1 *Article*

2 # Ventilation positive pressure intervention effect on
3 # IAQ in a school building with moisture problems

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12 **Abstract:** This case study investigates the effects of ventilation intervention on measured and
13 perceived indoor air quality (IAQ) in a repaired school where occupants reported IAQ problems.
14 Occupants´ symptoms were suspected to be related to the impurities leaked indoors through the
15 building envelope. The study's aim was to determine whether a positive pressure of 5-7 Pa prevents
16 the infiltration of harmful chemical and microbiological agents from structures, thus decreasing
17 symptoms and discomfort. Ventilation intervention was conducted in a building section comprising
18 12 classrooms and was completed with IAQ measurements and occupants´ questionnaires. After
19 intervention, the concentration of total volatile organic compounds (TVOC) and fine particulate
20 matter ($PM_{2.5}$) decreased, and occupants´ negative perceptions became more moderate compared to
21 those for other parts of the building. The indoor mycobiota differed in species composition from the
22 outdoor mycobiota, and changed remarkably with the intervention, indicating that some species
23 may have emanated from an indoor source before the intervention.

24 **Keywords:** ventilation; positive pressure; indoor air quality; mycobiota; indoor air questionnaire;
25 moisture damage

26

27 1. Introduction

28 The success of moisture- and mold-damaged building repairs depends on many factors.
29 Reaching a consensus about the necessary repair methods and schedule is not always simple, and
30 responding to problems might therefore be delayed. Occupants´ symptoms and discomfort can have
31 multiple causes, and detecting or treating them all is not always possible nor successful [1]. In cases
32 where harmful impurities remain in the structures or crawlspaces after repairs, indoor air problems
33 might still occur. It has been shown that negative pressure indoors may introduce harmful pollutants
34 [2], e.g. fungal spores [3], which may cause adverse health effects among occupants [4]. Preventing
35 infiltration of the possible impurities from the structures or surroundings, caused by high negative
36 pressure, is crucial for maintaining a good indoor air quality (IAQ). In moisture damage repairs, a
37 thorough renovation, including ventilation, is important [5].
38 Ventilation is strongly associated with perceived IAQ, health, and productivity [2,6]. Ventilation,
39 as well as indoor temperature and humidity, have a significant impact on human perceptions and
40 well-being [7,8]. Proper ventilation measurements should be an essential part of every IAQ
41 investigation [9]. In air-tight buildings with a mechanical ventilation system, the balancing and
42 controlling of the ventilation system and pressure differences are inevitable [10]. When evaluating
43 the effect of ventilation on perceived IAQ, pressure difference measurements are important [11].
44 In cold-climate countries, keeping structures dry is a main issue, and ventilation design is
45 strongly related to this objective. According to the National Building Code of Finland [12], pressure
46 conditions should not generate moisture load to structures and, at the same time, not assist pollutant
47 transfer through the structures. A ventilation design is typically balanced, or the extract airflow rate

48 is slightly higher than the supply, to prevent exfiltration of moist indoor air into the structures.
49 However, in well-ventilated buildings, the indoor air is often dry, and school buildings are typically
50 occupied only during normal office hours. In such buildings, the risk for condensation is improbable
51 despite the pressure conditions.
52   This ventilation intervention study was conducted as part of the Finnish EURA- and TOXICPM
53 -research projects concerning IAQ and ventilation in renovated school buildings and microbial toxin
54 transport mechanisms. The building discussed in this study has a history of moisture damage repairs,
55 yet occupants still report IAQ-related symptoms and discomfort. The building is awaiting new major
56 repairs. Our main hypothesis is that positive pressure differences across the building envelope could
57 prevent the infiltration of harmful chemical and microbiological agents into the indoor air of
58 damaged structures, thus decreasing occupants´ perceptions of symptoms and discomfort.
59   The aims of our research project were to determine the effects of significant ventilation system
60 changes on measured and perceived IAQ in a school building with unsolved indoor air-related
61 problems, and to provide information about the applicability of moderate positive pressure in a well-
62 ventilated building awaiting repairs. To test the hypothesis, chemical, microbial, and physical IAQ
63 measurements, as well as occupant questionnaires, were conducted before and after ventilation
64 system intervention.

65 **2. Materials and Methods**

66 *2.1 Building characteristics*

67   The study was carried out in a comprehensive school in Vantaa, Southern Finland. The school
68 was selected in cooperation with Vantaa Real Estate Center in the spring of 2016, based on its repair
69 history and the fact that a reasonable and controllable part of the building could be isolated for
70 implementing the positive pressure intervention without major ventilation system changes in the
71 building. Several microbial and structural investigations have been made since 2004, and the building
72 has experienced extensive moisture damage, air leakage, and ventilation system repairs during
73 previous years. Yet IAQ-related or unspecific complaints from the occupants have continued. New
74 structural repairs to the whole building have taken place since summer 2017.
75   The school was built in 1968 and fully renovated in 2003–2005. Approximately 700 students and
76 over 50 staff members work in the building. The mechanical supply and extract ventilation system
77 with heat recovery in all classrooms and corridors was installed in 2002. Each classroom has 2-3
78 supply air duct diffusers and 1-2 extract air grilles. Airflow rates are adjusted by dampers in the main
79 air handling unit and with regulation and measuring devices connected to each terminal device. The
80 studied section of the building as seen from the outside, and the typical supply and extract terminal
81 units of a classroom in the section, are shown in **Error! Reference source not found.**.

82

83 **Figure 1.** Studied building section, a typical supply air duct diffuser, and an extract air grille in a
84 classroom.

85   The studied part of the building consists of 12 classrooms, one corridor, six toilets, and a cleaning
86   storage area, and was served by one air handling unit. Most of the classrooms are occupied by 20–25
87   humans for a few hours per day during the normal five-day school week. The layout of the studied
88   part of the building and its orientation are presented in **Error! Reference source not found.**.
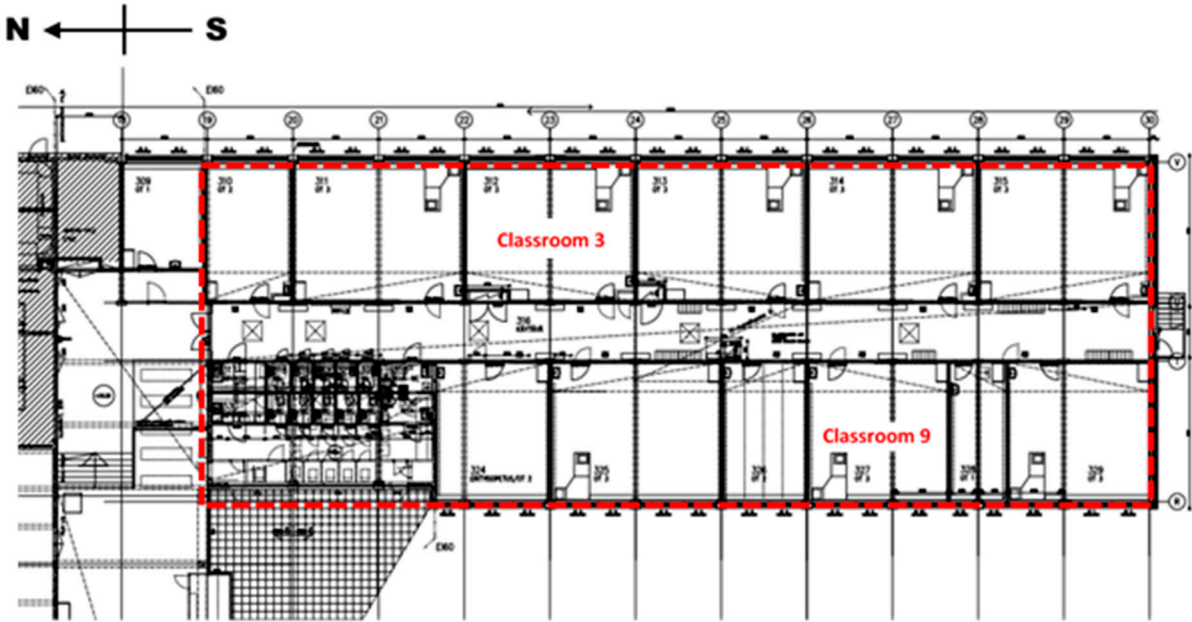

89

90   **Figure 2.** The ventilation intervention was conducted in the building section marked with red.
91   Measurements were carried out in Classrooms 3 and 9.

2.2 Previous investigations

93   Due to the prolonged IAQ-related complaints in the building, an indoor climate and structural
94   investigation (report August 24 2016 handed over to the Real Estate Center of the City of Vantaa) was
95   conducted in the whole building by a certified consultant company, Sweco Finland Oy, during April
96   2016 [13], prior to this ventilation intervention research project.

97   In the base floor tracer gas investigations, the air was found to infiltrate the room via wall/floor
98   junctions and service entries, and the investigated classroom had negative pressure in relation to the
99   ground filling. In outer wall tracer gas investigations, air leakages were found in the wall/floor
100   junctions, window/wall junctions, and the supports for radiators and windowsills.

101   In the surface humidity detection of floorings, high humidity was detected widely in the studied
102   building section, especially in the whole corridor area. In the cut measurement in Classroom 3, the
103   relative humidity (RH) under the flooring was normal: 28 %. In drill hole measurements of the
104   concrete slab, high humidity was measured at all eight measurement spots (corridor and classrooms),
105   with an RH between 87–95 %. Simultaneous volatile organic compound (VOC) measurements in
106   Classroom 3 did not suggest material deterioration (TVOC: 5 µg/m^3, 2-ethyl-1-hexanol (2E1H): 1
107   µg/m^3). However, it was recommended that the surface flooring be replaced with a more permeable
108   material to avoid future problems.

109   In Classroom 3, the structures were opened for investigation. It was found that the outer wall
110   structure did not follow the correct building design, i.e. the inner brick layer was covered by
111   insulation and a vapor-tight concrete layer, which could lead to vapor condensation during the cold
112   season. Material samples for microbiological analysis were taken from the structure's opening.
113   Microbial growth (fungi and bacteria) was found in the wooden structures of the window-frame
114   fastening (**Table 1**). Actinobacteria and *Exophiala** sp., which are indicators of moisture damage, were
115   found in the mineral wool layer (**Table 1**). These findings verify the assumption that structures have

116   been exposed to moisture and damaged because of incorrect building design. Microbial assessment
117   of indoor air did not show increased microbial levels or moisture indicator microbes.

118   **Table 1**. Microbial growth in outer wall structures of Classroom 3 [13].

119
120   *

Room	Place	Date	Fungi (cfu/g)	Bacteria (cfu/g)	Actinobacteria (cfu/g)
Classroom 3	Outer wall, window frame fastening wood	April 2016	170 000 *Aureobasidium* sp., *Mucor* sp., *Penicillium* sp., yeast, sterile	1 400 000	< 100**
Classroom 3	Outer wall, mineral wool in the plinth cut	April 2016	8 000 *Exophiala** sp.	100	29 000*
Limit value [14]			10 000	100 000	3000

121   Indicator for moisture damage

122   ** Below the definition limit 100 cfu/g

123   The investigation concluded that impurities from microbially damaged materials possibly
124   infiltrate indoor air, and might comprise a health risk. Infiltrations are caused by air leakages and
125   negative pressure, which is highest at night. Extensive structural repairs are needed in the lower parts
126   of the outer wall to improve the building design as well as seal the air leakage routes.

127   *2.3 Set-up for ventilation intervention*

128   The ventilation intervention was conducted in four phases: (a) airflow rates in the rooms were
129   measured to determine the initial state of the ventilation; (b) the air distribution ductwork was fully
130   balanced by an authorized company; (c) the air handling unit´s supply and extract fan speeds were
131   adjusted to generate the desired 5-7 Pa positive pressure over the building envelope in each
132   classroom; and (d) airflow rates in the rooms were re-measured after a setting period, and pressure
133   differences over the envelope were monitored during the entire set-up. Positive pressure was
134   maintained in the studied building section fairly well over the winter season, from August 2016 to
135   May 2017.
136   The aim of generating low 5-7 Pa positive pressure was to prevent potential infiltration by
137   harmful agents and avoid strong exfiltration of indoor air. In this ventilation intervention, it was
138   possible to establish a positive pressure in the building by balancing the ventilation system and by
139   adjusting fan speed control frequency in the air handling unit.
140   Related IAQ measurements were conducted simultaneously with phases (a) and (d). Occupant
141   perceptions were recorded, and microbial samples collected before the intervention and after five
142   months of positive pressure. Moisture behavior of the structures during the positive pressure period
143   was monitored, and will be reported in another journal article.

144   *2.4 Measurement methods*

145   Some of the measurements were conducted in the entire building section under study; others
146   were conducted in only the two classrooms with the most significant IAQ-related complaints from
147   the occupants: Classrooms 3 and 9. The measured factors and measurement devices are presented in
148   **Error! Reference source not found.**.

149   **Table 2.** Measurement methods and devices.

Measured factor	Device	Accuracy	Place	Time
Supply/extract airflow rate	Swemaflow 125D	Air flow: ± 3.5 %, not better than 0.4 l/s. With backpressure: ± 10 %, lowest 1 l/s. T ± 0.5 °C. Barometer ± 3.5 hPa.	Corridor, toilets	Instant
Pressure difference to calculate airflow rates	SWEMA 3000md	± 0.3 % read value, lowest ± 0.3 Pa	Classrooms	60 s average
Pressure difference across the envelope	KIMO CP101, logger Grant 1000	1.5 % of reading ± 3 Pa	Classrooms 3 and 9	Continuous
Temperature (T)	Rotronic CL11	± 0.3 K	Classrooms 3 and 9	Continuous
Relative humidity (RH)	Rotronic CL11	< 2.5 % (10...90 %)	Classrooms 3 and 9	Continuous
Carbon dioxide (CO_2)	Rotronic CL11	± 30 ppm ± 5 % of the measured value	Classrooms 3 and 9	Continuous
T and RH	ThermaData	± 0.5 °C (-10 to 85 °C)	Outdoors	Continuous
Formaldehyde	FM-801	± 10 ppb at 40, 80, 160 ppb	Classroom 3	Continuous
Carbon monoxide (CO)	TG-501 probe	< 4 % / year	Classroom 3	Continuous
Particulate matter 2.5 µm ($PM_{2,5}$)	MIE pDR-1500	± 5 %	Classroom 3	Continuous
Volatile organic compounds (VOC)	Tenax TA, TD-GC-MS	± 20 % (average)	Classrooms 3 and 9, corridor	40 min
Mycobiota of settled and filter dust			Extract air filter, Classrooms 3 and 9, outdoors	Cultivated for 4 weeks
Perceived indoor air quality	Örebro (MM40) – questionnaire (Finnish Institute of Occupational Health)		The occupants of the whole building	5/2016, 1/2017

150   2.4.1 Airflow rate measurements and pressure differences across the building envelope

151   Airflow rates were measured from each ventilation duct terminal unit in every room and in the
152   corridor in the studied building section before and after balancing the ventilation, and after
153   generating the positive pressure. Pressure differences across the building envelope were measured
154   continuously for one week before the ventilation intervention and for nine months in Classrooms 3
155   and 9 after generating the positive pressure. A plastic tube with a copper core was placed outside by
156   a window that was not normally open. A measurement device and the logger were placed inside near
157   the window. The outdoor temperature was monitored simultaneously.

158   2.4.2 Temperature, relative humidity, and CO_2 concentration of indoor air

159   Temperature, relative humidity, and CO_2 concentrations were measured in Classrooms 3 and 9
160   for a one-week period before the ventilation intervention, and for a nine-month period after the

161 intervention. Measurement devices were placed on the teacher's desk, away from the teacher's
162 breathing zone when seated and as close to the central area of the room as possible.

163 2.4.3 Indoor air quality (IAQ) measurements

164   VOCs were measured in Classrooms 3 and 9 and in the corridor before and after the ventilation
165 intervention. The total amount of volatile organic compounds (TVOC) and single compounds that
166 had concentrations over 1 $\mu g/m^3$ were analyzed. The VOC sampling and analyses were carried out
167 according to (ISO 16000–6) standard. Air samples were taken from the middle of an empty, closed
168 room, in the central area of the room, or in the main working zone at a height of 1.5 m. The samples
169 were collected during school working hours. Air samples were collected in Markes International Ltd
170 (Llantrisant, UK) stainless steel tubes packed with Tenax TA (60/80 mesh) using GilAir Plus air
171 sampling pumps (Sensidyne, St. Petersburg, USA) at a flow rate of 200 mL/min for 40 min.
172   The samples were desorbed using a thermal desorption unit, TD-100 (Markes International Ltd,
173 Llantrisant, UK) and analyzed by a gas chromatograph, Clarus 580 (Perkin-Elmer Ltd., Beaconsfield,
174 UK), equipped with a Clarus 600T (Perkin-Elmer Ltd., Beaconsfield, UK) mass selective detector. The
175 VOCs were quantified by the scan (50–400 m/z) mode. Concentrations of TVOC and individual
176 compounds were determined from TVOC area (n-hexane to n-hexadecane) and calculated as toluene
177 equivalents. Concentrations of single compounds were also determined from the chromatogram
178 before and after the TVOC area. In the case of such compounds, the quantitative result was indicative.
179 Reference compounds and the NIST 2011 Mass Spectral Library automated mass spectral
180 deconvolution and identification system (AMDIS) was used for identification. The detection limit
181 was 0.2 $\mu g/m^3$ (not included in sum concentration).
182   The formaldehyde concentration of indoor air was measured using an FM-801 formaldehyde
183 meter (GrayWolf Sensing Solution, Sheldon, USA), and carbon monoxide (CO) was measured with
184 an electrochemical sensor with a TG-501 probe using an AdvancedSense meter (GrayWolf Sensing
185 Solution, Sheldon, USA).
186   Fine particulate matter ($PM_{2.5}$) was measured using an MIE pDR-1500 (Thermo Fisher Scientific,
187 Franklin, MA, USA) nephelometer equipped with a $PM_{2.5}$ size-selective inlet cyclone. Formaldehyde
188 and $PM_{2.5}$ were measured continuously for a one-week period before and after ventilation
189 intervention, while CO was measured for a one-week period after the intervention, in Classroom 3.
190   Formaldehyde, CO, and $PM_{2.5}$ measurement devices were placed in the back of the room, at a
191 height of 1.5 m, as close to the central area of the room as possible. Inviolability of the devices had to
192 be considered since the measurements were carried out for several days in a room occupied by
193 children.

194   2.4.4. Characterization of the mycobiota in the indoor dust

195   The mycobiota of indoor dust was collected from the studied building section´s extract air filter,
196 as well as from the settled dust collected from Classrooms 3 and 9. Reference dust was collected from
197 the outdoor air. Characterization of the mycobiota was accomplished in three stages:
198 1.   Sampling of dust from the extract air filter, air, and surfaces above floor level.
199   Material samples from the extract air filter were collected in sterile plastic bags. Pieces of the
200 filter material (ca. 1 cm x 1 cm) were spread on malt extract agar plates (MEA, Sharlab, Spain; agar:
201 Amresco, USA, malt extract 15 g and agar (Ohio, USA) 12 g in 500 mL of H_2O). Dust samples were
202 wiped with a clean plastic bag (Minigrip) from ca. 30 x 30 cm^2 surfaces 1-2 m above floor level. The
203 dust (ca. 10 mg) was spread with a sterile cotton swab on MEA plates. Air samples were collected
204 with MEA fallout plates that were kept open for an hour. MEA culture plates were inoculated, sealed,
205 and cultivated at 22 °C for four weeks.
206 2.   Rapid toxicity screening of single colonies with boar sperm and somatic cell lines.
207   For initial toxicity screening, 10–20 mg of biomass (wet wt) from each colony of the original
208 culture plates was looped into 0.2 ml of ethanol and heated in a water bath for 10 min at 80 °C. The
209 obtained ethanolic lysates were exposed to porcine spermatozoa and kidney tubular epithelial cells
210 (PK-15, Finnish Food Safety Authority, EVIRA, Finland). The lysate was considered toxic when 2.5

vol% decreased boar sperm motility or 5 vol% decreased proliferation of PK-15 cells by > 50 % compared to the sham exposed control. Boar sperm motility inhibition assay (BSMI) measuring motility inhibition (i.e. inability to respond to induction of motility in resting sperm cells exposed for one day at room temperature) is described in [15]. The inhibition of cell proliferation (ICP) assay with PK-15 cells and the determination of EC_{50} concentrations followed the methods described by [16]. The colonies that displayed toxicity were streaked pure and identified to genus or species level.

3.   Characterization and identification of the fungal isolates.

Fungal colonies were grouped into 12 morphotypes based on colony morphology on MEA, ability to grow at 37 °C, light microscopy of the conidia and conidiophores, and responses in the two toxicity assays, BMSI and ICP. The isolates were compared to the identified strains from our strain collection, HAMBI, or identified according to [17]. Representatives for the morphotypes were identified according to their ITS sequences [18].

2.4.5 Indoor air questionnaire

Occupants´ indoor air-related symptoms and discomfort were recorded with the standardized Indoor Air Questionnaire of the Finnish Institute of Occupational Health (FIOH) twice during the research. The questionnaire was based on the Örebro Indoor Climate Questionnaire MM40 [19,20].

The questionnaire consists of four different foci: (1) the work environment; (2) the work arrangements; (3) the employees' allergy history; and (4) work-related symptoms. The questionnaire asked the respondents to recall environmental problems (draft, dry or stuffy air, etc.) that had occurred during the past three months.

Staff members of the whole school were requested to participate in the questionnaire, and the principal of the school arranged for the delivery of the questionnaires at the workplace. Staff members had two weeks to respond to the questionnaire. FIOH collected and reported the answers.

Potentially significant differences between the two questionnaires were analyzed at Aalto University by the SPSS statistical program, with a chi-squared test. The main interest was to determine whether symptoms supposedly related to impurities from the structures could be reduced by converting infiltration to exfiltration in the studied building section.

3. Results and discussion

3.1 Airflow rate measurements and pressure differences across the building envelope

Total airflow rates before and after the ventilation intervention are shown in **Table 2**.

Table 2. Supply and extract airflow rates before ventilation balancing, after balancing, and after generating positive pressure.

Air flow rates [L/s] Room	Designed Supply / extract	Measured before balancing 30.5.2016		Measured after balancing 22.7.2016		Measured after overpressure 2.9.2016	
		Supply	Extract	Supply	Extract	Supply	Extract
1	135/135	146	189	134	135	139	125
2	270/270	313	359	273	273	287	255
3	270/270	273	348	268	265	278	247
4	270/270	301	368	271	271	291	305
5	270/270	283	341	263	264	273	269
6	270/270	259	298	271	271	276	259
7	220/220	141	287	204	202	203	188
8	80/80	126	118	65	62	65	65
9	215/215	215	262	213	216	219	214
10	135/135	133	149	136	134	143	139
11	270/270	289	279	265	264	284	277
12	180/180	175	232	175	175	177	167

Classroom total	2585/2585	2655	3230	2538	2532	2636	2510
Cleaning storage	-/30		13		30		31
WC 1	-/30		10		30		32
WC 2	-/30		11		30		30
WC 3	-/30		13		30		36
WC 4	-/30		15		30		34
WC 5	-/30		17		30		30
WC 6	-/30		17		30		30
Corridor	320/110	330	90	329	114	303	79
TOTAL	2905/2905	2984	3415	2867	2856	2938	2812

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244   Before balancing, the airflow rates were found to be heavily unbalanced in most classrooms, as
245   well as in the corridor and the toilets. According to Finnish regulations, the acceptable deviation at
246   room level and system level is 20 % and 10 %, respectively. At classroom level, the supply airflow
247   rates were within +/- 20 % of the designed values, with two significant exceptions of -36 % and +57
248   %. Almost all the classrooms had extract airflow rates over 20 % higher than the designed values. The
249   corridor extract was 18 % lower than the designed values. The extracts from the toilet and storage
250   units were 55 % lower than the designed values, which was found to be caused by the wrong rotation
251   direction of the fan. At a system level, the total extract airflow rate was 18 % higher than the designed
252   values. After generating the positive pressure, all classrooms received more supply than extract air.
253   Airflow rates were measured as spot checks from some classrooms in spring 2017, and had been
254   maintained at the required level.
255   Pressure differences across the building envelope from one week before and after the
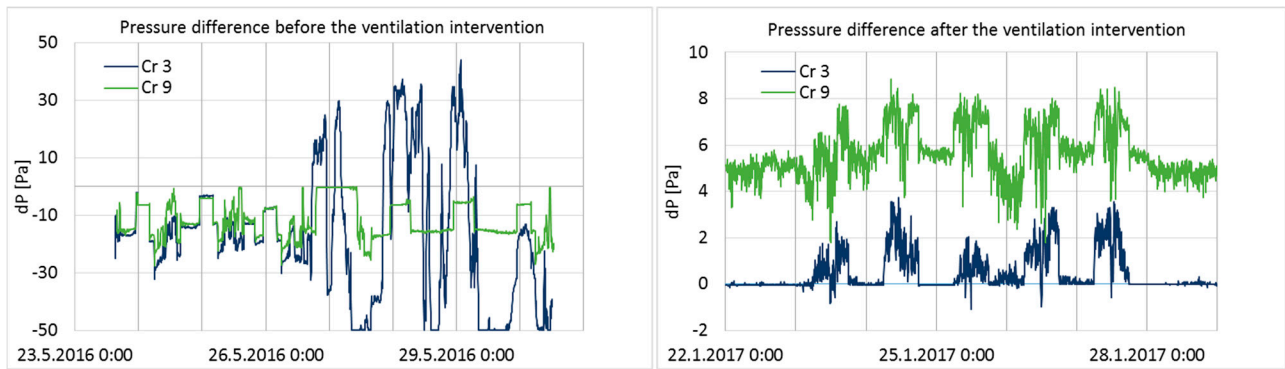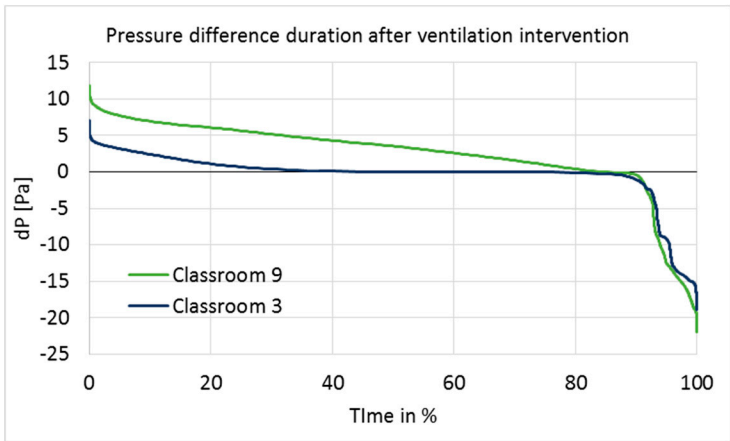256   intervention in Classrooms 3 and 9 are shown in **Figure 1**.
257

258   **Figure 1**. One-week pressure difference across the building envelope in Classrooms 3 and 9 before
259   and after the ventilation intervention.

260   Before the ventilation balancing, pressure differences fluctuated within a large range during a
261   one-week period, and both measured rooms had a significant level of negative pressure. It should be
262   noted that the prolonged readings of -50 Pa could also have been caused by mistreating the
263   measurement devices in Classroom 3. After the ventilation balancing, the pressure differences across
264   the envelope were moderately stable and positive, and fluctuation was minimal compared to the
265   conditions before the intervention. Pressure differences over the entire ventilation intervention
266   period are shown as cumulative frequency curves (duration curves) in **Error! Reference source not**
267   **found.**.

268

269   **Figure 2.** Duration of pressure differences across the envelope in Classrooms 3 and 9 during nine
270   months after ventilation intervention.

271   Positive pressure was maintained rather well in Classroom 9, but poorly in Classroom 3. In
272   Classroom 9, the pressure difference was at the optimal level of 5-7 Pa for 23 % of the measurement
273   time, and over 0 Pa for 84 % of the time. In Classroom 3, it was over 0 Pa for 45 % of the time; thus,
274   most of the time, Classroom 3 had a pressure difference very close to 0.
275   According to the set-up design, positive pressure should have been maintained continuously
276   throughout the entire intervention period. However, the results showed that the ventilation system
277   was turned off at night by the school maintenance or by the automatic remote-control system during
278   school holidays; it was also turned off during other short-term periods for unknown reasons. The
279   longest holiday period was the Christmas holiday, between December 21, 2016 and January 7, 2017,
280   during which time the ventilation system was clearly turned off every day from 4 pm to 6 am, and
281   the pressure difference became highly negative. Negative pressure differences during that period
282   were significant (up to -18 and -22 Pa in Classrooms 3 and 9; average pressure difference -7.9 and -
283   8.4 Pa), generating unwanted effects on the ventilation intervention. The building was unoccupied
284   during holiday periods; thus, pressure fluctuation did not have a direct impact on the occupants.
285   However, possible impurities inside the structures may have infiltrated indoors during those periods,
286   which would have influenced the indoor conditions and might have affected the user questionnaire
287   responses accordingly. Therefore, holiday times, especially the Christmas holiday, were not excluded
288   from the data. If the Christmas holiday period is ignored, then the pressure difference becomes
289   positive (> 0) for 46 % (Classroom 3) and 88 % (Classroom 9) of the time.
290   The measured results show an increase of positive pressure when the outdoor temperature
291   increases (**Figure 3**), and a corresponding decrease when the outdoor temperature drops. This has
292   provided an additional challenge for positive pressure as adjustments were done during warm
293   season. These results indicate typical phenomena of heat recovery ventilation units: During the cold
294   season, the mass flow of constant volume extract fans becomes higher because the temperature after
295   heat recovery is lower and the density of the air is correspondingly higher. At the same time, the
296   supply air fan operates at stable air temperature conditions and the mass flow does not change. To
297   avoid this phenomenon, an air handling unit with density-corrected air volume flow rate control
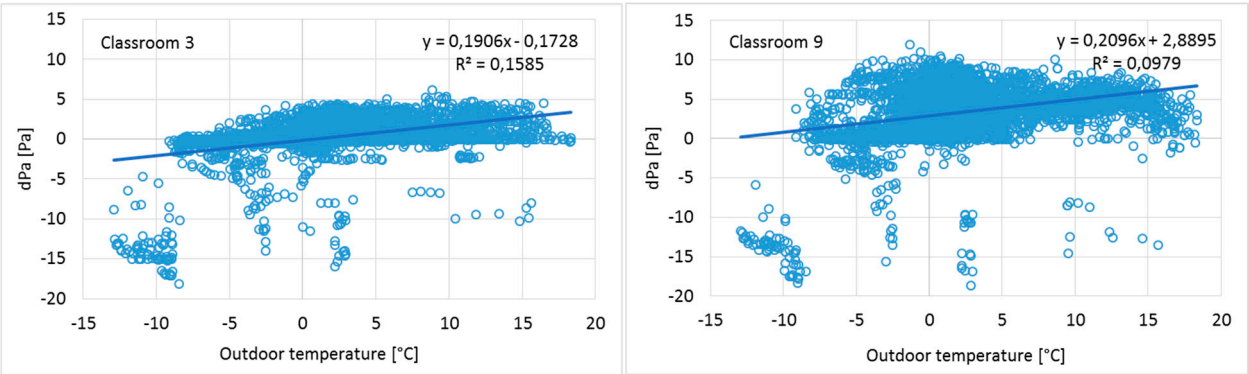298   should be used to maintain a continuous positive pressure in a building.

299

Figure 3. Relation between outdoor temperature and pressure difference across the envelope in Classrooms 3 and 9 with air handling unit without density-corrected airflow rates.

In a cold climate, water vapor condensation and moisture accumulation inside structures are seen as potential risks when pressure differences across the envelope are positive. To evaluate the risk of condensation inside the structures, excessive moisture in Classrooms 3 and 9 was calculated as the difference of measured absolute humidity of indoor and outdoor air, before the positive pressure period began. To monitor the possible moisture condensation risk in the structures during the ventilation intervention, T and RH probes were installed inside the structures at the most probable leakage paths, as well as in a reference room. According to humidity measurements, the structures were dry, indicating that this moisture risk was not present because of the modest humidity load in well-ventilated classrooms [21].

3.2 Temperature, relative humidity, and CO₂ concentration of indoor air

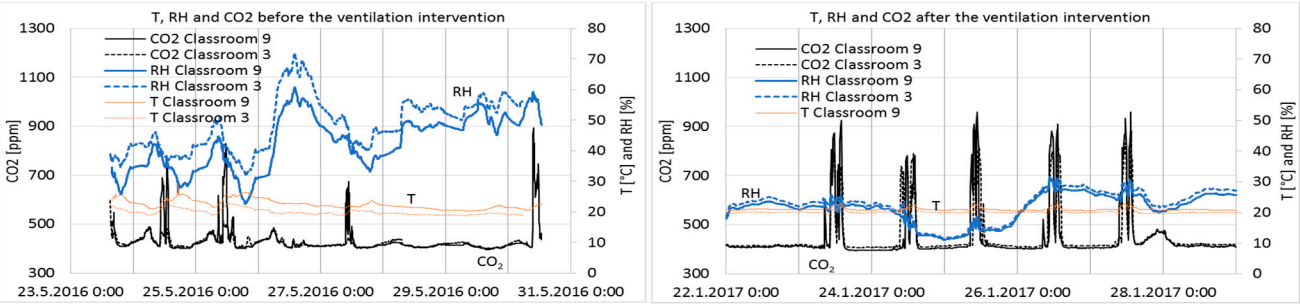Results from one week before and after ventilation intervention are shown in **Figure 4**.

Figure 4. Temperature, relative humidity, and CO₂ concentration in Classrooms 3 and 9 one week before and after the ventilation intervention.

The measurement results after the ventilation intervention are shown as a duration curve in Figure 5, and average, minimum, and maximum values are described in **Figure 5**. CO_2 concentration, relative humidity, and temperature duration in Classrooms 3 and 9 during school´s occupancy hours, from 8 am to 5 pm on Mon–Fri, measured continuously from 1/2016 to 5/2017 after ventilation intervention was conducted.

Table 3. Only results during school working hours, from 8 am to 5 pm, are shown to describe conditions during occupancy.
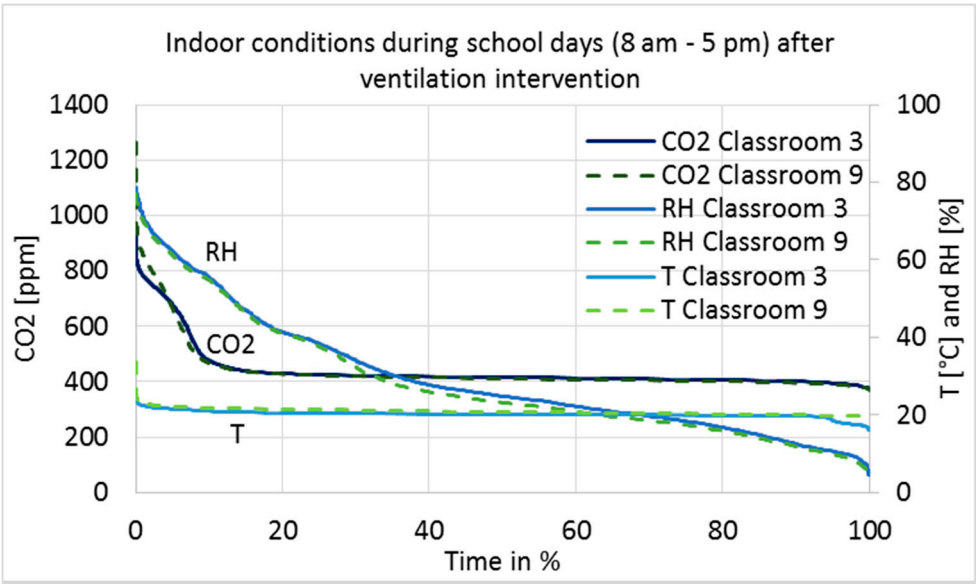
323

Figure 5. CO_2 concentration, relative humidity, and temperature duration in Classrooms 3 and 9 during school´s occupancy hours, from 8 am to 5 pm on Mon–Fri, measured continuously from 1/2016 to 5/2017 after ventilation intervention was conducted.

Table 3. Relative humidity, temperature, and CO_2 in Classrooms 3 and 9 during school´s occupancy hours, from 8 am to 5 pm on Mon–Fri, between 1/2016 and 5/2017.

	Classroom 3			Classroom 9		
	RH (%)	T (°C)	CO_2 (ppm)	RH (%)	T (°C)	CO_2 (ppm)
Average	31	21	518	30	21	520
Min	5	17	391	4	19	382
Max	75	24	972	77	34	1264

329

330   The maximum limit value for CO_2 concentrations in Category 1 of the Finnish Classification [22]
331 is 750 ppm; the limit value in Category 2 is 900 ppm, while in Category 3 it is 1200 ppm. The levels
332 of measured values were in Category 1 and 2. Temperatures were very stable and slightly higher in
333 Classroom 9, which can be explained by the location of the room on the western side of the building.
334   The RH of the classrooms closely followed the absolute humidity of the outdoor air, i.e. values
335 are very low in cold winters and reach 75 % on summer days. In Category 1 [22], it is recommended
336 that RH should not drop for long periods below 20 %; no recommendations exist for the other
337 categories. It can be seen in Classrooms 9 and 3 that RH was below 20 % for 31 % and 26 % of the
338 school hours, respectively. Such dry air causes irritation of the respiratory tract, eyes, and skin [23].
339 Indirectly, temperature and RH affect human perceptions of air quality and emissions from building
340 materials [24-26].

341   *3.3 Indoor air quality (IAQ) measurements*

342   TVOC, VOC, formaldehyde, and CO measurement results are shown in **Table 4**.

343

Table 4. TVOC, VOCs (concentrations over 1 µg/m³), formaldehyde, and CO before (a) and after (b) ventilation intervention.

Chemical compounds of indoor air [µg/m³]	Classroom 3 a	b	Classroom 9 a	b	Corridor a	b	Limit value [27]
TVOC	31	19	42	19	34	27	400
Acetic acid		2	1		1	2	50
Acetic acid, butyl ester						2	50
Octamethylcyclotetrasiloxane			4		2	4	50
Decamethylcyclopentasiloxane			4	1	2	3	50
2-ethyl-1-hexanol (2E1H)	2		1		3	3	10
Phenoxyethanol		2				2	50
1-Butanol						1	50
Nonanal	3	1	3	1	3	2	50
Decanal	2	1	2	1	2	2	50
Acetone			1				50
Formaldehyde	*	*	-	-	-	-	*50 / 100*
Carbon monoxide (CO)	-	*300-1300*	-	-	-	-	*7000*

(a) Sample taken 5.23.2016; (b) Sample taken 9.2.2016

* Below detection limit 10 ppb (~12 µg/m³)

TVOC values decreased 21–55 % in the classrooms and in the corridor after ventilation intervention. This result was statistically significant at a 95 % confidence interval (p = 0.045). Besides positive pressure, no other changes were undertaken; therefore, the only known explanation for the decreased concentrations is the positive pressure and infiltration mainly converted to exfiltration. Concentrations were very low in general, compared to the national threshold values [27], indicating good ventilation and off-gassing of materials.

Concentrations of single VOCs were 1-4 µg/m³, which is fairly below action level. TVOC concentrations consist mainly of compounds with concentrations below 1 µg/m³. In addition to the general limit value for single compounds, national limit values for the following VOCs are 2,2,4-trimethyl-1,3-pentanediol di-isobutyrate (TXIB) (10 µg/m³), 2E1H (10 µg/m³), naphthalene (10 µg/m³), and styrene (40 µg/m³) [27]. In these samples, only 2E1H was shown, but only as low concentrations from 1 to 3 µg/m³.

For formaldehyde, the maximum allowed value is 50 (annual average) or 100 µg/m³ (30 min average), while for CO it is 7 mg/m³ (momentary concentration) [27]. The formaldehyde concentration before and after the ventilation balancing was below 10 ppb (equivalent to approx. 12 µg/m³), which is the detection limit of the meter. After balancing, there was a concentration of 12–26 ppb during two hours on one day, which was probably due to some specific action in the classroom, e.g. art lecture. The CO concentration varied from 0.3 to 1.3 mg/m³.

366   Particulate matter 2.5 μm measurement results are presented as a duration curve in Figure 6,
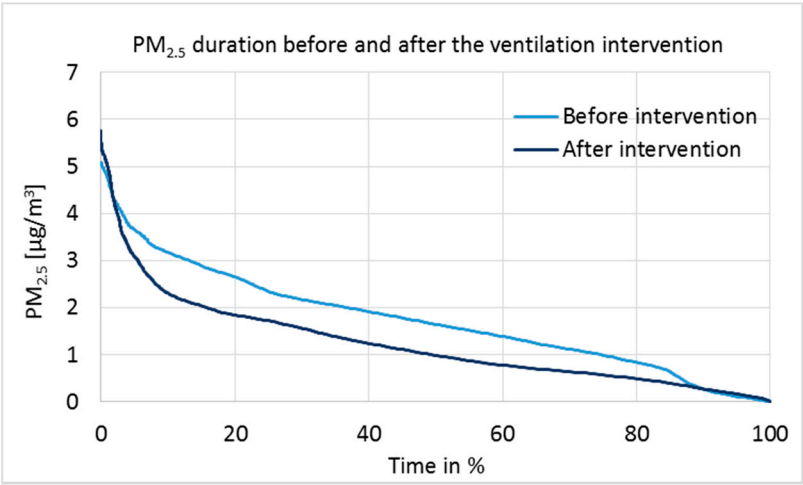367   and parameters for statistical analysis are given in **Table 5**.

368

Figure 6. Duration curves of particulate matter 2.5 μm before and after the ventilation intervention in Classroom 3.

Table 5. PM$_{2.5}$ concentrations in Classroom 3 before and after the ventilation intervention: Statistical parameters.

PM$_{2.5}$	Before	After
Measurement points	9 572	12 569
Mean	1.80	1.27
Standard deviation	1.06	0.97
Min	0.10	0.10
Max	5.90	5.90

373

374   The limit value for the PM$_{2.5}$ mean concentration following 24 hours in indoor air was 25 μg/m^3
375   [27]. All known PM$_{2.5}$ sources in the studied building are outdoor sources; for example, traffic and
376   burning products. PM$_{2.5}$ concentrations were very low before and after the intervention. However,
377   tested by the independent two-sample *t*-test, the difference in medians was statistically extremely
378   significant at the 100 % confidence interval (p = 0.000, 2-tailed). Daily actions can affect the PM$_{2.5}$
379   concentrations temporarily; but due to the one-week measurement time, the results are reliable and
380   show a clear correlation with the positive pressure.

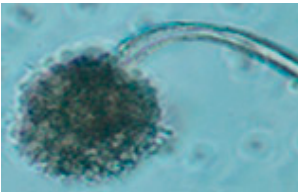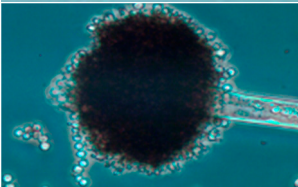381   *3.4 Characterization of the mycobiota in the indoor dust*

382   Diversity and the pathogenic and toxigenic potential of the mycobiota cultivable from indoor
383   dust were characterized. Dust from extract filters and surfaces above floor levels were sampled and
384   cultivated before and after the ventilation intervention. Outdoor dust and air were sampled as
385   references. The fungal colonies are shown in **Figure 7**.

386

Figure 7. Fungal colonies sampled from the outdoor air and from the extract air filter dust before and after the ventilation intervention. The outdoor air and dust contained black *Curvularia*-like colonies (A, B, C). Extract air filter sampled before the ventilation intervention contained green *Trichoderma* colonies (D), and green *Penicillium* and black *Aspergillus* colonies (E, F). Extract air filter sampled after the ventilation intervention contained yellow *Penicillium* colonies and yellow *Aspergillus* colonies (G, H, I).
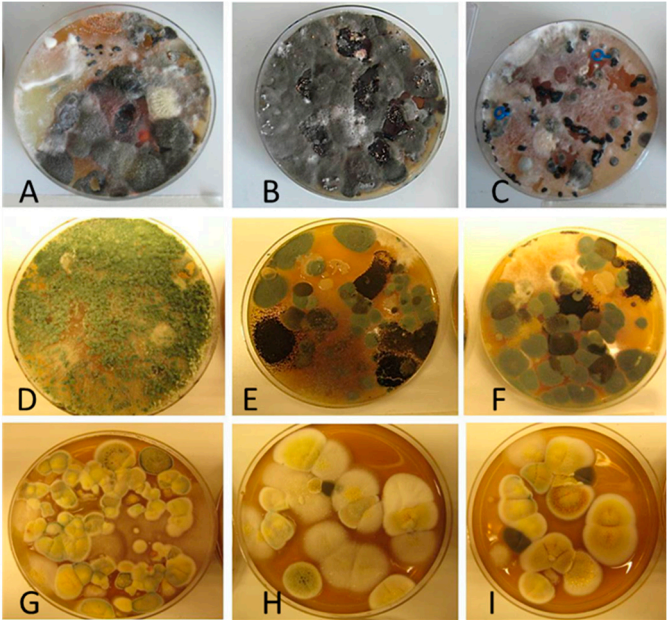
The fungal colonies representing the dominant morphotypes (**Error! Reference source not found.**) after four weeks of incubation were characterized to genus or species level (Table 7). The results show that *Rhizopus* sp. strains unable to grow at 37 °C were the most commonly isolated fungi in filter dust and settled dust collected before and after ventilation intervention. The results also show that toxigenic, potentially mycoparasitic *Trichoderma atroviride* strains represented the dominant morphotype on the three plates in both extract filter dust and settled dust collected before the ventilation intervention. The dominant morphotypes in this dust contained potentially pathogenic *Aspergillus* and toxigenic *Penicillium* species.

Table 6. The twelve morphotypes representing the dominant fungal genera and species isolated from the extract filter, settled dust and outdoor air.

	HA MBI Code	Growth at 37 °C	Toxicity		Colony color	Size of conidia/ spores (μm)	Morphology in light microscope
			BM SI	ICP	MEA		
1. Aspergillus section Flavi	834	+	-	-	green	5-8	
2 strains		+	-	-	green	5-8	
2. Aspergillus section Nigri	379	+	-	+	black	3.5-5	
10 strains		+	-	+	black	3.5-5	
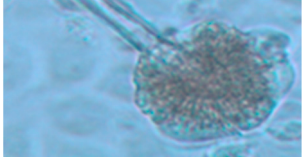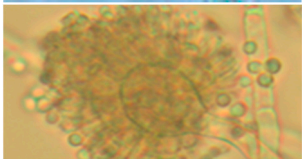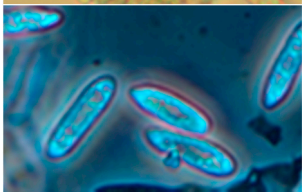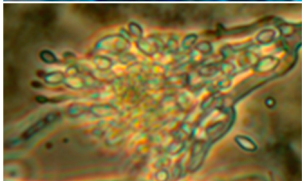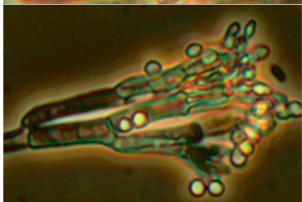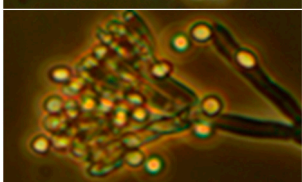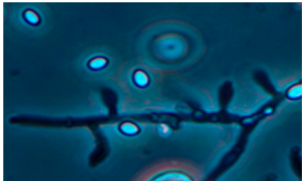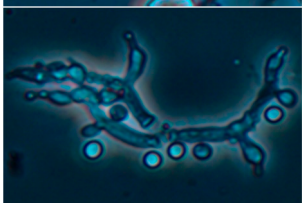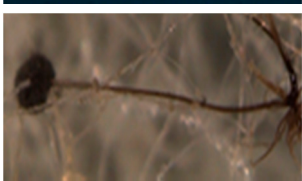
3. *Asp. versicolor*	3670	-	-	+	yellow	2-3
2 strains		-	-	+	yellow	2-3
4. *Asp. westerdijkiae*	3333	-	+	+	yellow	2.5-3
5 strains		-	+	+	yellow	2.5-3
5. *Curvularia* sp.			+	+	black-grey	15 x 5
10 strains			+	+	grey	Conidio-phore 15 x 5
6. *Paecilomyces variotii*	3342	+	+	-	yellow	3-5
2 strains		+	+	-	yellow	3-5
7. *Penicillium expansum*	3610	-	+	+	grey	3
1 strain		-	+	+	grey	3
8. *Penicillium chrysogenum P.commune*	3631	-	-	+	green	3-4
10 strains		-	-	+	green	3-4
9. *Penicillium* sp.		-	-	-	yellow	3
10 strains		-	-	-	yellow	3
10. *Trichoderma longibrachiatum*	3643	+	+	+	green	1.5 x 3
1 strain		+	+	+	green	1.5 x 3
11. *Trichoderma atroviride T. trixiae*	3369	-	+	+	green	3
6 strains		-	+	+	green	3
12. *Rizopus nigricans*	834	-	-	-	black	Spores 7-10
10 strains		-	-	-	black	Spores 7-10

Table 7. Cultivable mycobiota in indoor dust from the extract air filter and from classroom surfaces above the floor level. The dust was sampled before and after the ventilation intervention. Names in bold indicate a dominant frequency of that colony type on > 50 % of the sampling plates; names in brackets indicate the presence of a single colony on a single plate.

	Microbial genera by sampling month		Toxic colonies [%]	Number of plates containing colony morphotype
School samples	Settled dust	Extract air filter	Settled dust + Extract air filter	
Before ventilation intervention	5/2016	8/2016	80	
	Rhizopus sp.	*Rhizopus* sp.		3/10
	*T. atroviride**	*T. atroviride**		3/10
		*Penicillium chrysogenum.**		7/10
		P.commune *		
		Aspergillus niger[1]		7/10
		Aspergillus flavus[1]		2/10
		(Paecilomyces sp.)*[1]		1/10
	*Asp. versicolor**			2/10
After ventilation intervention	9/2016	2/2017	40	
	Rhizopus sp.	*Rhizopus* sp.		6/12
	Penicillium sp.	*Penicillium* sp.		10/12
		*Asp. westerdijkiae**		3/12
		*(Penicillium expansum)**		1/12
	*T.trixiae**			1/12
	(T. longibrachiatum) *[1]			1/12
Reference samples (outdoors)	Fall out plate	Settled dust		
Sampling date	8/2016	8/2016		
School yard	*Curvularia* sp.*	*Curvularia* sp.*	90	4/6
Barn dust	*Penicillium* sp.	*Penicillium* sp.	<10	6/6

[1] Potential pathogens able to grow at 37 ºC.

*Toxigenic when screened with boar sperm inhibition test and/or cytotoxicity against porcine kidney cells.

In dust collected after the ventilation intervention, the dominant mycobiota (except *Rhizopus* sp.) consisted mainly of nontoxigenic *Penicillium* strains and toxigenic *Aspergillus* species unable to grow at 37 °C. On one plate, a toxigenic *Trichoderma longibrachiatum* strain able to grow at 37 °C and one toxigenic *Penicillium expansum* colony were found. Reference samples collected outside of the school contained toxigenic *Curvularia* sp.–like colonies, rendering these outdoor samples the highest number of toxigenic colonies (Table 7). The hay barn dust did not contain toxigenic species or potentially pathogenic *Aspergillus* strains. The indoor mycobiota differed in species composition from the outdoor one, and changed simultaneously with the ventilation intervention. Interestingly, no mycoparasitic *Trichoderma* strains were cultivable from the outdoor samples or barn dust. This indicates that this species, isolated from the extract filter and settled dust before the ventilation intervention, may have emanated from an indoor source.

423   *3.5 Indoor air questionnaire*

424   Indoor air questionnaire results from the studied building section and from the other building
425   sections are presented in Table 8. Occupants answered the questionnaire in the studied building
426   section before the ventilation intervention (5/2016) and after the intervention (1/2017), as well as
427   simultaneously in the other building sections where no ventilation or other changes had taken place.
428   Because of the low amount of data, Fisher's exact test was used in the statistical analysis of several
429   factors instead of the chi-squared test.

430   **Table 8.** Indoor climate questionnaire (Finnish Institute of Occupational Health© 2006-2008, version
431   2.0) results from spring 2016 and winter 2017. Statistically significant changes at a 10 % confidence
432   interval (p < 0.1) are bolded. *P*-values marked with * were determined by the Fisher's exact test (SPSS).

	Comparison values [28-30]	Studied part 2016	2017	*p-value*	Other parts 2016	2017	*p-value*
Background information							
Number of answers		10	8		28	29	
Answer%	71	58	62				
Females (%)	21	60	75				
Daily smokers (%)		10	0		0	0	
Average age (years)		46	45				
Average employment in this work place (years)		8	6				
Work environment (%)							
Draught	22	10	38	*0.275**	7	21	*0.253**
Room temperature too high	17	20	0	*0.477**	7	7	*1.000**
Varying temperature	16	20	57	*0.162**	11	22	*0.295**
Room temperature too low	13	30	25	*1.000**	15	25	*0.345*
Stuffy air	34	30	38	*1.000**	46	69	**0.085**
Dry air	35	40	50	*1.000**	22	43	*0.103*
Insufficient ventilation	32	30	63	*0.342**	43	55	*0.352*
Smell of mold	9	20	25	*1.000**	14	21	*0.730**
Unpleasant odour	17	40	25	*0.638**	26	28	*0.889*
Environmental tobacco smoke	4	0	0	---	0	0	---
Noise	17	20	25	*1.000**	39	45	*0.672*
Dim light or reflections	14	10	0	*1.000**	7	10	*1.000**
Dust or dirt	25	40	38	*1.000**	32	43	*0.408*
Work regarded as interesting and stimulating (%)							
Often	75	100	100		89	86	
Sometimes	20	0	0		11	14	
Seldom or never	4	0	0	---	0	0	*1.000**
Too much work to do (%)							
Often	20	10	0		14	21	
Sometimes	59	60	75		61	72	
Seldom or never	21	30	25	*1.000**	25	7	*0.185**
Opportunity to influence work conditions (%)							
Often	35	60	50		46	38	
Sometimes	44	30	50		46	55	
Seldom or never	21	10	0	*0.798**	7	7	*0.839**
Fellow workers help with problems in the work (%)							
Often	72	80	100		82	83	
Sometimes	22	20	0		14	17	
Seldom or never	6	0	0	*0.477**	4	0	*1.000**
Allergic diseases (%)							

Asthma	8	10	13	*1.000**	18	7	*0.253**
Hay fever	38	40	75	*0.188**	46	45	*0.903*
Atopic eczema	28	40	38	*1.000**	14	17	*1.000**
Stress (%)							
Quite or very much	10	20	0		18	28	
Some	28	20	63		29	41	
No / only little	63	60	38	*0.214**	54	31	*0.226*
Symptoms (%)							
Fatigue	16	10	13	*1.000**	14	34	**0.077**
Heavy-feeling head	9	0	25	*0.183**	11	17	*0.706**
Headache	7	0	13	*0.444**	11	18	*0.705**
Difficulties in concentrating	3	0	13	*0.444**	4	14	*0.352**
Eye irritation	17	20	13	*1.000**	37	41	*0.740**
Irritated, stuffy or running nose	20	20	25	*1.000**	39	62	**0.085**
Hoarse/dry throat	14	10	50	*0.118**	36	45	*0.483*
Cough	5	20	50	*0.321**	11	17	*0.706*
Cough disturbing sleep	1	10	13	*1.000**	0	0	---
Dry of flushed facial skin	11	10	13	*1.000**	7	29	**0.036**
Hands: dry, itching, red skin	15	10	0	*1.000**	4	14	*0.352**
Shortness of breath	3	10	13	*1.000**	0	7	*0.491**
Wheezing	1	10	13	*1.000**	0	0	---
Fever or chills	2	0	0	---	4	7	*1.000**
Joint pain	3	10	0	*1.000**	4	0	*0.491**
Muscular pain	4	0	0	---	0	0	---
Other		20	25	*1.000**	4	3	*1.000**

433

434   In the studied building section, the known changes in the conditions between the 2016 and 2017
435   questionnaires were outdoor conditions (seasons) and the ventilation intervention. In other building
436   sections, the only known change was the season. Also, psychosocial factors have an impact on
437   perceptions [23]. In the studied building section, conclusions about the effect of psychosocial factors
438   on IAQ perceptions could not be drawn compared to other building parts.

439   The first questionnaire (5/2016) was conducted during the spring when pollen may increase the
440   symptoms of allergic diseases and thus effect the perception of indoor climate; however, the air
441   handling unit had effective fine F7 class filters. The second questionnaire (1/2017) was conducted
442   during the winter when the indoor air was very dry because of the low absolute humidity of the
443   outdoor air. Dry air typically increases the prevalence of cough, nose and eye irritation, and skin
444   symptoms [23]. Mechanical ventilation is shown to increase symptom prevalence, related especially
445   to air dryness [2,6,31]. The impact of the season (spring / winter) can be seen from the results of other
446   parts of the school that were not under intervention.

447   Due to the low number of occupants and the low response rate in the studied building section,
448   individual answers were emphasized and significant differences (p-value < 0.05) were not found in
449   the statistical analysis. The unwanted negative pressure differences, especially during holidays,
450   might have affected indoor conditions and occupants´ perceptions. Between 2016 and 2017, the
451   prevalence of hoarse, dry throat (p = 0.118), heavy-feeling head (p = 0.183), cough (p = 0.321), and
452   headache, as well as difficulties concentrating (p = 0.444), increased. Also, the prevalence of varying
453   temperature (p = 0.162), draft (p = 0.275), and insufficient ventilation (p = 0.372) increased.

454   However, when comparing the changes in the studied building section to changes in the other
455   building sections, a different trend emerged. The perception of low temperature (p = 0.345), stuffy air
456   (p = 0.085), dry air (p = 0.103), and visible dust (p = 0.408) increased between 2016 and 2017 in other
457   building sections; however, it was not statistically significant. This can be explained by seasonal
458   changes. However, in the studied building section, no worsening in the same factors (p = 1.000) was
459   reported.

460   A high temperature decrease ($p = 0.477$) was reported in the studied building section, while in
461   other sections the number of perceptions was already very low in the first place. Perception of
462   unpleasant odor decreased ($p = 0.638$) in the studied section to the same level as it was in the other
463   sections. An increase in the perception of draft ($p = 0.275$, $p = 0.253$) and insufficient ventilation ($p = $
464   0.342, $p = 0.352$) was reported correspondingly in both sectors.

465   In the other building sections, tiredness ($p = 0.077$), nose irritation ($p = 0.085$), dryness of facial
466   skin ($p = 0.036$), hand skin symptoms ($p = 0.352$), and shortness of breath ($p = 0.491$) increased, while
467   no change in the studied section was seen ($p = 1.000$). This is an interesting result considering that,
468   simultaneously, reported asthma decreased ($p = 0.253$) in the other sections but not in the studied
469   section. In addition, the prevalence of hay fever increased ($p = 0.188$) in the studied section. In the
470   studied section, the perceptions of heavy-feeling head ($p = 0.183$) and cough ($p = 0.381$) increased more
471   than in the other sections ($p = 0.706$ for both).

472   It can be concluded that IAQ in the building was perceived as being worse more frequently in
473   2017. In the studied building section, major improvements in occupants´ perceptions were not
474   reported; however, neither was reported significant worsening in many of the factors that worsened
475   in the other building parts during the follow-up time.

4. Conclusions

477   Ventilation is an essential part of indoor environment quality. As shown in this study, even
478   relatively small changes in air flow and pressure differences can have noticeable effects on the
479   measurable and perceivable parameters of indoor air. CO_2 concentration is often highlighted as an
480   indicator of sufficient ventilation rate, but should never be used alone to determine the state of
481   ventilation in an indoor space. In the studied building, CO_2 measurements alone would have
482   indicated good IAQ and sufficient ventilation. In order to study IAQ and occupants´ well-being in an
483   indoor space, a holistic ventilation investigation was revealed to be essential.

484   The aim of 5-7 Pa positive pressure for a period of nine months was only partly reached. In
485   another studied classroom, the pressure difference was mostly close to 0 Pa. The TVOC and $PM_{2.5}$
486   concentrations decreased significantly after ventilation intervention, yet these were initially very low.

487   The occupant questionnaire data analysis was weakened by the low number of occupants who
488   answered the questionnaire. Statistically significant improvement in occupants´ perceptions was not
489   demonstrated. The results were, however, analyzed to determine possible differences between the
490   studied building section and the other parts of the building, where no actions were taken. In the
491   follow-up questionnaire conducted after five months of positive pressure, the occupants´ perceptions
492   had worsened more moderately, if at all, compared to the occupants´ perceptions in the other
493   building sections, where perceptions had worsened significantly and the only known change in
494   conditions was the season. Seasonal effects on human perceptions were significant due to the cold
495   and dry air of the winter, and also likely due to psychosocial aspects, e.g. darkness during the winter.
496   This effect can be seen in the questionnaire data from the other building sections, but not as clearly
497   in the data from the studied building section. This indicates that positive pressure could be a practical
498   way to decrease perceived IAQ-related problems, but research with a larger occupant sample is
499   needed to confirm this indication.

500   This study also shows that the change in pressure conditions coincided with a partial but
501   important change in species composition of the indoor microbiome: The potentially pathogenic
502   species of *Aspergillus* able to grow at 37 °C (*Aspergillus* section Nigri and section Flavi strains) were
503   replaced with *Aspergillus* strains unable to grow at 37° C (*Asp. westerdijkiae* and *Asp. versicolor*-like
504   strains). There are only a few *Aspergillus* species that frequently cause infections in humans:
505   *A. fumigatus* and *A. niger* which are responsible for more than 90 % of systemic and lung infections
506   whereas *A. flavus* is the main cause of eye infections [32]. The occurrence of potentially pathogenic
507   isolates of *Paecilomyces* and *Trichoderma* species are of concern. However, these strains seem to be
508   minor representatives of the viable mycobiota.

509   The occurrence of potentially mycoparasitic *T. atroviride* strains disappeared after the
510   intervention. The small-sized conidia (< 4 μm) of *T. atroviride*, *Aspergillu*s, and *Penicillium* species from

511 extract filters collected under negative pressure differences may represent viable fungi emanating
512 from building constructions, as fungal spore penetration in indoor spaces under negative pressure
513 has previously been shown. However, the impact of the sampling season cannot be excluded in this
514 case. More investigations under circumstances in which the impact of outdoor air is standardized are
515 needed for the evaluation of the sampling method used. In the method, microbes are collected from
516 the extract air filters as representatives of the microbiome within building constructions, which are
517 potentially and occasionally liberated into indoor air due to fluctuations in pressure differences
518 across the building envelope. According to this study, this method could be a relevant way to
519 investigate sources of impurities in buildings with indoor air problems.

520   This study indicates that by situational ventilation interventions, conditions in a building with
521 unsolved IAQ problems or awaiting repairs can be controlled without other major temporary actions.
522 Positive pressure could be efficient, especially in a building with microbial damage or other
523 impurities infiltrating from the structures. When utilizing positive pressure, the pressure difference
524 should be high enough to constantly cover all spaces and the variation in ventilation. Potential excess
525 moisture indoors must be low or controlled by ventilation to prevent condensation inside the
526 structures.

533 **Author Contributions:** Camilla Vornanen-Winqvist wrote the paper and conceived, designed, and performed
534 every experiment; Kati Järvi analyzed the questionnaire data; Sander Toomla conceived, designed, and
535 performed the ventilation experiments and contributed the measurement devices; Kaiser Ahmed designed and
536 performed the ventilation experiments; Maria A. Andersson conceived, designed, and performed the mycobiota
537 experiments, analyzed the data, and participated in writing the paper; Raimo Mikkola designed the IAQ
538 experiments, contributed measurement devices, and analyzed the VOC samples; Tamas Marik and Laszlo
539 Kredics designed and performed the identification of the fungal morphotypes; Heidi Salonen was responsible
540 for designing and conceiving the IAQ experiments and questionnaires; Jarek Kurnitski was the principal
541 investigator responsible for the study design.

545 **Abbreviations**

546 The following abbreviations are used in this manuscript:

547 IAQ: Indoor air quality
548 TVOC: Total volatile organic compounds
549 VOC: Volatile organic compounds
550 PM: Particulate matter
551 FIOH: Finnish Institute of Occupational Health
552 2E1H: 2-ethyl-1-hexanol

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