatwave days, indicating that indoor and outdoor $PM_{2.5}$ concentrations were about the same. It's a sensible result since the empty unit didn't have any indoor sources, and outdoor particles were the main source of particles indoors. A similar I/O was observed in non-smokers' units in site M, where the median hourly I/O ratio ranged from 0.7 to 1.1 during heatwave days and from 0.9 to 1.0 during non-heatwave days. Site L contained only non-smokers' units, and the median values of their hourly I/O ratios ranged from 0.5 to 1.3 during both heatwave and non-heatwave days. The non-smokers' units in site F showed higher I/O (1.2 to 1.9) than the non-smoker's units at the other two sites.

For non-smoking apartments, the indoor $PM_{2.5}$ concentrations in sites L and M were close to or even lower than outdoor $PM_{2.5}$ concentrations, which could be explained by good ventilation or limited indoor sources. In particular, at site L, central AC was used in all apartments as well as common areas. In site M, the combination of window AC and natural ventilation provided sufficient airflow to reduce indoor $PM_{2.5}$, thus keeping I/O lower. On the other hand, at site F, window ACs in all investigated units, plus natural ventilation, failed to remove indoor particles, resulting in higher I/O. In addition, since building F is an older building, more particles were able to penetrate through the building envelope.

A Mann-Whitney test was applied to compare the differences between the hourly I/O ratios during the heatwave and non-heatwave days in each unit. The result indicated that fifteen units had lower median hourly I/O ratios during heatwave days than non-heatwave days; among those fifteen units, the difference was statistically significant for three smokers' and one non-smoker's units. The result suggests that when outdoor $PM_{2.5}$ concentrations increased, indoor $PM_{2.5}$ also increased, but by a smaller fraction. On the other hand, the empty unit, together with F207, M102, and M106, showed statistically significantly higher median hourly I/O values during heatwave days than non-heatwave days; all these units were non-smokers' units, suggesting that, in these units, indoor $PM_{2.5}$ concentrations increased more than the outdoor concentrations during heatwave days. The potential reason is indoor activities that generated particles (e.g., cooking) that became trapped indoors due to the lack of ventilation. In addition, the empty apartment could have received a "contribution" of particles from neighboring apartments and hallways. M105 and L002 showed the same median hourly I/O during the heatwave and non-heatwave days.

3.3 The effect of active and rest periods on $PM_{2.5}$ levels

The hourly $PM_{2.5}$ levels for each unit during active and rest periods are shown in Figure 4. $PM_{2.5}$ levels varied substantially among different units during both active and rest periods. During the active period (6:00 am to 10:00 pm), the median hourly $PM_{2.5}$ levels for different units varied between 7 $\mu g/m^3$ to 140 $\mu g/m^3$ during heatwave days and between 4 $\mu g/m^3$ to 91 $\mu g/m^3$ during non-heatwave days. During the rest period (10:00 pm to 6:00 am the next day), $PM_{2.5}$ concentrations varied between 7 $\mu g/m^3$ to 214 $\mu g/m^3$ during heatwave days and between 4 $\mu g/m^3$ to 87 $\mu g/m^3$ during non-heatwave days. Higher upper outliers were likely to be observed during the active period than the rest period, suggesting that particle-releasing human activities (e.g., cooking, smoking, and cleaning) mostly occurred during the active period. The Mann-Whitney test was applied to compare the $PM_{2.5}$ levels in each apartment between the active and rest periods; the results are shown in Table 2. Sixteen out of twenty-four units showed higher average hourly $PM_{2.5}$ levels during the active period than the rest period during heatwave days, including seven units in site F and nine units in site M; for fourteen of these units, the difference was statistically significant. No statistically significant difference in average hourly $PM_{2.5}$ concentration during active and rest periods was observed for all units in site L, which has central A/C, during heatwave days. During non-heatwave days, fifteen units showed higher $PM_{2.5}$ levels in the active period than the rest period, including all nine units in site F, one unit in site L, and five units in site M; for fourteen units, the difference was statistically significant.

Overall, heatwave days tended to increase indoor $PM_{2.5}$ levels during both active and rest periods compared to non-heatwave days (Figure 4). Mann-Whitney test was used to investigate the difference in median hourly $PM_{2.5}$ levels in each apartment between heatwave and non-heatwave days for both active and rest periods. During the active period, all apartments, except F201, showed higher hourly $PM_{2.5}$ levels during heatwave days than non-heatwave days. This increase was statistically significant for twenty-two of those twenty-three apartments. In addition, all apartments showed higher hourly $PM_{2.5}$ levels during the rest period during heatwave days than on non-heatwave days. For twenty-one of them, this result was statistically significant. In summary, heatwaves were associated with higher indoor $PM_{2.5}$ concentrations during both active and rest periods.

3.4 The effect of active and rest periods on I/O ratios

Figure S4 shows the hourly I/O ratio for each unit during the active (Figure S4A) and rest period (Figure S4B). During the active period, the median hourly I/O ratios varied between 0.5 and 11.8 during heatwave days and between 0.5 to 12.7 during non-heatwave days. During the rest period, the median hourly I/O ratios varied between 0.5 and 18.7 during heatwave days and between 0.5 to 10.9 during non-heatwave days.

A Mann-Whitney test was applied to compare the hourly I/O ratios between active and rest periods; the results are shown in Table 3. Twenty units showed higher median hourly I/O during the active period than the rest period during heatwave days, and for fourteen of them, this difference was statistically significant; these fourteen units also showed higher indoor $PM_{2.5}$ in the active period than the rest period during heatwave days as described in section 3.3. On the other hand, M105, which had no air conditioner, showed statistically significantly lower I/O during the active period than the rest period during heatwave days. During non-heatwave days, eighteen units showed higher I/O in the active period than the rest period, and the difference was statistically significant for seventeen of them.

The heatwave affected the I/O ratios during both active and rest periods. The result of the Mann-Whitney test showed that during the active period, twelve units showed a lower median hourly I/O ratio during heatwave days than non-heatwave days, including all units in site L. For seven of them, this difference was statistically significant. Nine units showed higher median hourly I/O ratios during heatwave days than non-heatwave days; this result was statistically significant for five of them. Twelve units showed lower median hourly I/O ratios during the rest period during heatwave days than non-heatwave days. For seven of them, this result was statistically significant. On the other hand, nine units showed significantly higher median hourly I/O ratios during heatwave days than non-heatwave days, and three of them were statistically significant. The effects of heatwave on the I/O ratio suggest that indoor $PM_{2.5}$ is affected not only by outdoor $PM_{2.5}$ but also by resident behavior.

In some cases, a heatwave affected the I/O differently during the active and rest period. For example, M104 showed statistically significantly higher I/O during the heatwave than non-heatwave days in the active period. Still, it showed statistically significantly lower I/O during the heatwave than non-heatwave days in the rest period. Yet, in other apartments, the heatwave could have had the same directional effect in both active and rest periods. For example, F209 showed statistically significantly higher I/O during heatwave days than non-heatwave days in both active and rest periods.

3.5 The effect of smoking status on $PM_{2.5}$ levels and I/O ratios

Apartments with smokers in sites F and M participated in the study. Smoking is an important contributor to indoor $PM_{2.5}$, and smokers' units tended to have higher $PM_{2.5}$ levels than non-smokers' units during both heatwave and non-heatwave days.

In site F, the highest median hourly $PM_{2.5}$ levels were measured in smokers' units during both heatwave (172 µg/m^3) and non-heatwave days (90 µg/m^3). The lowest median hourly $PM_{2.5}$ levels in site F were registered in non-smokers' units: 14 µg/m^3 on heatwave days and 11 µg/m^3 on non-heatwave days. Similar results were observed for site M, where the highest median hourly $PM_{2.5}$ levels were observed in smokers' units: 82 µg/m^3 on heatwave days and 49 µg/m^3 on non-heatwave days. On the other hand, the lowest median hourly $PM_{2.5}$ levels in site M were in non-smokers' units, which was 13 µg/m^3 on heatwave days and 6 µg/m^3 on non-heatwave days. As shown in Figure 2, the smokers' units had more pronounced (e.g., higher concentration) outliers than non-smokers' units in most cases. These outliers are likely due to the release of particles during smoking events. According to the Mann-Whitney test, smokers' units showed statistically significantly higher $PM_{2.5}$ levels than non-smokers' units in the same site during both heatwave and non-heatwave days (Table 4).

Meanwhile, the average hourly $PM_{2.5}$ levels in smokers' units increased by 33.4 µg/m^3 (38%) during heatwave days compared to non-heatwave days. For comparison, this increase in absolute $PM_{2.5}$ concentration was higher than increases in non-smokers' units (5.0 µg/m^3, 42%) and the empty unit (7.8 µg/m^3, 95%). This substantial increase in smokers' units could be due to a combined effect of the heatwave and personal behavior, like smoking and window opening. Window opening is an important variable in IAQ, and data from this study are presented in a separate publication (Tsoulou et al. 2023). Tsoulou et al. found that sometimes there was a thermal and air quality trade-off with natural ventilation. For example, to avoid increasing heat index during heatwave days, some residents may be less likely to open windows. Thus, the increased stay indoors during heatwave days could have led to the accumulation of indoor-produced $PM_{2.5}$, specifically from more frequent smoking, thus leading to higher $PM_{2.5}$ increases in smokers' units.

The smoking status also affected the I/O ratios of $PM_{2.5}$ levels, and smokers' units tended to have higher I/O than non-smokers' units. In site F, the median hourly I/O for smokers' units varied between 4.4 and 14.0 during heatwave days and between 5.1 and 12.2 during non-heatwave days; while I/O for the non-smokers' units in site F varied between 1.1 to 1.9 during heatwave days and between 1.3 to 2.4 during non-heatwave days. Site M also showed higher ranges of I/O in smokers' units than in non-smokers' units. Here, the median hourly I/O for smokers' units varied between 1.4 and 6.2 during heatwave days and between 1.4 and 5.6 during non-heatwave days; and the I/O for the non-smokers' units in site M varied between 0.7 to 1.1 during heatwave days and between 0.8 to 1.0 during non-heatwave days. According to the Mann-Whitney test, for both sites F and M, smokers' units had statistically significantly higher median I/O than non-smokers' units (Table 5) during both heatwave and non-heatwave days.

Although smoking status substantially affected indoor $PM_{2.5}$ levels and the I/O ratios, it didn't modify the heatwave effect on indoor $PM_{2.5}$ levels. According to the Mann-Whitney test, the median hourly $PM_{2.5}$ levels were statistically significantly higher during heatwave days than during non-heatwave days for all smokers' and non-smokers' units (Figure 2).

3.6 Differences between sites

The data above described the effects of heatwave on hourly $PM_{2.5}$ levels and the I/O ratios at a unit (i.e., apartment) level. Here, substantial unit-to-unit variability in $PM_{2.5}$ levels and I/O ratios was observed, likely due to different indoor activities by the residents and the resulting PM sources. Since the three investigated buildings differ in their design and ventilation systems, a site-to-site difference should also be considered, as that might help understand the effects of heatwaves on $PM_{2.5}$ levels and the I/O ratios at the site level. Thus, the $PM_{2.5}$ concentrations and I/O data were aggregated for each site (Figures 6 and 7).

Figure 5A shows each site's aggregated hourly $PM_{2.5}$ levels without separating apartments by smoking status. Here, site L showed the lowest median hourly $PM_{2.5}$ levels (10 $\mu g/m^3$ during heatwave days and 6 $\mu g/m^3$ during non-heatwave days). Site M had the median hourly $PM_{2.5}$ levels of 15 $\mu g/m^3$ during heatwave days and 9 $\mu g/m^3$ during non-heatwave days. Site F showed the highest median hourly $PM_{2.5}$ levels among the three sites, which were 30 $\mu g/m^3$ during heatwave days and 21 $\mu g/m^3$ during non-heatwave days. According to the Mann-Whitney test, $PM_{2.5}$ levels during heatwave days were statistically significantly higher than during non-heatwave days for all sites. The same result was observed when analyzing $PM_{2.5}$ levels for smokers' and non-smokers' units in each site separately (Figure 5B), suggesting that even for smokers' apartments, which already have elevated $PM_{2.5}$ levels, heatwave days resulted in even higher $PM_{2.5}$ concentrations, e.g., smoking status didn't modify the positive association of heatwave and $PM_{2.5}$ levels at the site level.

The I/O data for the three sites are presented in Fig. 7. When the hourly I/O data for each site were aggregated regardless of the smoking status (Figure 6A), site L showed a median hourly I/O of less than 0.75 for both heatwave and non-heatwave days, site M showed median hourly I/O around 1 and site F showed much higher median hourly I/O (2.1 during heatwave days and 2.5 during non-heatwave days). Here, sites F and L showed statistically significantly lower I/O during heatwave days than non-heatwave days, while site M showed the opposite result, although the absolute difference in the median I/O value was small: 1.1 during heatwave days and 1 during non-heatwave days. When the smoking status is considered (Figure 6B), we observe that the smokers' units in sites M and F showed lower median hourly I/O during heatwave days than non-heatwave days, and for site F, this observation was statistically significant. Meanwhile, non-smokers' units at site L also showed a statistically significantly lower median hourly I/O ratio during heatwave days than non-heatwave days.

According to the Kruskal-Wallis test for the $PM_{2.5}$ levels and their I/O ratios measured in non-smokers' units, each site was statistically significantly different from the others (Tables 6 and 7). For example, in non-smokers' units, site F had a median hourly $PM_{2.5}$ of 12 $\mu g/m^3$, and it was statistically significantly higher than the median hourly $PM_{2.5}$ concentration in site L (6 $\mu g/m^3$) and site M (8 $\mu g/m^3$). Site L had a median hourly I/O of 0.75, which was statistically significantly lower than that for site F (median hourly I/O = 1.3) and site M (median hourly I/O = 1). The difference in the $PM_{2.5}$ and I/O was also observed between sites F and M when only smokers' units were considered. Smokers' units at site F had a median hourly $PM_{2.5}$ of 50 $\mu g/m^3$ and median hourly I/O of 6, which were statistically significantly higher than the values for smokers' units at site M, which had the median hourly $PM_{2.5}$ of 21 $\mu g/m^3$ and median hourly I/O of 2.25.

Since unit M105 was the only unit without AC, the statistical tests above were performed by including and excluding data from M105. The inclusion or exclusion of those data had no effect on the statistical test results. One possibility is that the values measured in this single unit were not extreme enough to affect the overall results. Another possibility is that the effect of using AC on indoor $PM_{2.5}$ levels was not strong. More units without AC need to be analyzed to investigate these possibilities. The data shown in Figures 6 and 7 are without data from M105.

4. Discussion

4.1 The effect of heatwaves on indoor $PM_{2.5}$ levels

NJDEP (2020) showed that heatwaves affected ambient air quality, including ground-level O_3 and $PM_{2.5}$ concentrations. They suggested that the indoor $PM_{2.5}$ levels would likely increase when the outdoor $PM_{2.5}$ levels increase due to storms and wildfires. Other studies showed that extreme events like wildfires can increase the levels of indoor pollutants such as $PM_{2.5}$, black carbon, brown carbon, CO, and NO_2 (Henderson et al. 2005; Pauraite et al. 2021; Rajagopalan and Goodman 2021; Shrestha et al. 2019). However, because of limited indoor air quality data during heatwaves, an association between heatwaves and IAQ parameters, including indoor $PM_{2.5}$, still needs to be explored. This study begins to address that gap. Our data showed that indoor $PM_{2.5}$ was statistically significantly higher during heatwave days than on non-heatwave days (Figures 2 and 4).

In most cases, this trend was observed during both active and rest periods, i.e., the effect was observed when there likely were indoor sources of $PM_{2.5}$ (active period) and limited indoor sources (passive period). At the same time, although indoor $PM_{2.5}$ increased during heatwave days, its increase was not proportional to the increase in outdoor $PM_{2.5}$ concentrations during heatwave days compared to non-heatwave days. That resulted in a decrease in the I/O ratio during heatwave days in some apartments, including three, with a statistically significant decrease. On the other hand, in the empty apartment as well as three other apartments, the I/O was statistically significantly higher during heatwave days than non-heatwave days (Figure 3). When active and rest periods are considered separately, most apartments showed lower I/O during heatwave days than non-heatwave days in both active and rest periods. And this observation was statistically significant for some apartments. At the same time, the I/O ratios in some apartments were differently affected by heatwaves during active and rest periods. These differences among apartments could be explained by the different behaviors of the resident during the active and rest periods. In addition, particle sources in neighboring apartments could have also affected particle levels in investigated apartments. This is likely most pronounced in buildings without central AC.

Some studies took outdoor temperature into account when measuring indoor PM concentrations. Although they didn't specifically study the effect of heatwaves, their results could still be used for comparison. For example, Patton et al. (2016) presented 24-hr $PM_{2.5}$ data of 16 apartments measured three times a year and indicated that indoor $PM_{2.5}$ I/O decreased by 3%–6% per 1 °C increase in outdoor temperatures. Thus, that study and our study showed an increase in temperature (or the presence of a heatwave) can decrease the I/O. On the other hand, Meng et al. (2009) found that the fraction of the ambient $PM_{2.5}$ concentration found indoors reached its maximum when the outdoor temperature was approximately 20 °C and decreased at higher and lower temperatures. This was explained by the use of windows, heating and cooling equipment, and the additional airflow driven by the increased indoor-outdoor temperature difference (Meng et al. 2009). This observation helps explain why the indoor $PM_{2.5}$ concentrations in our study didn't increase proportionally as outdoor $PM_{2.5}$ concentrations during heatwave days.

4.2 $PM_{2.5}$ exposure

Our data shows that $PM_{2.5}$ indoor levels during heatwave days were higher than during non-heatwave days: the mean $PM_{2.5}$ level increased by 33.4 µg/m^3 in smokers' units and by 5.0 µg/m^3 in non-smokers' units. While our study lasted only for 3 months and health effects due to heatwaves were not directly investigated, we can infer potential health risks due to the increase in $PM_{2.5}$ levels based on the existing literature. Zanobetti et al. (2009) found that for a 10 µg/m^3 increase in 2-day averaged $PM_{2.5}$ concentration, there was an increase of emergency hospital admissions for cardiac causes by 1.89% (95% CI: 1.34- 2.45), myocardial infarction by 2.25% (95% CI: 1.10- 3.42), congestive heart failure by 1.85% (95% CI: 1.19- 2.51), diabetes by 2.74% (95% CI: 1.30- 4.2), and respiratory disease by 2.07% (95% CI: 1.20- 2.95). Orellano et al. (2020) reviewed the evidence of short-term exposures to $PM_{2.5}$ and cause-specific mortality and found a positive association between short-term exposure to $PM_{2.5}$ and all-cause mortality, as well as cardiovascular, respiratory, and cerebrovascular mortality. For every 10 µg/m^3 increase in short-term (the day of death and the previous day) $PM_{2.5}$ exposure, there was a 2.8% increase in mortality (95% CI = 2.0–3.5) (Kloog et al. 2013); even higher percent increase in mortality associated with $PM_{2.5}$ was observed in households with lower home values, lower median income, and people > 65 years old (Wang et al. 2016).

Increased $PM_{2.5}$ concentrations during heatwave days in our study could be considered short-term exposure events, and, based on the existing literature, even short-term increases could lead to increased morbidity and mortality in the exposed population. While the study timeframe was short and the number of participants not high enough to directly observe those negative health effects, the observed increase in $PM_{2.5}$ concentration due to heatwaves provides impetus to conduct broader studies on health effects due to heatwaves. In addition, negative health risks for smokers are likely even higher due to high baseline $PM_{2.5}$ levels (e.g., during non-heatwave days) and the larger absolute increase in $PM_{2.5}$ concentrations.

4.3 Comparison of observed $PM_{2.5}$ levels and I/O ratios with other studies in non-smokers' apartments

The indoor $PM_{2.5}$ levels measured in this study are similar to results from other studies. Our study showed that the hourly indoor $PM_{2.5}$ levels for non-smokers' units had an average concentration of 14.7 µg/m^3. Meng et al. (2005) measured the indoor $PM_{2.5}$ levels at Elizabeth, NJ, the same city as our study, from 1999 summer to 2001 spring using a single-jet, $PM_{2.5}$ Harvard impactor (Marple et al. 1987) with Teflon filters (37 mm, 2 µm pore, Pallflex Gelman Scientific, Ann Arbor, MI, USA). Their observed indoor $PM_{2.5}$ level for non-smokers' units was 20.1 µg/m^3. Baxter et al. (2007) measured $PM_{2.5}$ levels in 43 low-income families in Boston, Massachusetts, across multiple seasons from 2003 to 2005 by using Harvard Personal Environmental Monitor, a size-selective inertial impactor with 37 mm Teflon filters. Smoking was not considered as a separate variable as smoking was reported only in 4 out of 64 sampling sessions. They reported a mean $PM_{2.5}$ value of 20.3 µg/m^3 (Baxter et al. 2007). Stamatelopoulou et al. (2019) measured $PM_{2.5}$ in 13 residences across Athens, Greece, during summer using Grimm 1.108 optical particle counter (Grimm Technologies Inc., Douglasville, GA, USA). The mean indoor $PM_{2.5}$ concentration was 9.4 µg/m^3 for residences without smokers.

The I/O ratio depends on indoor and outdoor $PM_{2.5}$ levels. Our study showed that the I/O ratio for $PM_{2.5}$ also varied among units; the median I/O ranged between 0.5 and 1.4 for non-smokers' units and was similar to the I/O in other studies. For example, Stamatelopoulou et al. (2019) observed that I/O had a range of 0.19–1.55 with a median value of 0.79 in 13 residences in Athens, Greece. Baxter et al. (2007) observed that the median I/O ratio was 1.14 for low-income families in Boston, MA. Castro et al. (2010) collected $PM_{2.5}$ samples in a single apartment (no smokers) during the winter of 2008 in Oporto city in Portugal and found an I/O of 0.98. Overall, the I/O ratios for non-smokers' units in these studies were under or slightly above 1.

The difference in indoor $PM_{2.5}$ concentrations among different studies could be due to the differences in study locations, sampling seasons, measurement devices, different ventilation strategies, and differences in particle-releasing human activities that partially could be culturally driven, e.g., the use of candles or incense (Patton et al. 2016). In this study, we eliminated some of these variables by performing simultaneous measurements and using the same measurement methodology, allowing us to consider building- or location-driven differences in indoor $PM_{2.5}$. For non-smokers' units, site F had the mean hourly $PM_{2.5}$ level of 27.7 µg/m^3, which was higher than for site M (11.8 µg/m^3) and L (9.2 µg/m^3), and the difference between any two sites was statistically significant (Table 6). Adgate et al. (2002) also showed that $PM_{2.5}$ levels could vary community-to-community even in the same city. They measured $PM_{2.5}$ levels in a population of nonsmoking adults from three residential communities in the Minneapolis-St. Paul-Bloomington metropolitan area in the United States during the spring, summer, and fall of 1999. The mean $PM_{2.5}$ values were 10.6 µg/m^3, 17.4 µg/m^3, and 14.2 µg/m^3 for the three sites, with the data from the first site being statistically significantly lower than from the other two. Possible explanations of the site-to-site differences were different local sources and differences in local meteorology (Adgate et al. 2002). Differences in our study could be explained by the building age and their infrastructure. Site L has a central AC and is the newest building among the three sites, built in 2011, while site F was built in 1967, and site M was built in 1938. Although site L is located at an intersection of two streets, it still had the lowest $PM_{2.5}$ concentration among the three sites, likely due to a tighter building envelope and central AC. Site M is a community with multiple (15) buildings. Most of the apartments at site M use window AC and has operable windows, which facilitate natural ventilation. Thus, site M showed a relatively low $PM_{2.5}$ level. Site F, which had the highest $PM_{2.5}$ concentration, is a fully-occupied multi-story building with 121 apartments. There might not be enough windows or use to provide sufficient ventilation to minimize particle contribution from neighboring apartments and common spaces. Also, the role of local sources should not be excluded and should be analyzed separately. However, we do not have sufficient information to offer this analysis as part of this paper.

4.4 The effect of smoking

Tobacco smoke is a known important contributor to indoor $PM_{2.5}$, and smokers' units show much higher $PM_{2.5}$ levels than non-smokers' units (Canha et al. 2019; Chao and Wong 2002; Lu et al. 2020; Russo et al. 2014; Stamatelopoulou et al. 2019). Our study observed the same during both heatwave and non-heatwave days (Figure 5 and Table 4). However, the measured indoor $PM_{2.5}$ levels in smokers' units could be very different among studies. For example, the mean indoor $PM_{2.5}$ concentration for smokers' units in our study was 84.8 $\mu g/m^3$. It is relatively high compared to the $PM_{2.5}$ levels measured in smokers' residences in Athens, Greece, which had a mean $PM_{2.5}$ level of 14.3 $\mu g/m^3$ (Stamatelopoulou et al. 2019); in rural (Ponte de Sor) and urban (Lisbon and Vila Franca de Xira) areas of Portugal the mean indoor $PM_{2.5}$ level in five smokers' apartments was 61.2 $\mu g/m^3$ during the sleeping period (Canha et al. 2019); in Hong Kong, China, the mean indoor $PM_{2.5}$ level of 10 smokers' apartments was 50.6 $\mu g/m^3$ (Chao and Wong 2002); the modeled mean indoor $PM_{2.5}$ concentration was 51 $\mu g/m^3$ during a smoking event based on the data collected in 53 apartments northwestern Beijing, China, that randomly selected for analysis (Lu et al. 2020).

The I/O of $PM_{2.5}$ levels for smokers' units also varied among studies. The range of median I/O in our study was between 1.42 and 11.57, which was higher than the I/O measured in residences in Athens, Greece, during the summer of 2015 (1< I/O <1.55) (Stamatelopoulou et al. 2019), and in residences of Alexandria, Egypt during spring of 2010 (0.87< I/O <1.65) Abdel-Salam (2015). The $PM_{2.5}$ levels and I/O ratios in smokers' apartments could be affected by the frequency of smoking, the choice of smoking indoors or outside, and the choice of open/closed windows. Thus, it largely depends on the residents and their choices. While a questionnaire was administered, it did not specifically ask whether the participants smoked in their apartments or outdoors.

Jones et al. (2000) indicated that for non-smokers' families, I/O was lower than 1 between 0:00 and 8:00 o'clock (0 to 8 am) and much higher than 1 during 17:00 and 24:00 o'clock (5 pm-midnight) when particles were generated by human activities such as cooking. On the other hand, I/O was above unity for most of the day for smokers' apartments, indicating that smoking was a dominant source of indoor particles. Similar results were observed in our study: smokers' units had I/O higher than unity for the entire day. However, since our study divided the day into active and rest periods, we can only state that for most smokers' units, the I/O was higher during the active period (6:00 am to 10:00 pm, median I/O ranged between 0.5 and 12.7) than the rest period (10:00 pm to next day 6:00 am, median I/O ranged between 0.5 and 18.7). Specifically, 6/8 smokers' units showed higher I/O in the active period than the rest period during heatwave days, and 7/8 smokers' units showed higher I/O in the active period than the rest period during non-heatwave days (Table 3).

4.4 Ventilation

Different ventilation strategies can affect indoor $PM_{2.5}$ levels. For households with different natural ventilation strategies, Pope and Dockery (2006) showed that households that open doors and close windows for ventilation had lower $PM_{2.5}$ levels than households that open both doors and windows for ventilation. Chao and Wong (2002) found that households that frequently open windows had higher air change rates and tended to have lower I/O compared to households that always had the windows closed, resulting in lower air change rates. In naturally ventilated buildings with low indoor particle sources, the indoor and outdoor $PM_{2.5}$ levels are close, and the average I/O ratio is close to one. However, when there are strong indoor sources, the indoor $PM_{2.5}$ levels are less correlated with outdoor levels, and the I/O is higher than one (Chao and Wong 2002; Martins and Carrilho da Graça 2018; Monn et al. 1997; Morawska et al. 2001; Zhou et al. 2016). Similar results were observed in our study. Here, apartments in sites M and F had a natural-mechanical ventilation system but used natural ventilation in most cases, especially during non-heatwave days. The empty apartment and the non-smokers' apartments in site M had lower indoor particle sources resulting in I/O ratios close to one. In contrast, the smokers' apartments had strong indoor sources leading to I/O much higher than one (Figure 3).

For buildings that use mechanical ventilation systems, the system's filter efficiency plays an important role in limiting the entry of outdoor particles. A high-efficiency filter can reduce the indoor $PM_{2.5}$ originating from outdoor sources and reduce I/O. However, buildings without any central filtration or with low efficiency or damaged filters behaved the same as buildings with natural ventilation (Martins and Carrilho da Graça 2018). Thus, central AC with a high-efficiency filter can reduce indoor $PM_{2.5}$ levels and I/O ratios (Jung et al. 2015; Liu et al. 2021; Ren et al. 2017). Similar results were observed in our study: site L had central AC and lower $PM_{2.5}$ levels than sites F and M. Site L also had an I/O less or close to one. Therefore, the cleaning, maintenance, and replacement of filters in the ventilation system are important to reduce indoor PM exposure. On the other hand, the effect of using window ACs on PM concentrations may differ among ACs. The use of window ACs can either slightly reduce indoor PM mass concentrations compared to apartments without window ACs in the same building (Patton et al. 2016), or they could be inefficient at particle removal, thus even leading to particle accumulation indoors (Oh et al. 2014).

In our study, sites M and F used window ACs, and site L used central AC. For non-smokers' units, site L showed statistically significantly lower $PM_{2.5}$ than site F and site M, probably due to the use of central AC, which resulted in a higher air exchange rate and the filtration of particles. The actual window usage is an important variable for IAQ and will be examined separately. One unit that didn't install AC had the same median I/O during both heatwave and non-heatwave days.

4.6 Study limitations

When separating participating apartments into smokers' and non-smokers' units, our questionnaire asked only whether any of the residents smoked, without enquiring about the number of cigarettes smoked per day, whether they were smoked indoors or by an open window, or if it was a single-person or multi-person activity. A more detailed questionnaire and the use of windows during smoking will be addressed in a separate study (Tsoulou et al. 2023). Despite this limitation, it is clear that $PM_{2.5}$ levels in smokers' apartments were substantially higher, suggesting that smoking was a frequent activity undertaken inside an apartment.

When considering different ventilation strategies, our study separated the apartments into those that had central AC and window AC units. However, we didn't consider AC usage data, e.g., how long an AC was used in each apartment, its filtration efficiency, or the air exchange rate when using an AC. Also, there was only one unit that didn't use AC, which is obviously not sufficient to represent the units without AC. Therefore, AC usage will be addressed in a separate study.

The outdoor station and empty unit were located at Site M. While the study sites are within a 1.7-mile radius, local sources might have affected the outdoor $PM_{2.5}$ concentrations and their effect on indoor

$PM_{2.5}$ and the I/O ratios. Therefore, future studies must consider a local outdoor PM measurement for all sites.

The potential decrease in sensor accuracy over time has also been considered. Zamora et al. (2020) indicated that AirVisual exhibited an accuracy of about 86% and coefficient of determination $R^2 = 0.99$ over a 1-year of continuous indoor monitoring when compared to a personal DataRAM™ pDR-1200 (Thermo Scientific Corp., Waltham, Mass.). They also reported very good agreement between AirVisual units. Since the AirVisuals used in this project were all newly ordered, and the experiment lasted for only 3 months, we reasonably assumed that the accuracy and precision of AirVisuals used in our study did not have impactful decreases.

5. Conclusions and perspective

This study investigated the effects of heatwaves on indoor PM by measuring $PM_{2.5}$ levels in 24 low-income senior units in Elizabeth, NJ, from July to September 2017 using consumer-grade air quality monitors; the outdoor $PM_{2.5}$ was also monitored. Overall, we found that the indoor $PM_{2.5}$ levels during heatwave days were higher than during non-heatwave days. The heatwaves had similar effects on indoor $PM_{2.5}$ levels and their I/O ratios for all apartments, regardless of the building sites, the AC type, and individual behaviors such as smoking. Also, units with smokers had higher $PM_{2.5}$ levels than those without smokers, but they both showed higher $PM_{2.5}$ levels during heatwave days than non-heatwave days. During heatwave days, the average hourly $PM_{2.5}$ levels increased by 33.4 $\mu g/m^3$ in smokers' units and 5.0 $\mu g/m^3$ in non-smokers' units compared to non-heatwave days. The I/O ratios during heatwave days were lower than during non-heatwave days in most cases, but there was great variability among apartments. In general, during heatwave days, the average hourly I/O decreased by 6.9 in smokers' units and 1.1 in non-smokers' units compared to non-heatwave days. We also observed that indoor $PM_{2.5}$ greatly and significantly varied among the three sites; we posit that differences in the buildings' age and infrastructure (central AC vs. window AC) are likely explanations.

It is clear that air conditioner usage data and window opening and closing would play an important role in indoor air quality and ventilation strategies to address indoor air quality. The role of these variables is explored in a separate publication (Tsoulou et al. 2023). Future studies of IAQ should also strive to acquire more detailed data on indoor activities that lead to pollutant generation, such as smoking and its frequencies, that would help explain and eventually improve IAQ. It should also be mentioned that more data are needed on the real-world effectiveness of various strategies to reduce exposure to airborne PM in buildings, such as using portable air cleaners or Do-It-Yourself inexpensive air cleaners. The latter gained a lot of popularity in the past couple of years due to increased concerns about IAQ precipitated by the COVID-19 pandemic (Myers et al. 2022). In addition, a stronger and more convincing anti-smoking campaign might help reduce smoking inside the apartments, thus minimizing the presence of PM indoors.

Author contributions

Ruikang He contributed to conceptualization, data curation, formal analysis, investigation, methodology, original draft, review, and editing.

Ioanna Tsoulou contributed to data collection and review.

Sanjeevi Thirumurugesan, Brian Morgan, and Stephania Gonzalez contributed to data collection and sensor installation.

Deborah Plotnik and Jennifer Senick contributed to the study concept and coordination.

Clinton Andrews contributed to conceptualization, funding acquisition, coordination, supervision, methodology, and resources.

Gediminas Mainelis contributed to conceptualization, funding acquisition, supervision, review, and editing.

All authors have approved the manuscript.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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