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Effect of filter type in ventilation systems on NO_2 concentrations in classrooms

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Abstract
This study was conducted to assess how different filter types in the ventilation system affect the indoor NO_2, concentrations. Measurements were carried out in two classrooms and air intakes in a primary school located in Oslo, Norway. A regular F7 particle filter and an F7 combination filter with activated charcoal lining were compared. NO_2 concentrations were measured for five weeks during winter 2017 in a cross-over study design to compare: 1) NO_2-levels in classrooms with regular filter (RF) versus combination filter (CF); 2) indoor/outdoor ratio with regular filter versus combination filter. One-hour average concentrations are reported during operating time of the ventilation system (6:00-23:00) and during hours with high (> 40 µg/m^3) outdoor NO_2 concentrations.
The measured average NO_2 concentrations in both classrooms with an RF were significantly higher than with a CF. The median CF/RF ratios for the two classrooms were 0.50 and 0.81 during hours with high NO_2 concentrations, and 0.48 and 1.00 during the period the ventilation system was operational. During hours with high NO_2 concentrations, the median indoor/outdoor ratios for the two classrooms with an RF were above 1.00, while the corresponding ratios with a CF were 0.78 and 0.75.
Our results demonstrate that a combination filter is more efficient than a regular filter in reducing NO_2 concentrations in classrooms during hours with high outdoor concentrations.

Keywords: NO_2,Ventilation, Filtration, School, Filter efficiency, Indoor, Outdoor

1 Introduction

Studies have shown associations between high levels of traffic-related pollutants and respiratory health effects, especially among children as they are a sensitive subgroup [1]. Road traffic is one of the major sources of nitrogen dioxide (NO_2). In Nordic countries, exceedances of NO_2 concentration are recurrent during winter and specially associated with inversion periods. Children spend majority of their daytime indoors in schools and very limited of their time outdoors. Especially for schools situated near roadways with high traffic intensity, it is important to minimize the levels of air pollutants in the classrooms. The ventilation system is one of the factors influencing the concentration of NO_2 in classrooms in Norway. Conventional bag air filters are installed in most ventilation systems in Norwegian schools and studies have shown that ventilation systems with air filtration are efficient in reducing particle concentrations in classrooms [2–4]. However, these filters do not account for gaseous components such as NO_2. Furthermore, majority of the existing studies on indoor air quality in schools provide limited information on ventilation systems [5,6].

Given that buildings, such as schools, are more frequently built near roads with high traffic intensity, the aim of our study was to investigate how different filter types in the ventilation system can influence the NO_2 concentrations in classrooms in a school closely situated to a highway.

2 Methods

2.1 Study design

The study was carried out at a primary school situated 500 m southwest of a highway (Ring 3, see Figure 1). The school was finished in August 2016 after passive-house standards and has a capacity of 840 students. It has concrete floor slabs covered with linoleum, walls are timber frame insulated with 300 mm mineral wool, and are generally clad with 13 mm plasterboard with acrylic paint. Materials and paint are either M1-certified or implicitly low-emitting. The school has demand controlled ventilation (DCV) with CO_2- and temperature control in each classroom. All classrooms have balanced supply and exhaust mechanical ventilation with heat exchange. The ventilation system has bag air filters of class F7 type Standard-Flo XLT 7. An overview of the characteristics of the school and the classrooms is provided in Table 1.

Table 1. Characteristics of the study site.

Characteristics	
Traffic intensity	57 526 vehicles/day
Distance to highway	500 m
Floor area of study classrooms	61 m^2
Height of study classrooms	2.8 m
Volume of study classrooms	170.8 m^3
Air change rate	7.3 h^{-1}
Airflow rate	20.5 m^3/h per m^2

Inversion periods can occur during winter, which can result in elevated concentrations of outdoor air pollutants. Subsequently, continuous measurements were taken between 24 January and 1 March 2017, as high outdoor NO_2 concentrations can be expected. To compare the effectiveness of two different types of filters, measurements were taken inside two classrooms and in the corresponding air intakes. The two classrooms are similar in size and situated on the third floor, separated by a room in between. One of the classrooms was occupied by elementary pupils, whereas the other one was used sporadically. The ventilation system was operational between 6:00 and 23:00. To ensure similar air change rates in both classrooms during the sampling campaign, the ventilation was set to a maximum airflow rate of 20.5 m^3/h per m^2.

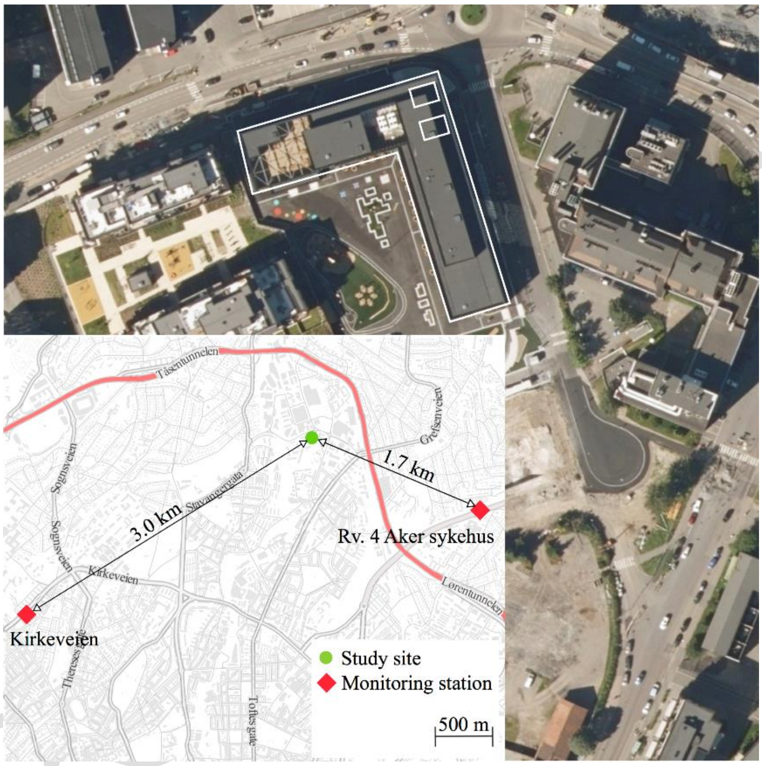

Fig. 1. Location of the school (white L-shaped, green circle) in Oslo, Norway, and the two classrooms (white square). The monitoring sites (diamond shaped) are situated 3.0 km southwest (Kirkeveien) and 1.7 km southeast (Rv. 4 Aker sykehus). The Ring 3 highway is marked in red. (Image source: norgeibilder.no)

New bag air filters were installed in the ventilation system at the study site. The filter types used in this study, provided by Camfil AS, consisted of a regular F7 particle filter (RF; Hi-Flo II XLT 7) and an F7 combination filter seeded with activated charcoal lining (CF; City-Flo XL7).

Two Teledyne Advanced Pollution Instrumentation (API), T200 and 200A models, were used to measure NO_2 at 1-minute intervals. For the *indoor* measurements, the instruments were placed in a small room adjacent to the classrooms to prevent noise nuisance. The air inlet tubes of the sampling instruments were placed between the supply air vents to ensure that the sampled air is representative for the classroom. To keep the air inlet tubes out of reach of the pupils in the classrooms, the measurements were done at a height of approximately 2 m. For the *outdoor* measurements, the instruments were placed outside the air intake chambers in the maintenance room at the 4th floor to protect them from rain and humidity. The air inlet tubes of the sampling instruments were placed inside the air intake chamber.

To make the most use of the two measurement instruments, the sampling plan, as shown in Figure 2, was divided into two parts:

- Effect of filter on indoor concentrations (sampling period 1 - 2)
- Comparison of indoor-outdoor concentrations (sampling period 3 - 6).

	Jan			**Feb**						**Mar**
	23	24-27	28.1-3.2	04-10	11-14	15-17	18-20	21-25	26.2-3.1	2
Sampling period			1	2	3	4		5	6	
Classroom 1			**RF**	**CF**	**CF**	**RF**				
Classroom 2			**CF**	**RF**				**CF**	**RF**	
Air intake room 1										
Air intake room 2										

Fig. 2. Measurement plan. CF = combination filter, RF = regular filter.

2.2 Data collection and analysis

The raw NO and NO_x data were extracted and calculated into 1-hour average NO_2 concentrations and used for statistical analysis. Separate analyses were done for the period the ventilation system was operational (6:00 -23:00) and for hours with high (> 40 µg/m^3) outdoor NO_2 concentrations. The annual mean NO_2 limit value of 40 µg/m^3 was used to indicate high outdoor concentrations.

To assess the effect of filter type on the indoor concentrations, we calculated the median ratios of 1) NO_2-levels in classrooms with combination and regular filter (CF/RF), and 2) the indoor/outdoor (I/O) with combination and regular filter. The median is less influenced by outliers. To see how representative the measurements taken at the air intakes at the study site are with the outdoor concentrations, we also collected NO_2 measurement data from two monitoring stations situated in a distance of 1.6 km and 3.0 km (see Figure 1).

The statistical differences between mean concentrations were calculated by t-test. Statistical analyses were performed with R (http://www.R-project.org).

2.3 Data quality and control

Measurements and quality control procedures were done in accordance with the EU's air quality directive 2008/50/EC. The instruments were calibrated and scaled with zero-gas and span-gas between each sampling period. Parallel measurements were done at the beginning and the end of the study in the air intake of one classroom to compare the two instruments. Co-location of the two instruments indicated an average measured

NO_2 concentration difference of 7%. A very high correlation was found between measurements obtained from the two instruments (R^2=0.99).

3 Results

3.1 NO_2 concentrations

During the entire measurement period, the average NO_2 concentration measured in the air intakes of the two classrooms was 26.51 µg/m^3 (range: 0.32-74.41 µg/m^3). In comparison, the average concentrations measured at the monitoring stations were higher, 44.16 µg/m^3 at the Kirkeveien monitoring station (3.0 km southwest) and 42.15 µg/m^3 at the Aker sykehus monitoring station (1.4 km southeast). NO_2 measurements taken at the study site were moderately to highly correlated with those taken at monitoring stations (Kirkenveien: R^2 = 0.61; Aker: R^2 = 0.52).

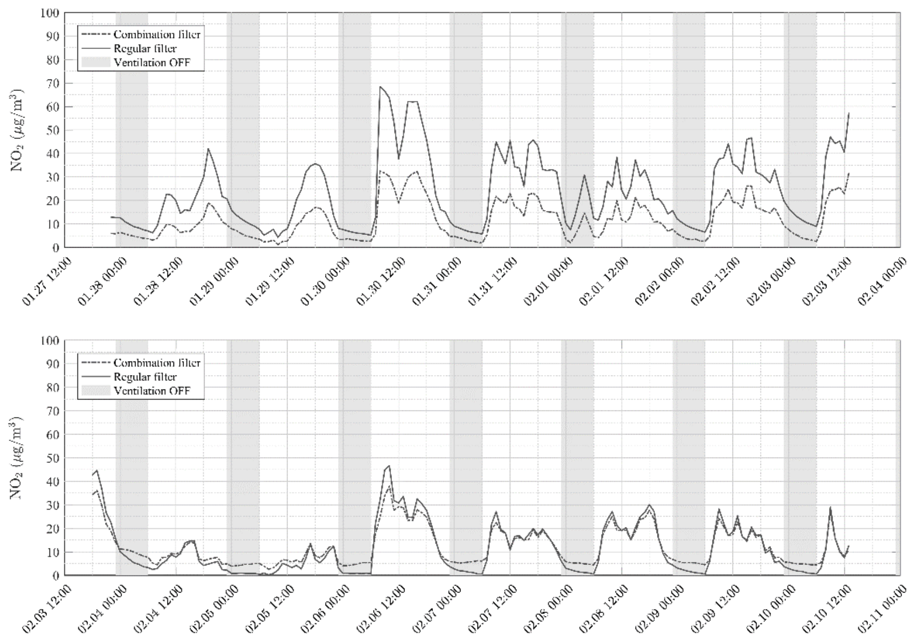

Fig. 3. NO_2 concentrations measured simultaneously inside two classrooms during sampling period 1 and 2. The filters in the ventilation systems of the two classrooms were switched between the measurement periods. Values are 1-h averages.

3.2 Impact of filter type on concentrations in classrooms

Figure 3 shows the measured NO_2 concentrations inside the two classrooms during sampling period 1 (upper, combination filter in classroom 2 and regular filter in classroom 1) and period 2 (lower, combination filter in classroom 1 and regular filter in classroom 2). For both sampling periods, the average NO_2 concentration in the classrooms were significantly lower with the combination filter (14.6 and 14.8 µg/m^3) than with the regular filter (29.6 and 15.4 µg/m^3) in the ventilation system, especially during sampling period 1 (see Table 2). The concentrations in the two classrooms with different filters were similar during sampling period 2, where also few hours with high outdoor NO_2 concentrations were observed (see Table 2, N=4).

As seen in Table 2, the median CF/RF ratios were lower for sampling period 1 than for sampling period 2, indicating a 52% reduction in indoor NO_2 concentrations with CF compared to RF during the period the ventilation system was operational. Furthermore, the reduction in NO_2 concentrations in the classrooms with CF was generally higher during hours with high outdoor NO_2 concentrations than during the period the ventilation system was operational.

Table 2. Mean (standard deviation) NO_2 concentrations measured indoor (with CF and RF) and outdoor during the period the ventilation system was operational and during hours with high (> 40 µg/m^3) outdoor concentrations, and the number of 1-h measurements.

		Indoor				
Sampling period	**N**	**Combination filter (CF)**	**Regular filter (RF)**	**Outdoor**	**Median CF/RF ratios**	**Median I/O ratios**
	Ventilation operating time (6:00 - 23:00)					
1	111	14.6 (7.9)**	29.6 (14.8)		0.48	
2	115	14.8 (8.1)*	15.4 (10.6)		1.00	
3	72	24.8 (14.9)**		29.6 (21.6)		0.90
4	39		45.6 (9.2)**	42.1 (8.1)		1.07
5	86	27.2 (12.4)		27.7 (15.4)		0.97
6	46		32.2 (12.9)**	28.1 (12.1)		1.14
	Hours with high outdoor NO_2 concentrations					
1	25	25.8 (4.1)**	50.4 (8.8)		0.81	
2	4	35.5 (1.9)**	44.7 (1.7)		0.50	
3	25	41.0 (6.2)**		53.6 (10.6)		0.78
4	28		50.0 (3.2)**	46.1 (3.1)		1.06
5	16	42.1 (8.8)**		55.3 (9.1)		0.75
6	9		51.2 (3.9)*	48.0 (3.7)		1.07

$^{*}p < 0.05$, $^{**}p < 0.001$

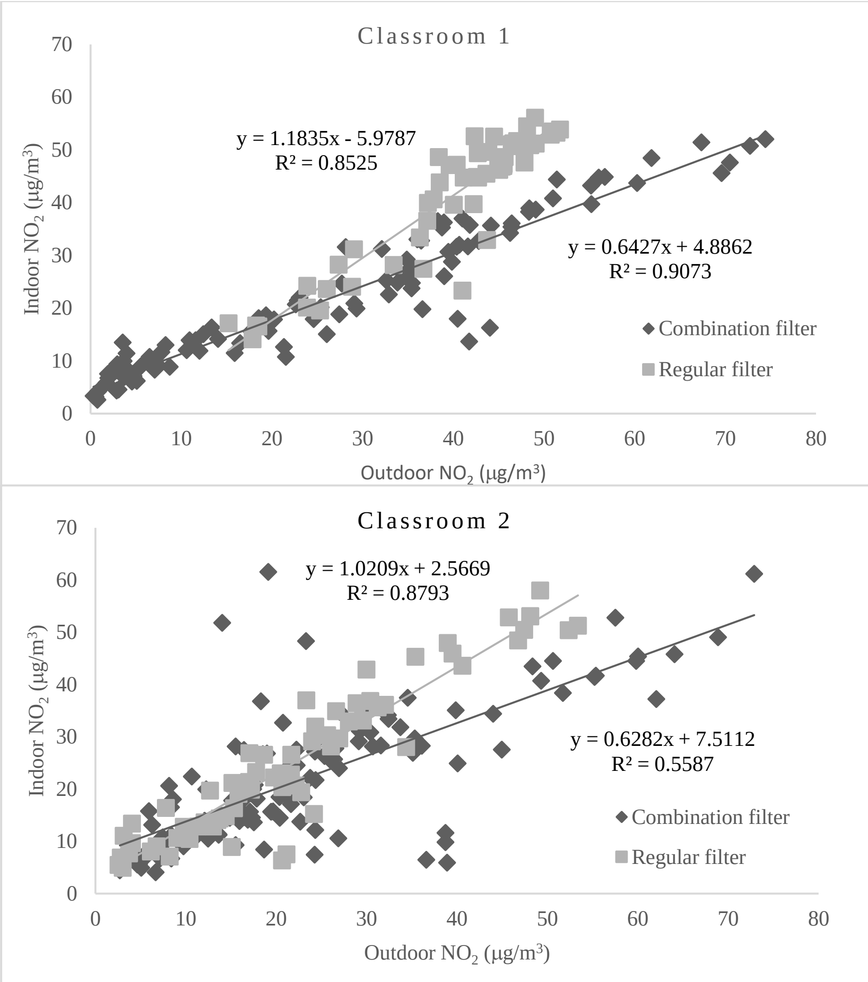

Fig. 4. Scatterplots of 1-h average (00-24 hours) NO_2 concentrations measured outdoor and indoor during sampling period 3-4 (upper) and 5-6 (lower).

3.3 Comparison of indoor/outdoor NO_2 concentrations

The measured indoor and outdoor concentrations and the median I/O ratios are shown in Table 2. The average outdoor concentrations were lowest (27.7 µg/m^3) during sampling period 5 and highest (42.1 µg/m^3) during sampling period 4. During the period the ventilation system was operational, the median I/O ratios were 0.90 and 0.97 with combination filter in the ventilation system. These median I/O ratios decreased with 13% and 23%, respectively, during hours with high outdoor NO_2 concentrations. These results indicate that a higher filter efficiency is achieved during hours with outdoor NO_2 concentrations. In comparison, the median I/O ratios were above 1.00 with the regular filter in the ventilation system, resulting in higher NO_2 concentrations indoors than outdoor. During sampling period 6, where few hours of high outdoor concentrations were observed, the median I/O ratio was 1.14 during the operational hours of the ventilation system. In comparison, the median I/O ratio for sampling period 5 was 1.07.

To evaluate how the CF reduces the NO_2 concentrations in the two classrooms compared with RF, median I/O ratios during sampling periods with CF (3 and 5) were compared to those during the sampling periods with RF (4 and 6). This resulted in a reduction of 15% and 16% in median I/O ratio by the CF during the period the ventilation system was operational, and a reduction of 26% and 30% during the hours with high outdoor NO_2 concentrations.

Scatterplots of indoor/outdoor NO_2 concentrations are shown in Figure 4. The slope of the regression equations represents the fraction of NO_2 penetrating into the classrooms. The high R^2 (0.56 – 0.91) demonstrates that the outdoor concentrations explained a large part of the total variation of the NO_2 concentrations in the classrooms.

4 Discussion

4.1 Outdoor versus monitoring sites

The outdoor NO_2 concentrations measured in the air intakes were on average 34% and 37% lower compared to the monitoring stations. This is probably due to the two monitoring stations being situated next to streets with higher traffic intensity, as traffic is a major source of NO_2. Nevertheless, the measurements at the monitoring sites correlated highly with the measurements taken at the air intakes of the classrooms. Similarly, a study in Norway found a higher correlation (R^2 =0.76) between NO_2 measurements taken at the location of the municipality instrument and at the office building [7]. The lower correlations found in our study could be due to the longer distances between our study site and the monitoring stations (1.7 and 3.0 km). In contrast, the distance between the office building and the monitoring station in the study by Reyes-Lingjerde [7] was only 300 m.

4.2 Effect of filter type

Our study has demonstrated that using a combination filter in the ventilation system results in lower NO_2 concentrations in the classrooms compared with a regular filter. Furthermore, the combination filter is able to remove a large percentage of the outdoor NO_2 penetrating indoor.

The regular filter resulted in increased NO_2 concentrations in the classrooms, with median I/O ratios of 1.07 to 1.14 during the hours the ventilation system is operational. This is in line with the findings by Reyes-Lingjerde [7] who also observed that the indoor NO_2 concentrations with a regular filter was 8% higher than outdoor. As there were no known NO_2 sources indoors, the observed higher indoor concentrations can be attributed to the chemical reactions between NO and background ozone. A study which assessed the I/O NO_2 concentrations in 16 schools in Sweden reported an average I/O ratio of 0.96 for schools and 1.07 for pre-schools [6]. These schools had mechanical ventilation. As there were no indoor NO_2 sources present, inefficient filter in the ventilation system was provided as a possible explanation to the high I/O ratios. Blondeau et al.[5] reported average I/O ratios of NO_2 in the range of 0.88-1.17 at six schools in France. With the exception of one school that had mechanical ventilation, all others had natural ventilation. Our findings and these studies suggest that ventilation systems without a proper filter are ineffective against infiltration of outdoor NO_2. Majority of studies on I/O ratios for NO_2 lack information on the ventilation system, especially for commercial buildings and schools. The type of ventilation system and air change rates are important factors that can influence the indoor NO_2 concentration.

Compared with a few studies that have assessed the effect of different filters in the ventilation system on indoor NO_2 concentrations, we found a somewhat lower filter efficiency with the combination filter. Reyes-Lingjerde [7] found the average indoor NO_2 concentrations in an office building to be 68% lower when a combination filter was used compared to a regular filter. They also compared the indoor-outdoor concentration difference and found the indoor concentrations to be on average 72% lower with a CF compared with an RF. Partti-Pellinen et al. [8] assessed the effect of ventilation and air filtration systems on indoor NO_2 concentrations in a children's daycare center in Finland. They found that the combination of mechanical filters (type EU1, EU5 and EU7) and a chemical filter with added gas filtration unit was most efficient in removing outdoor NO_2, with a 48% reduction during weekdays and 66% during periods with high (>50 µg/m^3) outdoor NO_2 concentrations. In comparison, the filtration efficiency of a mechanical filter (EU1) was 22% during weekdays and 50% during periods with high (>50 µg/m^3) outdoor NO_2 concentrations. The lower reduction observed in our study (26-30% during hours with high outdoor NO_2 concentrations) could be explained by that filter efficiency increases with increasing outdoor concentrations. As seen during sampling period 2, where there were only 4 hours with high outdoor concentrations, we found little impact of filter type on the NO_2 concentrations in the classrooms compared to sampling period 1. The outdoor concentrations measured in our study were in the range of 2.6-72.9 µg/m^3, whereas the outdoor concentration in the study by Reyes-Lingjerde [7] were in the range of 2.5 -154.0 µg/m^3.

Compared to previous years, the measured outdoor concentrations at the monitoring stations during the study period were moderate, with the highest observed concentration of 118 µg/m^3, well below the 1-h mean NO_2 limit value of 200 µg/m^3 set by WHO. Nevertheless, during cold winter periods in Nordic countries, it would be beneficial to install combination filters in the ventilation systems, especially in buildings near areas with high traffic. However, the cost-benefits of converting from regular to combination filter could be a deciding factor. Finally, it is also important to take into consideration the lifetime (6-12 months for the filters used in our study) and maintenance of the filters, as any type of filter is only effective if frequently replaced.

4.3 Strengths and limitations of the study

The sampling plan was set up systematically to make the best use of the two sampling instruments. The study rooms were similar in layout, size and ventilation conditions.

Although there were differences in occupancy and usage of the two classroom, we found no obvious contributions of indoor sources to the NO_2 concentrations, which could have influenced our results. Furthermore, the outdoor concentrations explained a large part of the total variation of the NO_2 concentrations in the classrooms. During the study period, the outdoor temperature ranged from -9.5 to 5.4 ºC, with an average temperature of -1.2ºC. Although temperature influences the level of outdoor air pollutants, the outdoor NO_2 concentrations in the sampling period 3 to 6 did not vary much.

5 Conclusions

Our study demonstrates that installing a combination filter in the ventilation system could reduce the NO_2 concentration in classrooms. During hours with high outdoor concentrations, the combination filter can reduce the NO_2 concentrations in the classrooms with 26-30%.

6 Acknowledgements

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