Article

Indoor and Outdoor Particle Number Concentration in the Sapienza University Campus of Rome

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Abstract: Exposure to ultrafine particles has been associated with short- and long-term effects on human health. The object of this paper was to assess Particle Number Concentration (PNC) and size distribution in a university environment and study the indoor/outdoor relationships. Measurements were carried out using co-located (indoor/outdoor) condensation particle counters and size spectrometers during two seasonal periods characterized by different meteorological conditions at five selected classrooms different for size, capacity, floor and use destination. PNC was dominated by particles in the ultrafine mode both indoor and outdoor. The indoor/outdoor ratios were on average between 1 and 1.2 in the summer and between 0.6 and 0.9 in the winter. Mostly the differences found among classrooms could be related to the condition of use (i.e., crowding, natural air exchange, air conditioning, seasonality). Only little differences were found among PNC measured immediately outside the classrooms. Based on information taken during the measurement campaigns, on the classrooms condition of use, it was possible to assess as a source of indoor particles in the coarse mode, the presence of students and teachers.

Keywords: ultrafine particles; particle number concentration; indoor measurements; particle modal size; indoor-outdoor ratios; source strength

1. Introduction

The dimensional range below 0.1 μm is defined as ultrafine mode or Aitken nuclei (0.02 < Dp < 0.1 μm). Particles in this size range are called ultrafine (UFP). They are numerically prevalent, compared to the total detectable in an air sample, although they contribute little to the overall mass.

In recent years, the results of several studies have contributed to increasing the knowledge on population exposure [1–3], spatial variability [4,5] and indoor exposure [6–8], toxicological mechanisms [9,10] and cardiovascular effects [11,12], taking into consideration alongside the classical metrics (PM_{10} and PM_{2.5}) also new metrics based on Particles Number Concentration (PNC) and on the size distribution of ultrafine particles. Exposure to ultrafine particles has been associated with short and long-term effects on human health [13]. However, the specific or differential toxicity of UFP with respect to particles of other fractions has not yet been established with certainty [13,14].

It should be considered that, at present, in consideration of the insufficient epidemiological evidence from which to derive a conclusion on the exposure–response relationship, there are no UFP-specific guides or reference values [15].

Airborne particles are generated by a great variety of natural and anthropogenic sources, both indoor and outdoor. The UFP levels in confined environments and the
relative temporal variability are strongly influenced by the external air infiltration, and therefore by the quality of the latter [16]. The ways in which the air exchange is carried out in the case of natural ventilation and the effectiveness of the treatment systems in the case of forced ventilation are decisive aspects in the temporal modulation of indoor PM levels and in the differences that can be found with the outdoor air [16–18]. An important role in the diffusion of particulate matter in various environments, and in the effectiveness of the removal mechanisms, is also represented by the internal microclimatic conditions (temperature, humidity, air velocity) [19,20].

Furthermore, different indoor sources can hide the dependence of indoor levels on outdoor levels, so much so that in many cases the temporal trends are poorly correlated and the indoor/outdoor concentration ratios are greater than one. The impact of indoor sources depends on the duration and frequency of the emission, which obviously depends on the habits of the occupants; consequently, the impact of these sources is widely variable [21,22].

The main sources that significantly influence indoor PM levels in the ultrafine mode, so as to modify indoor/outdoor ratios are: tobacco smoke, cooking foods (in particular frying) and the use of wood for heating, in particular in open chamber fireplaces [23–27].

Other sources of indoor PM may be relevant, such as the combustion products of incense and candles, the use of sprays and diffusers, emissions from printing and copying devices [28–34]. These sources have the characteristic of producing a large number of particles in the unit of time, mainly in the range of ultrafine particles. The estimated UFP emission rate ranges from $0.1 \times 10^{12}$ to $5 \times 10^{12}$ particles $\text{min}^{-1}$ [35].

It is therefore important to follow the evolution of phenomena caused by emission sources that vary rapidly over time, in order to identify the source responsible for the release of particles and to highlight acute exposures. Furthermore, it may be important to study the decay over time of the detected concentrations determined by the interruption of emissions or by the activation of abatement systems, for example to assess the effectiveness of prevention and protection measures [22]. Conventional monitoring devices are not very suitable for these purposes, since they typically allow to obtain information on the determined parameter with low temporal resolution (hour or day) [36]. The instruments based on optical techniques, on the other hand, allow to follow the trend over time of the parameter of interest (mass concentration, concentration of particles expressed in number) through high time resolution measurements (with the possibility of having up to one measurement per second) [37]. Furthermore, when optical techniques are coupled to techniques based on the electric mobility of particles, these assessments can be extended to the size distribution of concentrations (in number or mass) over the entire spectrum of diameters relevant for human exposure [15,38].

The aims of the study carried out in the framework of the VIEPI (Integrated Evaluation of Indoor Particulate Exposure) project [39] were to:

- Evaluate the PNC trends in the university environments under study through high temporal resolution measures, to highlight transient phenomena and to estimate the PNC levels and their seasonal variability in different environments in terms of size, level of occupation, altitude from the road level, destination prevalent use and air exchange methods [40];
- Identify the relationships between indoor and outdoor and explain how the variability of outdoor PNC affects indoor levels, in a context of real use of the environments.
- Estimate the average indoor/outdoor ratios and their seasonal variability.
- Understand the role of indoor sources other than combustion, such as the presence of people, on PNC levels in the different dimensional fractions.

2. Materials and Methods

2.1. Site Description

Five classrooms used for teaching activities (lectures, seminars, exams) were selected in the Physics Department of the Sapienza University of Rome (Enrico Fermi building, coordinates: $41^\circ54'06''\text{N}; 12^\circ30'57''\text{E}$). A scheme of the sampling sites is shown in Figure 1.
2. Materials and Methods

2.1. Site Description

Five classrooms used for teaching activities (lectures, seminars, exams) were selected. The A3 classroom faces north and looks towards the center of the University Campus. The A4 classroom, on the internal courtyard, and looks towards the border of the Campus and a traffic street, about 50 m away. The Computer Room (CR) faces East on the same courtyard as A4.

To evaluate the possible observable differences between classrooms located on the same level (the 2nd floor), but with different orientation of the windows compared to the outside, three classrooms (A3, A4, and the Computer Room) were chosen. The A3 classroom faces north and looks towards the center of the University Campus. The A4 classroom, on the internal courtyard, and looks towards the border of the Campus and a traffic street, about 50 m away. The Computer Room (CR) faces East on the same courtyard as A4.

To evaluate the possible observable differences between classrooms located at different heights from the street level, contemporary measurements were carried out at the Lecture Hall (LH, ground floor), which overlooks both the south and north sides, and at the A7 classroom (4th floor, faces South).

The A3, A4, A7 classrooms had identical volume (570 m$^3$), geometry and capacity (130 seats). They were naturally ventilated and a door in each classroom allowed accessing to the emergency staircase with an outward opening on the east side.

Compared to classrooms A3, A4 and A7, LH had double the volume (1150 m$^3$) and capacity (250 seats). CR is smaller than the others (450 m$^3$) and with less capacity as well (100 seats).

Both LH and CR were equipped with air conditioning devices, manually managed by the occupants.

Overall, hot-water radiators as heating appliances were operating during winter.

The classrooms were cleaned every working day before the lessons (6:00–8:00 a.m.). Information on the number of occupants, type of activity, opening of doors and windows, and type of ventilation (natural or mechanical) in each classroom were collected simultaneously, on an hourly basis, during the day from 8:00 a.m to 6:00 p.m. through visual inspections by filling a form.

2.2. Instrumental Description

Total Particle Number Concentration (TPNC) was simultaneously measured indoors and outdoors using co-located condensation particle counters (CPC3007, TSI Inc., Shoreview, MN, USA, min detectable particle (D50): 10 nm, time resolution: 1 s). The isopropyl alcohol reservoir has a capacity allowing 6–8 h of continuous operations. Thus, a 4-h measurements cycle was adopted (8:00 a.m.–12:00 a.m.; 2:00 p.m.–6:00 p.m.). Between each cycle, both isopropyl alcohol cartridge and batteries were changed together with zero check and leak proof test following the manufacturer instructions. Indoors, the samplers were located in a rack allowing for the sampling tube to be at 1.5 m from the ground. The outdoor sampling was performed immediately outside corresponding to the windows rooms, by passing the sampling tube from inside to outside, through a small hole.

In CR and LH, at the same time as the aforementioned measurements, size-resolved PNC measurements were carried out to study the temporal variability of the size distribution in number of particles. Indoor and outdoor number size distribution (0.3 ÷ 10 um) in
17 channels were performed using two optical particle sizers (OPS 3330 TSI Inc., Shoreview, MN, USA).

The measurement campaigns were carried out in different seasonal periods in order to capture different weather conditions and use of indoor environments typical of cold and hot seasons.

All the instruments used in this study were tested side by side before and after the seasonal campaigns. The instruments were brand new or calibrated in the first months of 2018 in the periodic maintenance factory service.

Data cleaning and statistical analysis were carried out using excel 2010 (Microsoft Inc., Redmond, WA, USA), R and R studio [41,42].

Table 1 shows the experimental campaign settings.

Table 1. Experimental campaigns settings.

| II Floor Ground/II Floor/IV Floor | 1st campaign 4/06/2018–08/06/2018 | 11/06/2018–15/06/2018 |
|-----------------------------------|------------------------------------|------------------------|
| 2nd campaign 26/11/2018–30/11/2018| 03/12/2018–07/12/2018              |                        |
| 3th campaign -                    | 17/06/2019–21/06/2019              |                        |

3. Results
3.1. Relationship between Occupation and UFP Indoor Measurements

Figure 2 shows the classroom occupation rate grouped by number of students and the time (as a percentage of the total) in which each classroom was occupied. It can be observed that in winter the classrooms were systematically occupied for a long time, often at the capacity limits, with a series of teaching activities without interruption from 8:00 a.m. to 6:00 p.m. on most days.

During winter, the rooms were mainly used with windows and doors closed, especially during lessons. The access doors to the outdoor emergency staircase were closed and only occasionally opened during breaks.

During summer, the prevailing ventilation conditions were those typical of the seasonal period: air conditioners turned on in LH and CR while in classrooms A3, A4, A7, almost systematically, the doors, access doors to the outdoor emergency staircase and anti-classroom windows were kept open.

The occupation of the classrooms was rather discontinuous during summer, with alternating periods of zero or very limited occupation and periods of greater crowding. In particular, the LH classroom on the ground floor was more frequently crowded since it was used for exams, while A7 was often unused or used freely for study by a few students.

The 1-min averages PNC time series plots for each couple of indoor/outdoor co-located measurements are provided in Figure 3. An almost perfectly correlated trend can be observed in the twin classrooms in the warm period (A3 and A4 on the 2nd floor); during winter, the trends are less overlapping even if a fair congruence is generally maintained. Transient peaks are observed alternately in one classroom that are absent in the other.

In the winter period, the trends were moderately overlapping in the classrooms overlook the south side at different floors (LH, A4, A7, CR). Particularly in A7, on the 4th floor, trends were observed to be more overlapping with that outdoors than those observed for the other classrooms.

The indoor/outdoor pattern in the five classrooms was almost overlapping, while the outdoor signal had much more noises than the indoor one.

In the summer period, in natural ventilation conditions (A3, A4, A7), the levels were comparable with those outdoors.
Figure 2. Classrooms occupancy rate and occupancy time (percentage of total observations) by seasons. Low: occupancy ≤ 10% of classroom capacity; medium: 10% < occupancy ≤ 40% of classroom capacity; high: occupancy > 40% of classroom capacity.

Figure 3. Daily time series plots indoor and outdoor PNC co-located measurements at A3, A4, A7, LH, CR during summer 2018–2019 (a) and winter 2018 (b).
Clear differences were observed between A3-A4-A7 and LH-CR, most likely due to the air conditioning, that substantially modifies the variability of the PNC in LH-CR compared to A3-A4-A7, not provided with AC: in classroom CR and classroom LH, the temporal variability is very little accentuated. Particularly in classroom LH, a moderately overlapping trend was observed with that outdoors, although the variability was very low indoors compared to that observed outdoors. The outdoor peaks were often observed inside the classrooms, less intense and with a delay of a few minutes.

In some cases, as shown in Figure 3, the indoor concentration was temporarily higher than the outdoor one. This happened in particular when the doors/windows of the classrooms were closed after a peak in outdoor concentration. In this case, indoor decay times may be longer than the times required for outdoor concentrations to go back to the background levels.

3.2. Characterization of Observed Distribution of UFP

Figure 4 summarizes the distribution of PNC 1-min averages measured simultaneously in the various classrooms and outside.

In winter, indoor concentrations were significantly (Student’s t-test, \( p < 0.05 \)) lower than outdoor ones (−20% in A3; −23% A4; −50% LH; −15% in A7; −44% in CR). The interquartile range was greater outdoors. Indoor variability was less pronounced.

Particularly, a less elongated shape of the indoor distribution than the outdoor distributions of classrooms LH and CR, was observed both in summer and in winter.

These differences persisted in the summer period for the PC classroom (−31%), while they were reduced (−9%) or absent in classroom LH.
In summer, in natural ventilation conditions (A3, A4, A7), the indoor median was of the same order of magnitude as that measured outdoors. The distributions of the data were comparable, even if the interquartile range was slightly greater indoors.

This happened also for CR and LH since the air conditioning system draws the air from the outside, so the observed levels reflected the outdoor trends also in terms of concentration.

### 3.3. Indoor/Outdoor Time Series

The correlations between indoors and indoor/outdoor time series are reported in Table 2 for the classrooms located on the same floor and in Table 3 for the classroom located on different floors.

**Table 2.** Pearson correlations between indoors and indoor/outdoor time series for the classrooms located on the same floor (p-value always <0.05).

|       | A3   | Out N | A4   | CR   | Out S |
|-------|------|-------|------|------|-------|
| A3    | 1.00 |       |      |      |       |
| Out N | 0.70 | 1.00  |      |      |       |
| A4    | 0.94 | 0.75  | 1.00 |      |       |
| CR    | -    | -     | -    | 1.00 |       |
| Out S | 0.76 | 0.83  | 0.81 | -    | 1.00  |

**Table 3.** Correlations between indoors and indoor/outdoor time series for the classrooms located on different floors (p-value always <0.05).

|       | LH   | CR   | A7   | Out ground floor | Out 4th floor |
|-------|------|------|------|------------------|----------------|
| Summer|      |      |      |                  |                |
| LH    | 1.00 |      |      |                  |                |
| CR    | 0.85 | 1.00 |      |                  |                |
| A7    | 0.16 | nd   | 1.00 |                  |                |
| Out ground floor | 0.52 | 0.59 | 0.81 | 1.00             |                |
| Out 4th floor    | 0.53 | 0.61 | 0.78 | 0.95             | 1.00           |

|       | LH   | CR   | A7   | Out ground floor | Out 4th floor |
|-------|------|------|------|------------------|----------------|
| Winter|      |      |      |                  |                |
| LH    | 1.00 |      |      |                  |                |
| CR    | 0.81 | 1.00 |      |                  |                |
| A7    | 0.52 | 0.68 | 1.00 |                  |                |
| Out ground floor | 0.56 | 0.62 | 0.34 | 1.00             |                |
| Out 4th floor    | 0.56 | 0.63 | 0.35 | 0.97             | 1.00           |

In summer, the correlation between the indoor co-located measurements was very good (ranging from 0.85 to 0.94, with p < 0.05). During winter, the correlation was weaker.

Regarding the indoor/outdoor co-located measurements, the correlation was high in summer (r > 0.7, with p < 0.05) for the classroom naturally ventilated, while it was moderately significant for those provided with AC (r = 0.5–0.6, with p < 0.05);

In winter, the indoor/outdoor correlation was low to moderate (between 0.32 and 0.63).
3.4. Indoor/Outdoor Ratios

The indoor to outdoor median ratios (calculated as the median of each 1-min average PNC time series ratios) are reported in Tables 4 and 5.

Table 4. Horizontal (same floor, North and South exposure) PNC ratios.

|          | A3/Out N | A4/Out S | CR/Out S | OutS/OutN | A3/A4 |
|----------|----------|----------|----------|-----------|-------|
| Summer   | 1.18     | 1.11     | 0.98     | 0.99      |       |
| Winter   | 0.77     | 0.76     | 0.84     | 0.92      | 0.89  |

Table 5. Vertical (different floors, exposure on the same side) PNC ratios.

|          | LH/Out Ground | CR/Out Ground | A7/Out 4th | Out Ground/Out 4 th |
|----------|---------------|---------------|------------|---------------------|
| Summer   | 0.99          | 0.76          | 0.98       | 1.15                |
| Winter   | 0.55          | 0.59          | 0.90       | 1.30                |

During the warm season, the indoor/outdoor ratios were higher than 1 (classroom A3 and A4) or close to 1 (classroom A7 and LH). In the CR the I/O ratio was lower (0.76) but it must be taken into account that often the classroom was not occupied during the measurements and the air conditioners were switched off (71% of observations), thus the exchange with outdoor air was limited compared with the other classrooms.

In winter, the indoor/outdoor ratios were significantly lower in all classrooms (ranging between 0.50 and 0.90); a similar value (0.45) was found with the intra-calibration procedure for MiniDISCs measuring ultrafine particles in indoor environments [43].

3.5. Outdoor Trends

Figure 5 shows the comparisons of the outdoor trends and the correlation in the summer (a) and winter (b) period, based on the outdoor measurements carried out simultaneously on the two sides of the building: North side, in correspondence with the classroom A3 windows, overlooking the university campus; and South side, in correspondence with the room A4 windows, facing De Lollis street (about 50 m away as the crow flies), and at two altitudes: about 10 m from the ground in correspondence with the LH windows, facing south, and about 25 m from the ground in correspondence with the A7 windows.

The outdoor levels were significantly higher in winter than in summer, as expected. Substantially specular trends between both co-located measurement points in the summer and winter period were observed. During the cold period, PNC levels were significantly higher on the ground floor than on the fourth floor; these differences were less marked during the warm season.

Some very intense transient peaks were detected on the south side on the morning of 8 June, which do not correspond to similar peaks on the north side.

The correlation of the summer and winter time series was very good (Figure 6).

3.6. Analysis of Indoor Sources

From the analysis of data, the importance emerges of a systematic reading of the data with high temporal resolution together with information on the use of the places in order to draw general conclusions. In particular, this may be relevant for particle fractions that can be affected by indoor sources. In general, with the exception of the occupants themselves (who can carry particles from the outside or release fragments of skin), there should be no other relevant sources of ultrafine particles present in the classrooms, as no combustion activity, including tobacco smoke, is expected or permitted.

However, occasionally, transient peaks of PNC cannot be correlated with outdoor peaks and are therefore attributable to the presence of indoor combustion sources.

Figure 7 illustrates one such example very well; a strong transient peak of PNC was observed in the afternoon of November 28, due to maintenance work, using welding equipment, carried out inside the classroom CR, which decays with an exponential trend.
Figure 8 shows the indoor/outdoor comparisons of the PNC distribution in three fractions detected in the PC room in the winter period: the fraction from 0.01 to 0.3 µm (A), the fraction from 0.3 to 1.0 µm (B), and the coarse mode (fraction C >1.0 µm), grouped by various class of occupation rate.

The first fraction (A) was the one that contributed most to the total PNC: the average value of the total concentration in number of particles (TPNC, 0.01–10 µm) was largely dominated by particles with an aerodynamic diameter of less than 0.3 µm, both indoors and outdoors.

It can be observed that the indoor median for all classroom occupancy classes (high, medium, low or empty) was always lower than that observed outdoors. The interquartile range was also in any case greater outdoors, indicating greater temporal variability. Furthermore, the indoor/outdoor relationships in the ultrafine mode seem to depend on the presence of people in an inverse way, that is, they tended to increase with decreasing classroom occupation (Figure 8A).

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Some very intense transient peaks were detected on the south side on the morning of June 8, which do not correspond to similar peaks on the north side.

The correlation of the summer and winter time series was very good (Figure 6).

Figure 5. PNC outdoor trends in (b) winter and (a) summer period (red and blue lines: same level, North and South sides of the building; green and purple lines: different levels, same side of the building).
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Figure 6. Correlation between outdoor summer and winter time series.

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From the analysis of data, the importance emerges of a systematic reading of the data with high temporal resolution together with information on the use of the places in order to draw general conclusions. In particular, this may be relevant for particle fractions that can be affected by indoor sources. In general, with the exception of the occupants themselves (who can carry particles from the outside or release fragments of skin), there should be no other relevant sources of ultrafine particles present in the classrooms, as no combustion activity, including tobacco smoke, is expected or permitted.

However, occasionally, transient peaks of PNC cannot be correlated with outdoor peaks and are therefore attributable to the presence of indoor combustion sources. Figure 7 illustrates one such example very well; a strong transient peak of PNC was observed in the afternoon of November 28, due to maintenance work, using welding equipment, carried out inside the classroom CR, which decays with an exponential trend.

Figure 7. PNC (1-minute averages), 28 November, CR: strong transient peak of PNC indoor due to internal source and exponential (II order) decay.

Figure 8 shows the indoor/outdoor comparisons of the PNC distribution in three fractions detected in the PC room in the winter period: the fraction from 0.01 to 0.3 µm (A), the fraction from 0.3 to 1.0 µm (B), and the coarse mode (fraction C >1.0 µm), grouped by various class of occupation rate.

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The scenario did not change significantly by passing to the analogous observations in the accumulation mode (Figure 8B). It should be noted that, overall, the accumulation mode shown in the figure represented less than 1% of the total PNC.

Figure 8. Box-plot of the indoor PNC (1-minute averages) by various mode and classroom occupation rate and comparison with outdoor co-located measurements.

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In the coarse mode ($d_a > 1 \mu m$, Figure 8C), on the other hand, a significant influence of the classroom occupation rate on the observed indoor levels was observed: the PNC is greater, the greater the classroom occupation is (in particular for the fractions starting from about $2.5 \mu m$). The indoor PNC for these fractions was significantly higher than the outdoor one when the classroom is crowded (over 40 people present) but it was higher or comparable even with medium-low occupancy rates.

4. Discussion

Parallel indoor/outdoor measurement campaigns with high temporal resolution of the PNC were carried out with different objectives:

- To estimate levels, trends, seasonal variability of PNC in the university environments covered by the study (different in size, level of occupancy, height from the road level, main use, mode of air exchange) and highlight transient phenomena;
- To identify the relationships between indoor and outdoor, the average indoor/outdoor ratios and their seasonal variability and understand how the variability of outdoor PNC is reflected on indoor levels, in a context of real use of the environments.
- To understand the role of indoor sources other than combustion, such as the presence of people on PNC levels in the different dimensional fractions.

Preliminarily, it should be noted that the measurements carried out in two seasonal periods made it possible to highlight profoundly different scenarios. Both the similarities and the differences can be traced back to the way the classrooms were used during the observations in the two seasons of observations.

In June, the occupation of the classrooms was rather intermittent, with alternating periods of no or very limited occupation and periods of greater crowding. In classrooms not provided with AC devices (A3, A4, A7), the doors, windows, lobby windows and the upper doors facing directly outdoors, were almost systematically kept open, due to the heat, ensuring a more effective exchange with the outside world. Air conditioners were on in the LH and CR classrooms. During summer, the average indoor concentrations in classrooms not provided with AC devices, tended to be very close to the outdoor ones; the indoor trend fairly faithfully reflected the outdoor one; while in the CR room and LH, the exchange with the outside is influenced by the use of air conditioners and the consequent closure of doors and windows.

During winter, the scenario was radically different, with systematic occupation of the classrooms with a succession of teaching activities without interruption from 8:00 a.m. to 6:00 p.m. on most days. However, as there were no particularly cold temperatures, the rooms were mainly used by keeping the windows and doors closed, especially during lessons, representing a barrier to the penetration of ultrafine particles that dominate PNC. Thus, indoor levels were significantly lower than outdoor ones.
As regards the classroom located on different floors, the PNC values were higher in the classroom on the 4th floor than on the ground floor, but this difference is clearly influenced by the different geometries and use of the classrooms considered rather than by the altitude with respect to the ground.

As for the outdoor measurements, in the comparison on the same level between the two measurement points on the North and South side, the PNC levels were very similar and with the same modulation, with slightly higher concentrations on the side of the road.

The comparison between the outdoor measurements in height consistently gave higher PNC values at the lowest level, with excellent correlation between the two series.

Indoor number concentration decrease, in conditions of limited infiltration (closed doors and windows), has a typical exponential trend, indicative of the importance of coagulation phenomena in the reduction of PNC over time, in the absence of relevant indoor sources.

The register of didactic activities, although discontinuous, provided a useful key to reading the indoor data.

The PNC, dominated by the number of ultrafine particles, in many cases showed an unintuitive anticorrelation with the presence of people in the classrooms.

A more in-depth analysis, based on the data of the different particle size fractions, has instead made it clear that human activity leads to an increase in concentrations in specific fractions of the coarse mode. Our data confirm that the human presence itself can represent a relevant source of particles.

From the joint analysis of the data obtained with size spectrometers and the information relating to the occupation of the classrooms, the contribution to indoor PNC concentrations clearly emerges in the coarse mode attributable to the presence of students and teachers in the classrooms.

In the literature, the role of people is described in terms of lifting from the ground of particles deposited in the indoor environment and the transport of the individuals themselves of particles from the outside (on clothes, shoes, e.g., [44]).

From what we have seen so far, it is clear that indoor PNC concentration is highly dependent on indoor sources. When these are not active, however, the penetration of the particles from the outside becomes relevant. It is therefore important to define an efficient and easily reproducible approach to estimate the infiltration factor.

The infiltration factor can be defined as the ratio between the portion of the indoor concentration of a pollutant penetrated from the outside environment, and the outdoor concentration. This ratio varies according to parameters that depend on the characteristics of the building, the pollutant and the microclimatic conditions.

The general infiltration factor equation is [16,45]:

\[
F_{\text{Inf}} = \frac{C_{\text{pin}}}{C_{\text{out}}} = \frac{P \cdot \text{Aer}}{\text{Aer} + k}
\]  

where:
- \( F_{\text{Inf}} \): Infiltration factor (particles/cm\(^3\));
- \( C_{\text{pin}} \): Penetrated particle concentration (particles/cm\(^3\));
- \( C_{\text{out}} \): Ambient particle concentration (particles/cm\(^3\));
- \( P \): Penetration efficiency (dimensionless);
- \( \text{Aer} \): Air exchange rate (h\(^{-1}\));
- \( k \): Deposition rate (h\(^{-1}\)).

The variability in the particle infiltration is mainly caused by the air exchange rate (in buildings with natural ventilation, the air exchange rate depends on the temperature difference between the indoor and outdoor air, the wind pressure outside the building and whether the occupants keep windows open or closed). Furthermore, penetration efficiency and deposition rate are influenced by the geometry of the homes and air intake ducts and leaks, other than by the specific properties of the sampled aerosol.
For our objective, it was convenient to start from the indoor particle concentration that can be described as follows [46]:

\[
C_{in} = \frac{P \cdot A_{er} \cdot C_{out}}{A_{er} + k} + \frac{Q_{is}}{(A_{er} + k)V} = F_{Inf} C_{out} + C_{ig}
\]  

(2)

where:
- \(C_{in}\): Indoor particle concentration (pt/cc);
- \(C_{ig}\): Indoors generated particle concentration (pt/cc);
- \(Q_{is}\): Emission due to indoor sources (pt/h);
- \(V\): Home volume (m\(^3\)).

Consequently, the infiltration factor, \(F_{Inf}\), is expressed by [47]:

\[
F_{Inf} = \frac{C_{in} - C_{ig}}{C_{out}}
\]

(3)

Among these parameters, only the ambient particle concentration (\(C_{in}\), \(C_{out}\)) were variables measured in this study, whereas the indoors generated particle concentrations, \(C_{ig}\), had to be estimated following these steps (schematically represented in Figure 9):

**Figure 9.** Indoor/outdoor ratio (a) vs. infiltration factor estimation (b). Red lines represent indoor PNC with (a) or without (b) peaks by indoor sources; blue lines represent outdoor PNC.
The method is based on the following steps [48]:
- The time series of the concentration in number of particles (PNC) determined at the same time indoor and outdoor are compared, and the moments of start and end of activities, that potentially can influence indoor levels and modify air exchange rate, are identified (i.e., opening/closing windows, activation of air conditioning systems, etc.);
- Concentration peaks are identified, separating those that are clearly attributable to outdoor sources from those attributable to indoor sources;
- A baseline underlying the indoor peaks is extrapolated, useful for estimating the contribution of the indoor source to the PNC;
- PNC peaks determined by indoor sources show a longer decrease time than that generally observed in the case of intrusion of particles from the outside. It may therefore happen that a peak, usually asymmetrical and thin, is superimposed on the PNC decay curve, due to a phenomenon of intrusion from the outside, which must be taken into account when the contribution of the indoor source in question is estimated;
- At this point the area underlying the peak determined by the indoor source is subtracted from the time series of data, allowing to obtain a series of PNC data in which the indoor concentration depends exclusively on the outdoor concentration and on the infiltration mode of the exterior of the particles. On the basis of the indoor PNC series thus obtained and the contemporary outdoor PNC series, it is now possible to estimate the infiltration factor simply on the basis of the ratio of indoor and outdoor PNC.

5. Conclusions

This work highlighted a seasonality of indoor levels linked to the different natural ventilation conditions of indoor environments in summer and winter.

In different periods, during 2018–2019, parallel indoor/outdoor campaigns of the PNC were carried out at the Physics Department of the Sapienza University of Rome. This made it possible to estimate levels, trends, seasonal variability of PNC and describe how the variability of outdoor PNC is reflected on indoor levels in a number of selected classrooms with different dimensions, position and occupancy rate.

The main relations between indoor and outdoor PNC, the average IN/OUT PNC ratios and their seasonal variability and the main transient phenomena were identified so as to understand the role of no-combustion indoor sources, such as the presence of people, on PNC levels and how it can affect a correct estimation of the infiltration factor.

In winter, indoor concentrations were significantly lower than outdoor ones (from −20% to −50%). The inter-quartile range was significantly greater outdoors and indoor variability was less pronounced.

In summer, in the classrooms with natural ventilation conditions, the indoor median was of the same order of magnitude as that measured outdoors. The distributions of the data were comparable, even if the interquartile range is slightly greater indoors.

During the winter period, the indoor PNC trends were moderately overlapping with the outdoor in the five classrooms, while, during summer, in natural ventilation conditions, the levels were comparable with those outdoors.

In the warm season, the correlation between the indoor co-located measurements was very good (ranging from 0.85 to 0.94) and the indoor/outdoor ratios were higher than 1, while, in winter, the indoor/outdoor ratios were lower in all classrooms (ranging from 0.50 to 0.90).

The results could be generalized with regard to the exposure in similar microenvironments (where no combustion sources are allowed indoors) in the same climatic zone as that of our study, when classrooms are naturally ventilated. In this case, the outdoor PNC concentrations can be considered a good proxy for average indoor exposure to particles in the ultrafine–accumulation mode, during the warm season. If the classrooms are equipped with air conditioning devices, as well as if winter-time exposure is concerning,
a site-specific analysis is needed since the relationships with outdoor total PNC could become too weak to allow for using outdoor PNC as an indoor exposure proxy.

In these cases, the proposed way to estimate the infiltration factor could be a possible choice when the use of tracer is not allowed.

If the exposure to coarse fraction is the topic of interest, the presence of people and the activities carried out indoors must be registered since they can be relevant sources of indoor particles.

Author Contributions: Conceptualization, A.D.M.d.B., G.C. and A.P.; data curation, A.G., G.L., A.D.M.d.B., M.C., R.G., G.C., F.B. and R.F.; formal analysis, G.C. and A.D.M.d.B.; funding acquisition, A.P. and G.C.; investigation, A.G., G.L., A.D.M.d.B., M.C., R.G., G.C., F.B. and R.F.; methodology, A.D.M.d.B. and G.C.; project administration, G.C. and A.P.; resources, G.C., A.D.M.d.B. and A.P.; supervision: G.C.; validation, A.D.M.d.B. and G.C.; visualization: A.G., G.L., A.D.M.d.B., M.C., R.G. and G.C.; writing—original draft preparation, A.D.M.d.B., G.C. and A.P.; writing—review and editing, A.G., G.L., A.D.M.d.B., M.C., R.G., F.B., R.F., G.C. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by INAIL in the frame of its scientific research programs (2016–2018).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We would like to thank Annamaria Iannarelli and Marco Cacciani (Physics Department, Sapienza University of Rome) for their patient and precious support during the measurement campaigns.

Conflicts of Interest: The authors declare no conflict of interest.

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