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ARTICLE

PM10 Indoor/Outdoor Air Quality Relationship in School Buildings: A Case Study in Barreiro

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ABSTRACT

This article analyses the relationship between PM_{10} concentrations inside and outside two schools in Barreiro, Portugal: Primary School No. 5 and D. Luís Mendonça Furtado Basic School. The main objective was to understand the impact of external and internal sources on indoor air quality (IAQ) in school environments. Monitoring campaigns were carried out in different indoor spaces, including classrooms, the gym, and the canteen, and the results were compared with PM_{10} levels outside the building. At Primary School No. 5, indoor PM_{10} concentrations were consistently higher than the outdoor values measured on Avenida do Bocage, with an average Indoor/Outdoor (I/O) ratio of 2.2, indicating a significant impact of indoor activities on particle levels. Similarly, at the D. Luís Mendonça Furtado Basic School, there was an increase in PM_{10} and $PM_{2.5}$ concentrations during school hours, with the highest I/O ratio (3.04) recorded on school days. In the evenings and at weekends, when the spaces were unoccupied, particle concentrations dropped considerably, reaching an I/O ratio of 0.70. Said results suggest that indoor activities are a determining factor for particle levels in indoor air, emphasizing the need for ventilation and pollution control strategies in schools to protect the health of students and staff.

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ARTICLE INFO

Received: 7 March 2025 | Revised: 20 March 2025 | Accepted: 28 March 2025 | Published Online: 9 May 2025

DOI: https://doi.org/10.30564/jees.v7i5.8999

CITATION

Garcia, J., Cerdeira, R., 2025.PM10 Indoor/Outdoor Air Quality Relationship in School Buildings: A Case Study in Barreiro. Journal of Environmental & Earth Sciences. 7(5): 413–423. DOI: https://doi.org/10.30564/jees.v7i5.8999

Keywords: Indoor/Outdoor Relation; Air Quality; Schools

1. Introduction

Indoor air quality (IAQ) in schools is a critical factor influencing the health, comfort, and academic performance of students and staff. Since children spend a significant portion of their day in school buildings, they are continuously exposed to the indoor environment, making it essential to maintain healthy air quality. Poor IAQ in educational settings has been linked to various negative outcomes, including respiratory issues, increased absenteeism, and reduced cognitive function, which can directly impact learning and development[1]. The indoor environment of schools is influenced by a combination of outdoor air quality and internal factors such as building design, ventilation systems, cleaning practices, and occupant activities. Pollutants such as particulate matter (PM), carbon dioxide (CO_2), volatile organic compounds (VOCs), and biological contaminants like mold and allergens are commonly present in these spaces. Among these, particulate matter—especially PM_{10} and $PM_{2.5}$—poses a significant concern due to its ability to penetrate deep into the respiratory system, leading to both short- and long-term health effects. Understanding the relationship between indoor and outdoor air quality is essential for identifying the sources of pollutants and implementing effective mitigation strategies. In school environments, where ventilation systems may be inadequate or outdated, indoor pollutant levels can often exceed outdoor concentrations, particularly during periods of high occupancy and activity. Therefore, improving IAQ in schools requires a multifaceted approach, including proper ventilation, air filtration, regular maintenance, and the adoption of policies aimed at minimizing exposure to harmful pollutants. This article explores the complexities of IAQ in schools, emphasizing the importance of monitoring and managing air quality to create healthier learning environments. By addressing the factors that influence IAQ, educational institutions can safeguard the well-being of students and staff, promoting both health and academic success.

2. Air Quality and Health

Air quality and its relationship with health are increasingly important aspects in understanding public health issues. Said issues are more important when demographic changes and the aging of the national and European population lead to new efforts to develop health policies, urban planning and sustainable development at local and global levels. These aspects are closely linked, since good air quality is crucial for human health and the balance of the planet's environmental system. Also, it is also well known that air pollution affects the quality of life of the population in general, both socially and in terms of public health. According to the WHO, around 7 million people die every year as a result of exposure to air pollution[1], and this organization, through its International Agency for Research on Cancer (IARC), has classified air pollution as a carcinogen for humans, thus considering air pollution to be an environmental cause of death from cancer[2]. However, despite the fact that such issues are much discussed today and deserve increasing attention from both the scientific community and public opinion in general, there is still a wide-ranging debate on how to study and evaluate the impact of air quality on health. The assumption that air pollution could cause deaths in situations of high concentrations of pollutants arose in the middle of the 20th century, essentially due to a series of disasters that occurred in the United States and Europe[3]. Subsequently, work associated with the study of time series in various locations showed that even lower levels of pollution, but persistent over time, could lead to increased levels of mortality and morbidity in the population[4]. More recent studies have sought to associate air pollution levels (even if not high) with the onset of respiratory problems in certain groups that are more susceptible to said problems, such as children, the elderly and the chronically ill[5]. However, all these types of studies are still trying to consistently correlate air pollution levels with public health in general. Although several studies have been carried out, mainly by physicians, looking at the relationship between health and pollution levels, these studies have been given great impetus, particularly through the systematization of methodologies and the application of statistical methods[6]. Of note are the studies that have analyzed the association between daily air pollution and the respiratory health of children[7–10]. The strongest correlations were found with bronchitis, bronchiolitis, as well as pneumonia[9–13]. Numerous studies conclude that exposure to exhaust fumes due to heavy road traffic can have significant adverse effects on the respiratory health of children living in metropolitan areas, thereby increasing the occurrence of respiratory infections and causing the onset of symptoms of lung diseases at school age [13–15]. Some authors have analyzed the correlation between air pollution and the number of visits to emergency for asthma and other respiratory diseases and concluded that there is an association between air pollution and daily visits to emergencies for asthma and other respiratory diseases [15–17]. The most significant associations were observed in children and the most important pollutants that potentiated these effects were Nitrogen Dioxide (NO_2), Carbon Monoxide (CO) and Sulphur Dioxide (SO_2) [14]. Particulate matter (PM_{10}) is the pollutant with the most direct results and health consequences [17].

3. The Relationship between Indoor and Outdoor Air Quality

The relationship between indoor and outdoor pollutant concentrations has been a subject that has undergone extensive development in recent years [18]. The deepening of studies in this area is related to the knowledge that in urban environments people spend around 90% of their time indoors. Therefore, in terms of exposure, this factor is of paramount importance in understanding the phenomena that govern this outdoor-indoor relationship in air quality. It is a complex study, since it depends on numerous factors such as the level of ventilation in the space, the type of filtration, the activities carried out inside, meteorological factors such as wind and temperature, the level of external pollution in the surroundings, among others. Some authors have studied and quantified this relationship between indoor/outdoor air quality [19]. Indoor air quality is directly related to outdoor air quality, depending on internal factors such as ventilation, type of use, occupancy, building materials, chemical products and maintenance of air conditioning systems [20]. In urban areas, the presence of outdoor pollutants such as carbon monoxide and particulate matter ($PM_{2.5}$ and PM_{10}) can penetrate indoor environments through doors, windows and ventilation systems, especially when these environments are not properly filtered or sealed [21]. This means that even inside buildings, exposure to air pollutants can occur, impacting the respiratory and cardiovascular health of occupants. However, in addition to the influence of outside air, indoor air quality is impacted by internal factors such as the use of cleaning products, which can release volatile organic compounds (VOCs), and the presence of internal combustion sources such as gas cookers and heaters. Other pollutants, such as mould, dust, dust mites and even carbon dioxide exhaled by people in poorly ventilated environments, also negatively affect the air quality inside buildings [22]. Adequate ventilation is a key factor in reducing the entry of external pollutants and dispersing internal contaminants. Ventilation systems with efficient filters can minimize the penetration of harmful particles and gases, while poorly maintained air conditioning systems can accumulate dust and micro-organisms, worsening air quality [23]. Studies show that prolonged exposure to environments with poor air quality, whether due to the effect of external or internal pollutants, is associated with respiratory diseases, allergies, worsening asthma and even psychological effects such as tiredness and irritability [24]. Thus, indoor and outdoor air quality are interlinked, requiring control measures in both spheres to protect the health of occupants [25]. In addition to monitoring and improving outdoor air quality, it is crucial to promote good ventilation and cleaning practices in the indoor environment to ensure healthier and safer air. The relationship between indoor air quality and outdoor air quality in schools is particularly critical, as children and adolescents spend much of their time in school environments, where poor air quality can directly impact their development and well-being. Schools are often located in urban areas, close to sources of pollution such as busy streets, factories, as well as other industrial activities, which facilitates the entry of external pollutants into indoor environments. Studies indicate that exposure to pollutants such as particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2) and ozone (O_3) are related to an increase in respiratory problems in children, such as asthma and allergic rhinitis [26]. In addition to external pollutants, indoor air in schools can be affected by internal factors such as inadequate cleaning products, poor air circulation and crowding, which contributes to the accumulation of carbon dioxide (CO_2) [27]. In poorly ventilated rooms, children can show symptoms of tiredness, difficulty concentrating and increased irritability, which directly affects school performance. An important work in this area is the EPA report which describes the results of a pilot air quality monitoring experiment carried out in nine New England schools during the summer and autumn of 2001 [28]. The intention of this project was to develop methods that would characterize the impact of outdoor environmental pollution and human activity on indoor air quality in schools. Said methods would be used to determine the levels of outdoor pollution entering the interior of the schools and to establish a baseline for the exposure to which individuals might be subjected in this specific environment. A secondary objective of this study was to investigate the extent to which urban areas and areas close to major roads would have higher values of indoor pollutant concentrations.

4. Characterization of the City of Barreiro

The city of Barreiro is located in the municipality of Barreiro, in the district of Setúbal, on the south bank of the River Tagus, relatively close to Lisbon and Almada. The municipality of Barreiro, occupying an area of approximately 33 km^2 today, despite the gradual deactivation of part of its industry, continues to be a municipality with significant industrial activity. These emission sources (traffic and industry) are very important for the city's air quality. The municipality is part of the Lisbon Metropolitan Area and a significant number of its residents work in the city of Lisbon, with a mixed urban typology of dormitory, industrial and agricultural. The city has permanent river connections with the capital. Avenida do Bocage (38º39'20.93"N; 9º03'45.63"O) is one of the main roads in the city of Barreiro. It is characterized by heavy road traffic in both directions, with four lanes (two in each direction) and residential, office and service buildings on both sides of the road. It is one of the main access routes to the city of Barreiro, namely for road traffic coming from the IC21. Next to this road is Barreiro Primary School No. 5. **Figure 1** shows an aerial photograph of the street in question and the main buildings.

5. Study of the IAQ/OAQ Relationship at Barreiro School No. 5

In order to study the interaction between outdoor air quality and indoor air quality in terms of PM_{10} particles, a campaign was carried out to measure particle concentrations at Barreiro's Primary School No. 5. Primary School No. 5 is located next to Avenida do Bocage, with the north façade of the building located on Rua Diogo Cão, which is characterised as an access road to residential areas with little traffic, and the south façade located on Avenida do Bocage. The school is open from 9 a.m. to 12 p.m. and from 1:15 p.m. to 3:15 p.m. on weekdays and is attended by 7 teachers, 5 staff and 121 pupils (25 pre-school and 96 primary). It consists of two buildings, each with two floors above ground. Each of the buildings has four classrooms and the floors are made of wooden planks. Building A has two classrooms, a playroom with photocopiers and a room that has been converted into a kindergarten lined with wallpaper. There is also a storeroom and a room for educational assistants. In building B, one of the rooms on floor 0 is used as a canteen with a maximum capacity of 80 people. The other room on this floor has been varnished and is used as a gym. There is also a support office for the school headmaster, two bathrooms for teachers and a small kitchen. It should be noted that this school (like most schools in Barreiro) is not equipped with a mechanical ventilation system or air treatment units. Ventilation is provided only by opening doors and windows, which can influence indoor air quality, particularly in areas with higher occupancy. **Figure 2** presents two photographs of Primary School No. 5 in Barreiro. **Figure 2a** shows an aerial photograph that situates the school within its urban context, while **Figure 2b** provides a frontal photograph of the building's main façade.

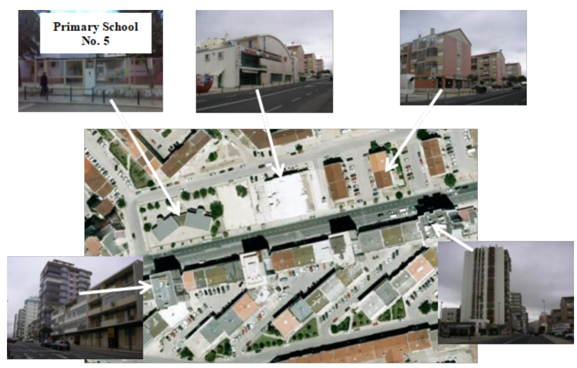

Figure 1. Avenida do Bocage and Its Main Buildings.

Figure 2. (**a**) Aerial of Primary School No. 5 in Barreiro; (**b**) Frontal View of Primary School No. 5 in Barreiro.

The minimum number of points to be monitored in each of the zones defined above was calculated using the following formula:

$$N_i = 0.15 * \sqrt{A_i} \quad (1)$$

Where:

N_i: number of monitoring points in zone i

A_i: Area of zone i (sqm)

The activities developed in each area of the building were also considered to choose the monitoring points.

The sites selected for monitoring are identified in **Table 1**.

Table 1. Identification of the Points Monitored in the IAQ Audit.

Location	Floor	Area (sqm)	Site Identification
Building A	0	160	1st grade classroom Kindergarten
	1	155	Playroom 3rd grade classroom
Building B	0	160	Kitchen Cafeteria Gym Main door
	1	155	2nd grade classroom 4th grade classroom G.A.D

The measurement campaign was carried out during periods representative of the building's normal occupancy profile, between 9 a.m. and 4 p.m. on working days, in the occupied areas of each space. The monitoring points are shown in **Table 2**. Indoor monitoring was carried out at least one metre from possible sources of contamination and at the level of the occupants' airways, using DustTrak Model 8520 particle concentration measuring equipment [29], with a collection time of 15 minutes. The reference concentration value of PM_{10} inside buildings considered, was 0.15 mg/m3 (threshold values), that concentration was not exceeded at any point during the measurements. The results obtained are summarised in **Table 2** and in **Figure 3**.

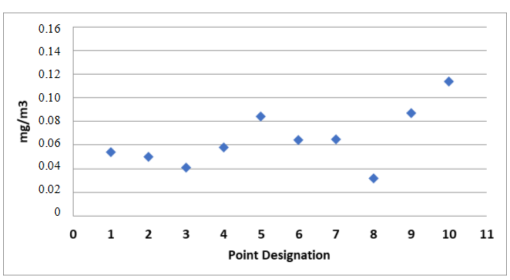

Figure 3. PM_{10} Concentration Values in the Air Inside the Building.

Table 3 shows the CO_2 concentration values recorded on the date of the audit, as this is a frequently used indicator of air quality levels. Analysing this table shows that about half of the places had values above the maximum reference value according to the legislation in force at the time (1800 mg/m^3), namely the teachers' room (1825 mg/m^3), 2nd year room (2424 mg/m^3) 4th year room (2208 mg/m^3) 3rd year room (1972 mg/m^3) and Cafeteria (1963 mg/m^3).

Table 4 summarizes the values obtained for the ratio between the indoor concentration of PM_{10} at each monitored point and the average outdoor concentration on Avenida do Bocage (30 µg/m^3). It can be seen that indoor concentrations are always higher than the average outdoor value, with the lowest value of 0.032 mg/m3 for the Ludoteca area and a maximum value of 0.114 mg/m^3 for the gym. Analysing the ratio between indoor and outdoor PM_{10} concentration values (Indoor/Outdoor), the indices vary between 3.8 (maximum value) for the gym and 1.1 (minimum value) for the Ludoteca and show an average value of 2.2, indicating in this case a higher concentration of PM_{10} indoors than outdoors due to classroom activities.

The results indicate that PM_{10} concentrations inside the monitored spaces consistently exceed the average outdoor concentration measured on Avenida do Bocage (30 µg/m³). Analysing the Indoor/Outdoor (I/O) ratio revealed indices

Table 2. PM_{10} Concentration at Each Monitoring Point.

Floor	Point Designation	Location	PM_{10} µg/m³ conc.
0	1	Kitchen	54
1	2	Teachers' Room	50
0	3	1st grade classroom	41
0	4	Pre-school classroom	58
1	5	2nd grade classroom	84
1	6	4th grade classroom	64
1	7	3rd grade classroom	65
1	8	Playroom	32
0	9	Cafeteria	87
0	10	Gym	114
–	–	Exterior	30

Table 3. CO_2 Concentration at Each Monitoring Point.

Floor	Point Designation	Location	CO_2 mg/m³ conc.
0	1	Kitchen	1301
1	2	Teachers' Room	1825
0	3	1st grade classroom	1269
0	4	Pre-school classroom	1086
1	5	2nd grade classroom	2424
1	6	4th grade classroom	2208
1	7	3rd grade classroom	1972
1	8	Playroom	995
0	9	Cafeteria	1963
0	10	Gym	1200
–	–	Exterior	857

ranging from 1.1 in the Ludoteca to 3.8 in the gym, with an overall average of 2.2, suggesting that particulate pollution in the indoor environment is considerably higher than in the outdoor environment.

The Ludoteca had the lowest concentration of PM_{10} (0.032 mg/m³), possibly due to its lower occupancy density and less intensive activities in terms of particle generation. In contrast, the gym recorded the highest concentration of PM_{10} (0.114 mg/m³) and the highest I/O index, which can be explained by the nature of the physical activities carried out in the space, which tend to generate more suspended particles.

6. Reliability of Measurements

To assess the robustness of the results, it is important to highlight that the measurement campaign was conducted during periods representative of the building's normal occupancy, specifically between 9 a.m. and 4 p.m. on working days, ensuring that recorded concentrations reflect typical indoor conditions. The consistently higher PM_{10} concentrations indoors compared to outdoors, with an average Indoor/Outdoor (I/O) ratio of 2.2, reinforce the reliability of the data. The variations observed between different indoor spaces align with expected patterns based on their usage, such as the gym, which exhibited the highest PM10 levels and the highest I/O ratio (3.8), likely due to physical activities generating more suspended particles. Similarly, the lower PM_{10} levels in the playroom (I/O = 1.1) can be attributed to lower occupancy density and reduced activity levels. The CO_2 measurements further support these findings, as higher concentrations were recorded in rooms with greater occupancy, exceeding 1800 mg/m³ in several cases. This correlation

Table 4. Relationship Between PM_{10} Concentrations Inside the School and Outdoors (Street).

Area	PM_{10} µg/m^3 Outdoor conc.	Relationship Indoor/ Outdoor	Difference I-O µg/m^3
Kitchen	54	1.8	24.0
Teachers' Room	50	1.7	20.0
1st grade classroom	41	1.4	11.0
Pre-school classroom	58	1.9	28.0
2nd classroom	84	2.8	54.0
4th classroom	64	2.1	34.0
3rd grade classroom	65	2.2	35.0
Playroom	32	1.1	2.0
Cafeteria	87	2.9	57.0
Gym	114	3.8	84.0
Outdoor	30	–	–
Minimum	32	1.1	2.0
Average	65	2.2	34.9
Maximum	114	3.8	84.0

between indoor air quality indicators suggests that the results accurately reflect pollutant accumulation dynamics rather than random fluctuations. While short-term variability is inherent in air quality measurements, the sampling approach used in this study—covering multiple spaces and capturing peak activity periods—helps mitigate potential biases. Although future studies with extended measurement periods could provide further insights, the observed trends and consistency across different locations indicate that the results are robust and representative of the indoor air quality conditions in the monitored spaces.

7. Study of the IAQ/OAQ Relationship at D. Luís Mendonça Furtado Basic School

Also, with the aim of characterizing the air quality inside schools in the city of Barreiro, a complementary air quality study was carried out inside a classroom at the D. Luís Mendonça Furtado 2nd and 3rd Cycle Basic School in Barreiro. This work made it possible to study the relationship between the concentration of particles inside and the concentration of particles ($PM_{2.5}$and PM_{10}) outside (indoor air quality/outdoor air quality–IAQ/OAQ). In this case, children's exposure to atmospheric particles was characterized by measuring the concentrations of PM_{10} and $PM_{2.5}$ outside and inside the school. The school chosen had an air quality monitoring station outside the school building, which allowed for a real-time comparison between indoor and outdoor PM_{10} measurements. $PM_{2.5}$ was not measured by the air quality monitoring station. Indoor concentrations were measured hourly by the Beta Gauge Dust Monitor particle monitoring equipment over two weeks at different times (due to equipment limitations), one for PM_{10} and the other for $PM_{2.5}$. In order to understand the generation of PM indoors, all the activities carried out were recorded, from classes to cleaning activities, according to the start and end time of the activity. Said records are summarized in **Table 5**. It was found that the classroom is cleaned every day at 7:30 a.m. and only extraordinary cleaning activities are recorded in this table. Lessons are represented by shading and extraordinary cleaning activities are represented by the designation "Clean". The X represents the periods of teaching activity when the monitoring equipment was switched off, since some teachers switched off the equipment due to the noise.

Table 5. Activities Carried Out in the Classroom.

Time	Mon.	Tue.	Wed.	Thu.	Fri.
8:30 a.m.					
9:15 a.m.					
10:30 a.m.			X		
11:15 a.m.			X		
12:10 a.m.				Clean	
1:15 p.m.	X			Clean	Clean
2:00 p.m.	X				Clean
3:00 p.m.			Clean		
3:45 p.m.					
4:40 p.m.					

It should be noted that this school (like most schools in Barreiro) is not equipped with a mechanical ventilation system or air treatment units and ventilation is provided only by opening doors and windows. One of the factors that can contribute to the release of PM is the material used in the classroom so to analyse the behaviour of the PM inside, the classroom was characterized. The classroom is equipped with standard school furniture and a blackboard. The size and orientation of the windows were also considered, as well as the material of the floor and the type of window protection. This characterization is summarized in **Table 6**.

Table 6. Classroom Characterization.

Classroom Characteritics	
Volume (m^3)	180
No. of windows	7
Window area (sqm)	2/window
Window orientation	NE/SE
Window protection	Blinds
Type of floor	Wood
Furniture	Wood and metal chipboard

Although the measurements of PM_{10} and $PM_{2.5}$ indoors were made at different times, the evolution between these two classes of PM was also analysed, but since the monitoring periods are different, no direct analysis of the $PM_{2.5}/PM_{10}$ relationships can be made. **Figure 4** shows the behaviour of PM_{10} and $PM_{2.5}$ measured indoors at the same time of day on two different measurement days. As we can see, the PM shows a similar behaviour, whether they are PM_{10} or $PM_{2.5}$, in their daily evolution. Once more it's clear from analysing the evolution that activity inside the classroom is key for the concentration of particles, both PM_{10} and $PM_{2.5}$. This can be seen in the fact that the concentrations on Saturdays and Sundays are much lower than the particle concentrations during the week, when there is teaching activity. In the evenings and at weekends, both PM_{10} and $PM_{2.5}$ concentrations are low, indicating that the main source of particles comes from teaching activities inside the classroom. This can also be seen in **Table 7** where the ratio between indoor PM_{10} concentrations and outdoor PM_{10} concentrations is greater than 1 on weekdays (school term time) and less than 1 at night and at the weekend.

In order to compare the influence of the different PM sources inside the classroom, the PM_{10} concentration values and $PM_{2.5}$ were analysed in two different main periods: weekdays and weekends. Said two periods make it possible to study the behaviour of PM with and without potential indoor sources. **Figure 5** shows the behaviour of PM_{10} concentrations and $PM_{2.5}$ indoors, as well as PM_{10} outdoors at the weekend. This figure refers to the PM_{10} concentrations measured indoors and PM_{10} measured outdoors on one weekend (values represented by lines), together with the $PM_{2.5}$ concentrations measured indoors and PM_{10} measured outdoors on another weekend.

Table 7. Ratio between Indoor and Outdoor PM_{10}.

		Ind. PM_{10} **Out. PM_{10}**
Week total	Global	1.29
	Day	2.41
	Night	0.70
Weekend	Global	0.40
	Day	0.53
	Night	0.27
Weekday	Global	1.94
	Day	3.04
	Night	0.85

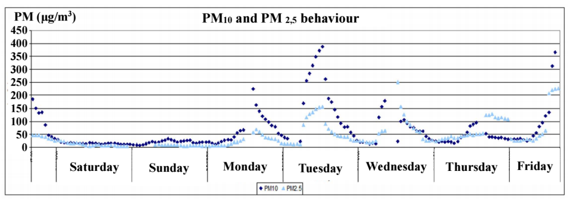

Figure 4. Changes in the Concentration of PM_{10} and $PM_{2.5}$ Inside the Classroom.

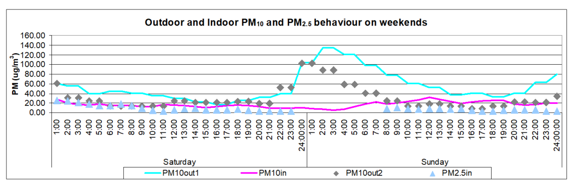

Figure 5. Changes in the Concentration of PM_{10} Outdoors and PM_{10} and $PM_{2.5}$Indoors at the Weekend..

Bearing in mind that **Figure 5** represents two different weekends, you can see the consistency in the outdoor concentration profiles on both weekends. The highest value is reached at around 1 a.m. on Sunday morning, which is probably due to road traffic from night-time entertainment activities. Analysing the evolution of the outdoor and indoor concentration values shows that the building provides good protection from outdoor sources, as there is almost no variation in the indoor concentration values even during peak outdoor concentration periods, or immediately after they occur. **Table 7** shows the average ratio between indoor and outdoor PM_{10} concentrations in three different periods: weekends, weekdays and all weekdays. The individualized night and day periods were also taken into account. The table shows that the ratio of indoor PM_{10} to outdoor PM_{10} for the whole week is over 1 (1.29), indicating the importance of indoor sources in the concentration of PM_{10} in the classroom. This is even more apparent during the day when the ratio reaches 2.4. On the other hand, at night this ratio drops to 0.70, indicating that during periods when there is no activity in the classroom, indoor concentrations are lower than outdoor concentrations. At weekends, the ratio is always less than 1 because the lack of activity in the classroom contributes to the lack of indoor sources. It can also be seen that during weekdays this ratio reaches a maximum value of 3.04 during the day, leading to the conclusion that classroom activity is an important indoor source of PM_{10}.

Measurements of PM_{10} and $PM_{2.5}$ were taken inside a classroom and compared with the concentration of PM_{10} outside to study the impact of outdoor and indoor sources in a school environment. The measurements were made in two different weeks, one for PM_{10} and the other for $PM_{2.5}$, but the results were compared for the same period of the day. The two classes of PM studied behave identically, increasing during activity hours due to indoor sources. The lowest indoor concentration is reached at weekends and at night, when the classroom is closed and without activity, which shows good protection from outdoor pollution. The ratio between indoor and outdoor PM_{10} concentrations showed the importance of indoor sources, as during weekdays, especially during the day, this ratio shows the highest value (3.04).

8. Evolution on Air Quality on Barreiro

The evolution of air quality in Barreiro has been influenced by a combination of industrial, traffic, and residential factors. Although specific and recent data for the city is limited, national and regional air quality reports suggest notable trends in pollutants such as particulate matter (PM_{10}), carbon dioxide (CO_2), and other airborne contaminants. Historically, industrial activities in Barreiro, coupled with the high volume of traffic, have been significant contributors to local air pollution. These factors, along with urban sprawl, have posed challenges to maintaining healthy air quality levels in the area. In recent years, however, there has been a positive shift due to the deactivation of several industrial plants in the region. This reduction in industrial activity has likely contributed to a significant improvement in air quality, particularly in areas that were previously heavily affected by emissions from factories and other industrial sources [30]. Alongside this, various other measures have been implemented to address air pollution, including stricter vehicle emissions standards, improvements in public transportation infrastructure, and tighter regulations on remaining industrial emissions. These efforts, along with increased public awareness, have likely further contributed to the improvement of air quality in certain areas, although pollution hotspots still remain, particularly in regions close to busy roads. Despite these improvements, challenges persist, especially in areas with dense traffic or near other industrial sites, where air quality remains a concern. The variability in air quality over time can also be attributed to factors such as seasonal weather conditions, fluctuations in traffic patterns, and changes in industrial activities [31]. While some areas have experienced significant improvements, others still struggle to meet air quality standards set by health authorities. Looking ahead, continuous monitoring of air quality is crucial in understanding the effectiveness of current policies and guiding future interventions. Ongoing efforts to reduce traffic emissions, enhance public transportation, and promote sustainable urban development will play a pivotal role in further improving air quality in Barreiro. Furthermore, enhancing public awareness and engaging local communities in air quality monitoring will be key to ensuring that future generations benefit from cleaner, healthier air.

9. Conclusions

The studies carried out at Primary School No. 5 in Barreiro and D. Luís Mendonça Furtado Basic School in Barreiro, Portugal, provided a detailed analysis of the relationship between indoor and outdoor PM_{10} particle concentrations, emphasising the significant role of indoor sources in pollutant concentrations in school environments.

At Primary School No. 5, measurements showed that indoor PM_{10} concentrations are constantly higher than those outside. The Indoor/Outdoor index ranged from 1.1 to 3.8, with an average of 2.2, suggesting that specific activities indoors, such as in classrooms and the gym, are responsible for the increase in suspended particles. Said result indicates that although outside air contributes to indoor pollution, the intensity of the activities carried out in the different spaces has a more significant impact on particle concentration.

At D. Luís Mendonça Furtado Basic School, continuous monitoring of PM_{10} and $PM_{2.5}$ particles revealed that indoor sources play a major role in air quality during school days. Analysing the data showed that during periods of classroom activity, PM_{10} and $PM_{2.5}$ concentrations increase considerably, with the Indoor/Outdoor index reaching 3.04 during the weekday. In contrast, during periods of inactivity (evenings and weekends), indoor pollution levels decreased, resulting in lower indices, such as 0.70 at night, when indoor sources are absent.

These results show that although buildings provide protection against external sources of pollution, the activities carried out inside schools are a determining factor for air quality. The concentration of indoor particles can be reduced through mitigation strategies, such as improving ventilation, as well as controlling particle sources inside classrooms and other school spaces. These results highlight the need for specific policies for air quality management in schools, aimed at minimising students' exposure to high levels of particles during school hours, thus protecting the health and well-being of students, teachers and non-teaching staff.

Author Contributions

Conceptualization, J.G. and R.C.; methodology, J.G. and R.C.; validation, J.G.; formal analysis, R.C.; data curation, R.C.; writing—original draft preparation, J.G.; writing—review and editing, J.G. and R.C.; visualization, J.G.; supervision, J.G.; project administration, J.G. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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