Assessment of PM2.5 particulate matter exposure under different ventilation and air filtration strategies in a kindergarten

J.L. Sánchez-Jiménez*[1], M. Ruiz de Adana[1]

1 Department of Chemistry, Physics and Applied Thermodynamics
University of Cordoba, Spain
**Corresponding author: p02sajij@uco.es*

ABSTRACT

Many children between 1 and 3 years of age spend a fraction of their time in kindergartens. Poor indoor air quality, IAQ, could negatively affect children's health, particularly respiratory health, attendance, and academic achievement. Children are at greater risk of getting severe health consequences from indoor air since their bodies are still developing, and children are more susceptible to the effects of air contaminants because they play closer to the ground, engage in more hand-to-mouth activities, and have a decreased ability to identify and protect themselves from potential threats. IAQ and exposure of children to PM2.5 particulate matter in kindergarten depends on the strategy of ventilation and filtration used. In this paper, an assessment of PM2.5 particulate matter exposure under different ventilation and filtration systems strategies in a kindergarten was performed.

This study was carried out in a kindergarten for children aged 1-3 years located at Cordoba, Spain. A classroom of 114.87 m3 with 12 children and one teacher was chosen. PM2.5 particulate matter values were measured in the breathing zone of children (0.65 m) under three scenarios: a) no ventilation system; b) mechanical ventilation system; c) portable air cleaner and d), a combination of mechanical ventilation and portable air cleaner. The measured data were analysed according to the type of activity performed by the children during the school day (9:05-13:30). The results showed that the intake mass was reduced indoor the classroom with the ventilation system (11%) when concentration of PM2.5 particles outdoor was low. However, if concentration of PM2.5 particles outdoor was high the intake mass was worsened by using the ventilation system (353%), by using the portable air cleaner (50%) and by a combination of both systems (144%).

These results suggest that outdoor concentration has a high influence on indoor concentration. Therefore, to improve indoor air quality it is suggested the use of adequate air filters to avoid the ingress of outdoor contaminants to control the indoor PM2.5 particles concentration.

KEYWORDS

Air quality, particulate matter, kindergarten, ventilation system, portable air cleaner

1 INTRODUCTION

Respiratory diseases are one of the main conditions in the paediatric population, especially at an early age. These common illnesses include asthma, bronchitis, pneumonia, influenza and more recently covid19 (Cho, 2019), (Peláez, 2019). Indoor air quality is a critical factor that can significantly influence the incidence and severity of these diseases. Kindergartens, where children spend a large amount of time indoors (Daisey, 2003), are particularly sensitive environments. Children have developing respiratory systems and are more vulnerable to air contaminants such as fine particulate matter (PM2.5). These particles can come from a variety of sources such as outdoor (Guo, 2010), from furniture or the children themselves depending on the daily activities indoor the classroom (Wang, 2015). Young children are more vulnerable to indoor air contaminants compared to adults (Ciencewicki, 2008). Long-term exposure to contaminated air can affect children's lung development, causing them to be less resistant to air contaminants (Hou, 2015). Therefore, ensuring good indoor air quality in these environments is crucial to protect children's respiratory health and promote healthy development.

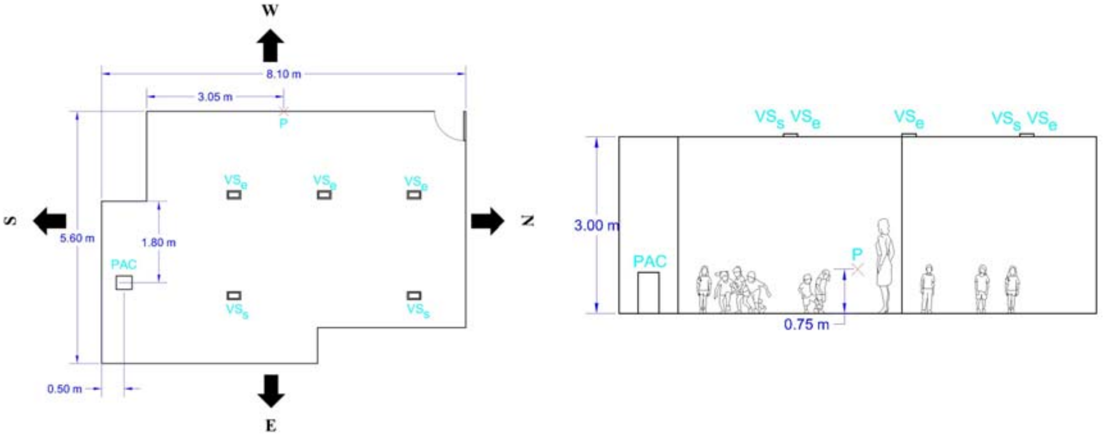
Recent research has shown that the implementation of adequate ventilation strategies and the use of air cleaners can significantly reduce indoor air contaminant levels. In (Han, 2023) the evolution of the concentration of PM2.5 in a kindergarten was studied. The increase in the flow rate of the ventilation system increased the concentration of PM2.5 by 20%, as the system did not have a filter installed, thus supplying contaminated air indoors. In order to compensate for this, two portable air cleaners were used at their maximum air flow rate. With the installation of a MERV13 filter in the ventilation system, the concentration of PM2.5 was reduced by 52%. In a similar study in a kindergarten in Shanghai (Gao, 2019), a mechanical ventilation system with a high efficiency filter (HEPA) significantly reduced the concentration of PM2.5 (from 85.7 µg/m3 to 29.1 µg/m3) by 66%.

Due to the limited experimental data available in the literature, the need for experimental studies emerged. The main objective of this work was to evaluate the indoor air quality in a kindergarten located in Cordoba (Spain) under different strategies using ventilation systems and/or portable air cleaners. In addition, the influence of the outdoor concentration on the indoor air quality of the kindergarten was analysed. The concentration of PM2.5 inhaled by a child was also evaluated according to the activity performed during a school day.

2 METHODOLOGY

2.1 Experimental classroom

The experimental study was carried out in a classroom in a kindergarten located in the city of Cordoba, Spain. The classroom, 8.10 m length, 5.60 m width and 3.00 m height, has an area of 41 m^2 and a volume: 123 m^3, see figure 1, is occupied by 11 children and one teacher. The experimental study was carried out on different days, always in the same period from 9:05 am to 1:30 pm. The classroom had no openings with the outdoor environment through windows or doors. Only a door leading to the kindergarten corridor, was opened temporarily with the movement of children or opened for a period when the children were outdoor the classroom.



(a) (b)

Figure 1. Experimental classroom setup: (a) Plan view (b) Elevation view.

2.2 Ventilation/filtration systems

The classroom had a ventilation system, VS, (CDA0707F145M41H, NINSUR, Spain) previously installed. VS supplied air from outdoor into the classroom through two grille diffusers, VSs, (0.24x0.12 m) and exhausted it to the street through three grilles with the same dimensions, VSe, see figure 1. VS supplied and exhausted an airflow rate of 175 m^3/h (1.4 h^{-1}). The VS did not incorporate any filters; therefore, the outdoor air was supplied unfiltered into the classroom. A portable air cleaner, PAC, (Pure Airbox Home, ZonAir 3D, Spain) was placed near the South wall of the classroom, see figure 1. PAC exhausted classroom air from the bottom and supplied filtered air through a rotational diffuser (DLQ, Trox, Germany) with an airflow rate of 235 m^3/h (1.9 h^{-1}). PAC incorporated a G4/Coarse 60% filter and an ePM1 95% filter.

2.3 Measurement equipment and experimental tests

For the measurement of the indoor concentration of PM2.5 particles, a sensor, P, (EcomZen2, DILUS, Spain) was placed on a wall of the classroom at the height of the children's breathing zone, 0.75 m, as can be seen in figure 1b. The sensor was placed on the West wall, see figure 1a, of the classroom. Outdoor particle concentration data were obtained from the Cordoba-Lepanto outdoor measuring air quality station (Junta de Andalucía, 2024). The air quality station is located 500 metres from the kindergarten studied and used a PM2.5 sensor (SPS30, Sensirion, Switzerland).

Five experimental cases were carried out: without ventilation (NV), using the ventilation system (VS1), using the portable air purifier (PAC), combining both systems (VS+PAC). Since the outdoor concentration was different in VS and VS+PAC, therefore, another experimental case was performed using the ventilation system (VS2), see table 1.

Table 1. Experimental tests.

Experimental case	Date	Timetable	Airflow rate		Equivalent airflow rate	
			m^3/h	h^{-1}	m^3/h	h^{-1}
NV	14/03/2023	9:05 to 13:30	49	0.4	0	0
VS1	09/03/2023		175	1.4	0	0
VS2	29/03/2023		175	1.4	0	0
PAC	28/03/2023		235	1.9	0	0
VS+PAC	21/03/2023		175	1.4	410	3.3

The classroom teacher had a fixed method of working: every 30 minutes she changed her activity (events). In order not to interfere with her working method, this study was adapted to this methodology. Depending on the activity performed by the children, the rate of inhaled airflow varied (Wang et al., 2015). All this can be seen in table 2.

Table 2. Working methodology.

Event	Time	Description	Inhaled airflow rate (m3/min)
1	9:05-9:30	Children's entrance	$1.2 \cdot 10^{-2}$
2	9:30-10:00	Playing standing up	$1.2 \cdot 10^{-2}$
3	10:00-10:30	Sitting talking	$2.1 \cdot 10^{-2}$
4	10:30-11:00	Outdoor the classroom	0
5	11:00-11:30	Playing standing up	$2.1 \cdot 10^{-2}$
6	11:30-12:00	Sitting watching TV	$4.5 \cdot 10^{-3}$
7	12:00-12:30	Sitting at lunch	$4.5 \cdot 10^{-3}$
8	12:30-13:00	Sitting watching TV	$4.5 \cdot 10^{-3}$
9	13:00-13:30	Playing standing up	$2.1 \cdot 10^{-2}$

2.4 Indoor/Outdoor (I/O) ratio

To assess the relationship between the indoor and outdoor PM2.5 concentration, the I/O index has been used (Chen & Zhao, 2011), (Abhijith, 2024), (Li, 2024):

$$I/O = \frac{\bar{C}_{in}}{\bar{C}_{out}} \tag{1}$$

Where $\bar{C}_{in}$ is the average concentration of PM2.5 (µg/m^3) in the indoor and $\bar{C}_{out}$ is the average concentration of PM2.5 (µg/m^3) in the outdoor in the same period of time.

2.5 Intake mass

To assess the exposure of children to PM2.5 particles under different ventilation strategies, an index indicating intake mass, IM, by a child (2) has been used (Nazaroff, 2008):

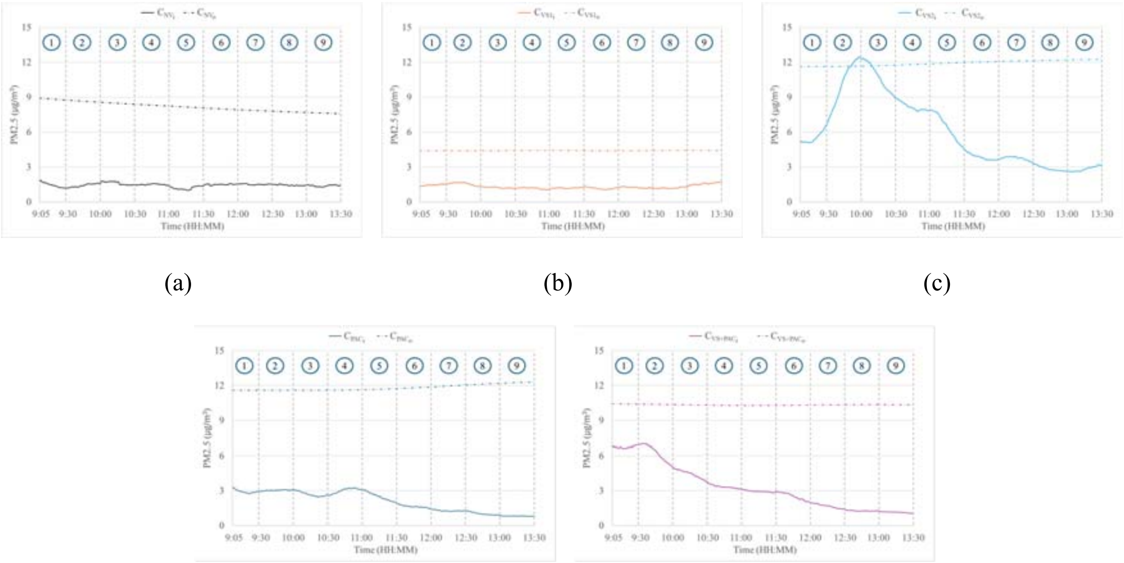
$$IM = \int_{t_0}^{t_f} C(t) \cdot \dot{Q}(t) \cdot dt \tag{2}$$

Where IM is the intake mass (µg) by a child, C is the concentration of PM2.5 (µg/m^3), $\dot{Q}$ is the inhalation airflow rate of a child (m^3/min), t_f and t_0 are final time (min) and initial time (min) respectively.

3 RESULTS

3.1 PM2.5 concentration: indoor vs outdoor

The figure 2 shows the temporal evolution of indoor and outdoor PM2.5 particle concentration during the school day for all experimental (Martins & Carrilho da Graça, 2017).



(a) (b) (c)

(d) (e)

Figure 2. Temporal evolution of the concentration PM2.5 indoor and outdoor: (a) NV (b) VS1 (c) VS2 (d) PAC (e) VS+PAC

For the experimental case NV, it can be observed how the indoor concentration of PM2.5 particles, figure 2a, remained steady with the entry of children into the classroom (event 1). From 10:30 the concentration started to increase slightly when children started to play freely (event 2). Subsequently, concentration remained steady when the children sat on the floor to do an activity (event 3). On this day, the children left the classroom earlier, in the middle of event 3, and the corridor door was kept open. Therefore, concentration decreased in event 3 and remained steady until 11:00 (event 4). When children entered the classroom, they were playing freely (event 5). However, it can be observed that the concentration decreased, this was due to the fact that on this day the teacher kept the corridor door open until 11:15. At that time the corridor door was closed, and concentration started to increase due to the children's activity. At 11:30, the children sat down to watch TV until 12:00 (event 6) which made the concentration steady. This concentration remained steady until 13:00 as the children remained seated. From 13:00 onwards, the children went back to playing freely around the classroom and concentration increased slightly. For this day, the outdoor particle concentration (average concentration of 8.1 $\mu g/m^3$) was not high, figure 2a. However, for this experimental case, as the ventilation was not turned on, there was no entry of particles from outdoor. Therefore, the only source of particles was from the children and the teacher.

For the experimental case VS1, it can be seen in the figure 2b how the concentration of PM2.5 increased exponentially in event 1. This increase occurred until the middle of event 2. From that moment on, the concentration decreased as the children started the activity corresponding to event 3. At the beginning of event 3, the concentration started to stabilise until the end of event 4. Therefore, there was no reduction in concentration, but it remained constant. When the children entered the classroom, the concentration increased slightly in event 5. Already in event 6 the concentration decreased again because the children were seated and therefore their exhalation rate decreased. Until 13:00 the concentration remained steady. However, at event 9, the concentration increased because the children's exhalation flow increased as they were playing freely in the classroom. In figure 2b it is shown that the outdoor concentration (average concentration of 4.4 $\mu g/m^3$) on this day remained steady. A low concentration was observed, so although it was constantly entering the indoor of the classroom, it did not have much effect on the indoor concentration.

Just the opposite happened for the experimental case VS2. In figure 2c it can be seen how the outdoor concentration was high (average concentration of 12.0 $\mu g/m^3$) and therefore influenced the indoor concentration, as the ventilation system did not filter the outdoor air. Figure 2c shows how the initial concentration was higher than in the previous experimental cases, possibly due to the outdoor concentration supplied through the ventilation system before the measurement started. During event 1 and 2 the concentration increased until it reached a peak of 12.3 $\mu g/m^3$. Thereafter, the concentration decreased because the children's airflow decreased in event 3 and because they left the classroom in event 4. In the middle of this event, the concentration stabilised until the beginning of event 5. This led to a decrease in concentration until stability was reached in the middle of event 6. This stability was maintained until the middle of event 9, after which the concentration increased slightly due to the children's increased exhalation.

In the PAC experimental case, the concentration was different from the previous days, as can be seen in figure 2d. Although the exhalation flow rate of the children was high in event 1 and 2, the concentration did not increase due to the operation of the PAC. Furthermore, it should be noted that the children performed the activity corresponding to event 3 in the middle of event 2. Therefore, the children left the classroom in the middle of event 3 and re-entered the classroom in event 4. However, the concentration stabilised at levels similar to the beginning of the day, possibly due to the effect of the PAC. From event 5 onwards, the children were seated. This facilitated the task of the PAC, therefore the concentration decreased until the end of event 8. Already at event 9 the concentration stabilised because the children were playing freely, which led to an increase in the children's exhalation rate and meant that the concentration did not continue to decrease. During the school day, the outdoor concentration was high (average concentration of 11.9 $\mu g/m^3$), see figure 2d. However, as the ventilation system was not switched on, this concentration had no influence on the indoor concentration.

For the VS+PAC experimental case a high initial concentration was assumed, figure 2e, due to the fact that the ventilation system supplied a high external concentration (average concentration of 10.3 $\mu g/m^3$), see figure 2e. The ventilation system caused the high initial concentration; however, this concentration did not increase due to the PAC effect. As in the PAC experimental case, the activity corresponding to event 3 was carried out in the middle of event 2, which led to a decrease in the concentration, due to the decrease in the airflow of the children and the operation of the PAC. This lead from event 3 to event 2 caused a lead in event 4, so the children left the classroom during the middle of event 3. The children returned to the classroom in the middle of event 4 and kept playing freely until the end of event 5. From event 6 onwards, the children sat down, and the concentration decreased again until it stabilised in event 9 due to the children playing freely in the classroom again.

3.2 Indoor/Outdoor (I/O) ratio

The relationship between the concentration of outdoor PM2.5 and indoor PM2.5 was obtained using the I/O index. The results obtained for each experimental case are shown in figure 3.

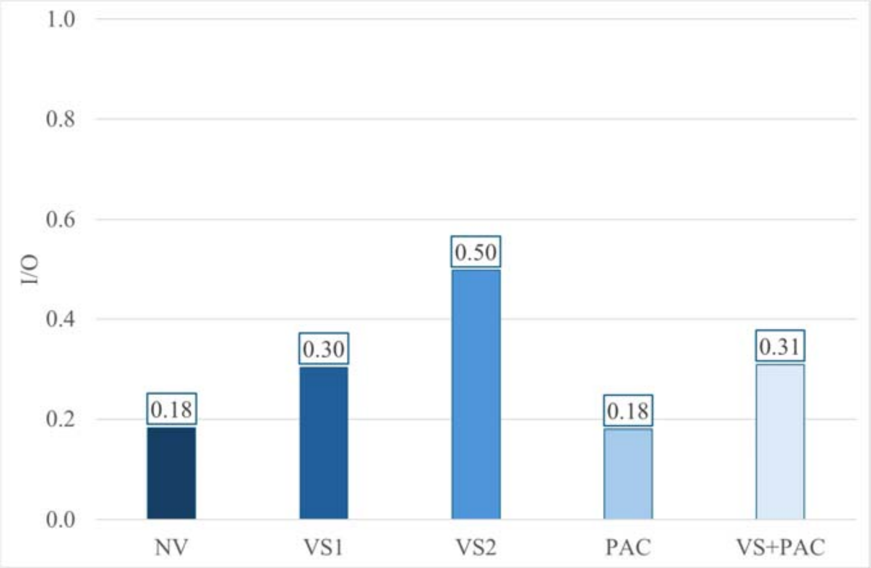


Figure 3. Indoor/Outdoor PM2.5 concentration ratio under different ventilation strategies.

In NV, an I/O value of 0.18 was found as can see in figure 3. The non-ventilation case was very effective in controlling indoor PM2.5 concentrations, thus suggesting that particles from outdoor were not entering significantly, which is to be expected when the environment is controlled. The low initial concentration, as shown in figure 2a, together with the non-existent ventilation, probably allowed the indoor concentration to stabilise close to the outdoor levels, resulting in a low I/O value. For VS1, the I/O value increased to 0.30, showing that although most of the outdoor PM2.5 was not entering indoors, the unfiltered mechanical ventilation allowed a higher ingress of PM2.5 compared to no ventilation. The low initial concentration (figure 2b) contributed to the value not being higher, but the non-filtered inlet air allowed more particles to enter indoors. At VS2, an even higher I/O value of 0.50 was reached, indicating that the indoor PM2.5 concentration was half of the outdoor concentration. This higher value suggests a higher accumulation of PM2.5 before the start of ventilation, as seen in figure 2c. Ventilation without a filter allowed the indoor and outdoor concentrations to equalise more quickly, resulting in a high I/O value. A similar value of I/O was found in (Evans, 2000) to that achieved in VS2. In PAC, an I/O value of 0.18 was again found, similar to NV. The use of a portable air cleaner was very effective in keeping indoor PM2.5 concentrations low, thus proving its efficiency in removing particles from the air. At VS+PAC, an I/O value of 0.31 was achieved, similar to VS1. This indicates that approximately one third of the outdoor PM2.5 was present indoor, resulting in moderate protection against outdoor PM2.5. Combining the ventilation system with the portable air cleaner improved the situation compared to ventilation alone (VS1 and VS2) but was not as effective as the air cleaner alone or no ventilation. The high initial concentration (figure 2e) required more time to achieve low indoor concentrations. The I/O value reflects a significant reduction, but not as low as with the air cleaner alone, due to the high initial concentration. These results indicate the importance of filtration in ventilation systems to control indoor air quality and the effectiveness of filters air cleaner in reducing PM2.5 concentrations. In addition, the initial PM2.5 concentration had a significant impact on I/O values. Higher initial concentrations tended to result in higher I/O values, as the ventilation system required more time to remove the accumulated particles. Systems with effective filtering, such as the PAC, show a superior ability to keep I/O values low, even if the initial concentration was moderate. The combination of different ventilation strategies can significantly influence the indoor PM concentration and the resulting I/O values.

3.3 Daily intake mass

The daily intake mass, IM, by a child indoor the classroom at the end of the school day is shown in figure 4 for all experimental cases.

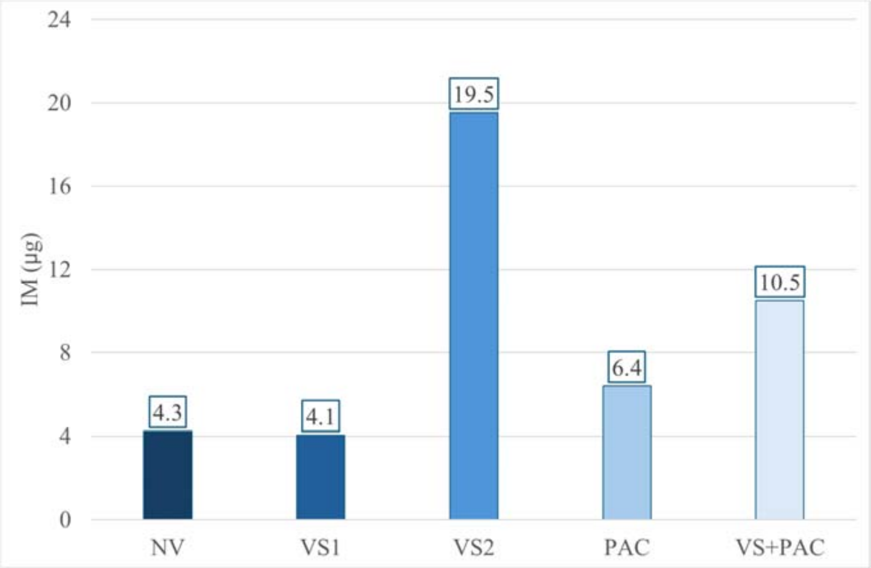
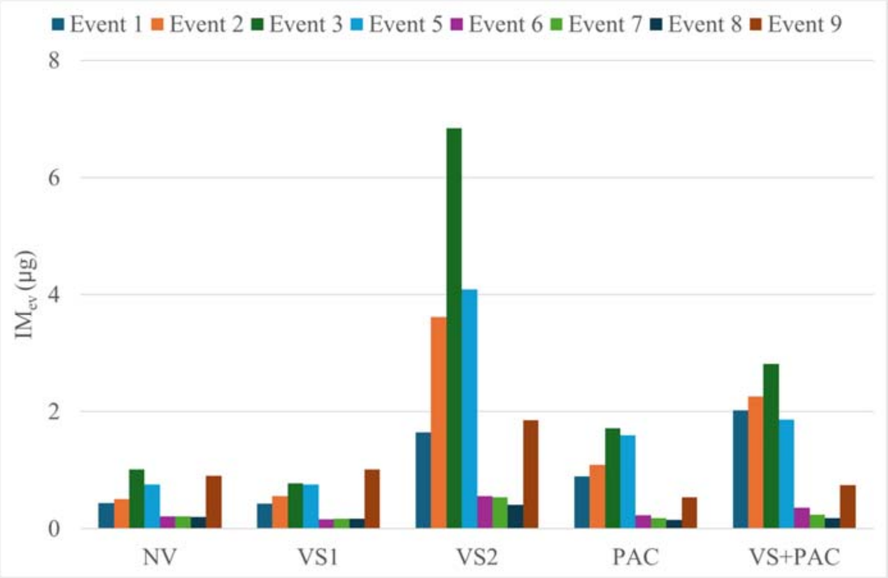


Figure 4. Daily intake mass, IM.

The maximum value of IM (19.5 µg) was found for VS2. However, for VS1 the minimum value of IM (4.1 µg) was achieved, as can been see in figure 4. In figure 2 it can be observed clearly that the initial concentration influences the IM at the end of the school day. For the experimental cases NV and VS1, the initial concentration was low, as can be seen in figure 2a and 2b. For NV the outdoor concentration had no influence, as the ventilation system was turned off. For VS1 it also had no influence on the indoor concentration, as the outdoor concentration was low on that day. This caused that for NV and VS1, the IM was 4.3 µg and 4.1 µg respectively. However, for the experimental cases VS2, PAC and VS+PAC the initial concentration did influence the IM. Moreover, on these days the outdoor concentration was high in VS2 and VS+PAC, which caused the IM to be high, 19.5 µg and 10.5 µg respectively. On the other hand, although the ventilation system was not turned on for PAC, the high initial concentration caused the IM to be 6.4 µg.

3.4 Daily intake mass by events

The daily IMev by a child indoor the classroom in each event during the school day is shown in figure 5 for all experimental cases. For each experimental case the IMev value in µg and in % is shown. In % corresponds to the percentage of IMev in each event with respect to the total (figure 4). Event 4 was not considered in this analysis, as the children were outdoor the classroom.



Event 1	0.44	10%	0.43	11%	1.65	8%	0.89	14%	2.02	19%
Event 2	0.50	12%	0.56	14%	3.61	18%	1.09	17%	2.26	22%
Event 3	1.02	24%	0.78	19%	6.84	35%	1.71	27%	2.82	27%
Event 5	0.75	18%	0.75	19%	4.09	21%	1.59	25%	1.87	18%
Event 6	0.21	5%	0.17	4%	0.56	3%	0.24	4%	0.36	3%
Event 7	0.22	5%	0.18	4%	0.54	3%	0.18	3%	0.24	2%
Event 8	0.21	5%	0.17	4%	0.41	2%	0.15	2%	0.18	2%
Event 9	0.90	21%	1.02	25%	1.85	9%	0.54	8%	0.75	7%

Figure 5. Daily intake mass by events, IM_{ev}.

Figure 5 shows that the event with the highest IM was event 3, 6.84 µg (35%), 2.82 µg (27%), 1.71 µg (27%) and 1.02 µg (24%), for the experimental cases VS2, VS+PAC, PAC and NV respectively. These measurements are in accordance with the fact that event 3 is the event that proceeds the initial events, which is when there was the most activity in the classroom. However, for VS1, although the IM in event 3 was high, 0.78 µg (19%), the highest IM was obtained in event 9, 1.02 µg (25%). For NV and VS1 the initial IM were similar, 0.44 µg (10%) and 0.50 µg (12%) (event 1 and 2) and 0.43 µg (11%) and 0.56 µg (14%) respectively. In contrast, for VS2, PAC and VS+PAC, the IM in event 1 was 1.65 µg (8%), 0.89 µg (14%) and 2.02 µg (19%) respectively and 3.61 µg (18%), 1.09 µg (17%) and 2.26 µg (22%) in event 2 respectively. This once again confirms that on these days the initial concentration played an important role, as it affected the measurements made during the school day. The lowest concentrations were found in events 6, 7 and 8 for all experimental cases. These events were the ones in which the children were least physically active. The IM increased in all experimental cases in event 9, as the children were playing around the classroom freely.

4 CONCLUSIONS

This study assessed the PM2.5 concentration in a kindergarten located in Córdoba (Spain) under different strategies: no ventilation (NV), only ventilation system (VS1-VS2), only portable air cleaner (PAC) and combination of both systems (VS+PAC). The main conclusions derived from the research are presented below:

- The indoor concentration of PM2.5 behaved in relation to the activity carried out in the classroom by the children. However, the PM2.5 indoor concentration in the classroom was also influenced by outdoor PM2.5 concentrations.
- Intake mass (IM) and I/O ratio showed a significant correlation in different scenarios. In situations without outside air intake (NV and PAC), both IM and I/O ratio were low, indicating effective protection against external particles. However, in situations with outdoor concentration input (VS2 and VS+PAC), the correlation was also significant. However, in VS1, where ventilation without adequate filtration was used under low outdoor concentration conditions, no such a clear correlation was observed.
- Depending on the I/O ratio, an adequate ventilation strategy should be used with an adequate filtration system. If I/O ratio are high, ventilation system with inappropriate air filters increases the daily IM by a child. In these situations, a PAC with appropriate air filters are useful to reduce the daily IM by a child.

These results show the needs to understand the indoor-outdoor concentration of PM2.5 in order to limit the exposure of children to PM2.5 under different ventilation strategies.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support received from the Spanish Ministry of Science, Innovation and Universities to the National R&D project BIORISK with reference RTI2018-094703-B-I00, entitled "Bioaerosols in hospital environments. Control and evaluation of the infection risk". This project is financed by the European Regional Development Fund (ERDF).

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