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Indoor air quality in Michigan schools

Abstract Indoor air quality (IAQ) parameters in 64 elementary and middle school classrooms in Michigan were examined for the purposes of assessing ventilation rates, levels of volatile organic compounds (VOCs) and bioaerosols, air quality differences within and between schools, and emission sources. In each classroom, bioaerosols, VOCs, CO_2, relative humidity, and temperature were monitored over one workweek, and a comprehensive walkthough survey was completed. Ventilation rates were derived from CO_2 and occupancy data. Ventilation was poor in many of the tested classrooms, e.g., CO_2 concentrations often exceeded 1000 ppm and sometimes 3000 ppm. Most VOCs had low concentrations (mean of individual species $< 4.5\ \mu g/m^3$); bioaerosol concentrations were moderate (< 6500 count per m^3 indoors, $< 41,000$ count per m^3 outdoors). The variability of CO_2, VOC, and bioaerosol concentrations within schools exceeded the variability between schools. These findings suggest that none of the sampled rooms were contaminated and that no building-wide contamination sources were present. However, localized IAQ problems might remain in spaces where contaminant sources are concentrated and that are poorly ventilated.

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Key words: Indoor air quality; Schools; Volatile organic compounds; Bioaerosols; Ventilation; Exposure assessment.

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Practical Implications

Indoor air quality (IAQ) is a continuing concern for students, parents, teachers, and school staff, leading to many complaints regarding poor IAQ. Investigations of these complaints often include air sampling, which must be carefully conducted if representative data are to be collected. To better understand sampling results, investigators need to account for the variability of contaminants both within and between schools.

Introduction

Primary and secondary education is the largest public enterprise in the United States, employing over 3 million teachers and staff who instruct over 47 million children in 92,012 elementary, middle and high schools in 15,000 districts (GAO, 1995; NCES, 2002). Despite this large population, concerns regarding poor indoor air quality (IAQ), and evidence that building systems in half of the US schools have significant defects that may degrade IAQ, systematic assessments of IAQ and health and comfort issues have been rarely undertaken in schools. Consequently, the understanding of exposures and the association of symptoms and health effects remain incomplete. Pollutant emissions can occur in many school settings, e.g., cafeterias, wood shops, gyms, swimming pools, science labs (often without fume hoods), arts and crafts, and computer rooms. IAQ problems may be exacerbated in schools owing to the potential sensitivity of occupants, the simple and inexpensive building construction at most schools (commonly slab-on-grade construction with flat roofs), minimal landscaping with poor drainage, basic and minimally engineered heating, ventilation, and air conditioning HVAC units (typically wall or roof-mounted unitary systems with fixed and constant flows and exchange), the lack of preventative maintenance, and crowded conditions.

Many investigations examining IAQ problems in US schools have been complaint-driven in response to specific concerns or worker compensation issues, while in some European and other industrialized nations investigations have been driven by legislative initiatives or building standards. Often a specific pollutant, e.g., radon, asbestos or bioaerosols, or combination of pollutants are addressed (GAO, 1995). In the United States, almost half of the US schools were estimated to have one or more building defects, with HVAC systems being the most common building feature in need of repair (GAO, 1996). A review of the literature examining European schools found similar conditions (Carrer et al., 2002). Microbial and chemical exposures related to indoor sources and building characteristics found in schools, e.g., excessive dampness and poor ventilation, have been linked to reduced school attendance, respiratory infections, asthma, and allergy in children and adults (Mendell and Heath, 2004). Another recent review found that although levels of the pollutants most commonly measured (formaldehyde, total volatile organic compounds, bioaerosols) were generally below workplace standards and guidelines, pollutant exposures were sufficiently high and were found to be associated with allergy, asthma, and other respiratory symptoms (Daisey et al., 2003).

The goals of this paper are to characterize selected IAQ parameters in a mid-size school district, assess the variability in pollutant levels between and within schools, and to link pollutants to classroom activities, ventilation rates, and other factors.

Methods

School and room selection

We randomly selected four elementary schools and all five middle schools in a suburban school district in southeast Michigan that had a total of 21 elementary schools, 5 middle schools, 3 high schools, and over 1200 teachers and staff. High schools were excluded in part owing to their size and dissimilarity with other buildings. Within each school, at least one art room, one miscellaneous use room (e.g., music, library), two general classrooms, two science rooms (in middle schools), and two office/clerical rooms were selected at random from the pool of candidate rooms. The selected buildings were diverse, ranging from 31 to 81 years of age. Several schools had fixed (unopenable) windows, and two were equipped with air conditioning (Table 1). All schools had mechanical ventilation and none used displacement ventilation (Table 1). Middle schools were slightly newer, one had air conditioning, and all had openable windows. Five to eight classrooms in each school were simultaneously studied for a period of 1 week in spring and early summer (March 31 to June 7, 2003). Rooms were selected randomly among candidate types and included general, science, music and art classrooms, offices, media/computer centers, and so on. Three portable classrooms (self-contained, prefabricated, free-standing buildings) were studied at one middle school. Participant recruitment, consenting, and other procedures were approved by the Institutional Review Board at the University of Michigan.

IAQ sampling and analysis

Sampling included volatile organic compounds (VOCs), bioaerosols, temperature, relative humidity (RH), and CO_2 in each room, and VOCs, bioaerosols, temperature, and RH outdoors. Monitoring was conducted in occupied rooms over a 4.5-day period in most schools (3.5 days in schools 3 and 8 owing to holidays). We attempted to place samplers in representative locations that were secure from tampering, at least 0.6 m above the floor and below the ceiling, away from windows, doors, and obvious sources of potential contaminants (kilns, animal enclosures, and the like), at least 0.5 m away from bookshelves and other potentially stagnant areas, and out of reach of children. Simultaneous outdoor air samples were taken at rooftop locations at each school, in a sheltered location out of direct sunlight and away from stacks, vents, and so on.

VOC samples were collected passively onto thermally desorbed adsorbents (Tenax GR) using a validated method (Batterman et al., 2002; Peng and Batterman, 2000). Collected samples and quality assurance samples (blanks and spiked samples) were analyzed for over 80 compounds within several days of collection using an automated short-path thermal desorption/cryofocusing system (Model 2000; Scientific Instrument Services, Ringoes, NJ, USA) and a gas chromatograph/mass spectrometer operating in scan mode (GC/MS, Model 6890/5973 running Chemstation, G1701BA, Version B.01, Hewlett-Packard, Palo Alto, CA, USA). The sampling volume was temperature-adjusted. Laboratory and field blanks, collected in each school, showed concentrations below method detection limits (MDLs) in all cases. All samples were collected in duplicate, and replicate precision for measurements $\geq 1\ \mu g/m^3$ was better than 15%, therefore averages of replicates were used in all reported analyses. Nondetects were set to one-half of the MDL ($\sim 0.02\ \mu g/m^3$ for most compounds). The total VOC (TVOC) concentration, defined here as the sum of both target and nontarget peaks (excluding hexane) normalized to toluene equivalents, was determined for each sample.

Temperature, RH, and CO_2 were measured every 5 min using integrated data loggers (Hobo HO-8; Onset Computer Corporation, Bourne, MA, USA), which were calibrated at four temperatures and two humidities (using MgCl and NaCl saturated salt solutions for 33% and 72% RH, respectively). CO_2 sensors (GMW-20; Vaisala Corporation, Helsinki, Finland) were calibrated using pure nitrogen and a 1011-ppm CO_2 standard. CO_2 data were lost in 17 rooms owing to equipment problems or tampering; data are complete for 47 rooms. Bioaerosol and particle concentrations were measured using 5-min (indoor) or 10-min (outdoor) sampling periods and filter cassette sampling systems (Air-O-Cell; SKC Corp., Eighty-four, PA, USA). Speciated spore counts, pollen, fibers, insect and skin fragments were optically determined by a certified laboratory. Bioaerosol levels were reported as counts per m^3 (includes both viable and nonviable spores), and particle concentrations as 'total background particle density'. Blanks taken at each school were negative.

Visual inspections

A walkthrough inspection and checklist was completed for each school to document HVAC system operation and hygiene, air intake location, sources of

Table 1 Characteristics of schools and rooms, temperature, relative humidity, CO_2 concentration, and air exchange rate (AER)

												CO_2				Ventilation	
School ID	Date built	HVAC AC Type	Dates studied (M/D)	Room ID	Room type (1)	Openable windows (2)	Floor area (m^2)	Room volume (m^3)	No. of children	Temp Mean (C)	RH Mean (%)	Mean (ppm)	Min (ppm)	Max (ppm)	SD (ppm)	Steady state AER (hr^{-1})	Decay-based AER (hr^{-1})
1	1955	Main fan distribution, some unit ventilators AC	3/31–4/4 2003	11	gen	Y	84	229	15	23	28	719	513	1236	159	4.4	0.3
				12	sci	N	60	184	30	22	31	755	459	1654	269	6.6	0.1
				13	gen	Y	84	255	30	24	26	728	541	1186	160	7.7	0.3
				14	off	N	14	34	1	24	30	631	458	1006	142	5.4	0.2
				15	off	N	14	34	3	25	27	–	–	–	–	–	–
				16	gen	N	46	142	7	24	29	–	–	–	–	–	–
				17	gen	Y	51	156	10	21	31	–	–	–	–	–	–
2	1960	Main fan, tunnel distribution, stream heat	4/7–4/11 2003	21	sci	Y	111	306	27	22	27	998	579	1267	155	2.9	1.01
				22	mus	Y	167	611	33	22	24	619	414	995	122	10.3	1.3
				23	gen	Y	84	255	30	20	27	–	–	–	–	–	–
				24	off	Y	17	41	0	21	23	697	557	1100	89.9	1.4	0.5
				25	gen	Y	84	229	29	–	–	–	–	–	–	–	–
	1968 (3)	Unit ventilator, only	6/9–6/13 2003	26	port	Y	65	158	28*	22	47	1836	529	3082	925	1.9	0.4
				27	port	Y	65	158	28*	22	57	1148	505	1668	285	2.9	0.9
				28	port	Y	65	158	28*	22	48	1554	523	3279	853	5.4	0.5
3	1972	Main fans, ducted distribution	4/14–4/17 2003	31	mus	N	84	229	30	23	28	533	398	796	87	10.3	1.1
				32	gen	Y	70	212	30	23	31	1166	541	2617	455	12.2	0.25
				33	HE	Y	84	255	24	23	29	–	–	–	–	–	–
				34	gen	Y	84	255	28	–	–	–	–	–	–	–	–
				35	off	Y	19	45	1	–	–	–	–	–	–	–	–
				36	sci	Y	89	272	25	–	–	–	–	–	–	–	–
4	1968	Main fan distribution	4/28–5/2 2003	41	sci	Y	88	269	28	24	33	773	513	963	109	6.0	0.8
				42	HE	Y	84	255	28	25	33	661	414	995	98	12.9	0.7
				43	art	Y	102	311	28	26	35	647	506	941	83	17.9	1.3
				44	sci	Y	88	269	28	24	34	–	–	–	–	–	–
				45	gen	Y	70	212	28	24	35	–	–	–	–	–	–
				46	sci	Y	88	269	28	23	37	–	–	–	–	–	–
				47	sci	Y	88	269	28	23	35	–	–	–	–	–	–
				48	off	Y	14	34	1	25	32	665	576	812	56.4	4.1	
5	1951	Main fan, ducted distribution	5/5–5/9 2003	51	mus	Y	139	509	30	22	43	736	513	1027	128	8.2	0.9
				52	SE	N	19	45	6	24	36	835	428	1332	201	4.0	0.4
				53	gen	Y	79	241	30	22	43	1522	557	2686	538	4.4	0.9
				54	sci	Y	111	340	30	23	40	820	521	1128	129	4.7	0.4
				55	mus	Y	51	156	15	23	39	689	474	918	89	8.5	0.4
				56	sci	Y	111	340	28	24	38	764	500	969	85	5.7	0.37
				57	sci	Y	111	340	28	24	40	–	–	–	–	–	–
				58	gen	Y	91	276	30	24	40	800	550	1086	134	4.3	0.8
6	1922	Original bldg main fan ducted distribution.Additions unit ventilators	5/12–5/16 2003	61	off	Y	28	85	1	23	30	589	529	802	52	5.2	0.6
				62	gen	Y	79	216	25	20	36	678	428	1208	180	4.5	0.5
				63	MC	N	NA	651	varied	22	32	592	523	750	52	20.6	0.3
				64	MC	N	93	283	varied	23	31	581	468	1000	72	5.9	0.3
				65	gen	Y	74	226	25	25	28	860	474	1249	191	4.2	1.0
				66	gen	Y	84	255	16	22	34	660	489	958	106	5.3	1.7

Table 1 Continued

												CO_2				Ventilation	
School ID	Date built	HVAC AC Type	Dates studied (M/D)	Room ID	Room type (1)	Openable windows (2)	Floor area (m^2)	Room volume (m^3)	No. of children	Temp Mean (C)	RH Mean (%)	Mean (ppm)	Min (ppm)	Max (ppm)	SD (ppm)	Steady state AER (hr^{-1})	Decay-based AER (hr^{-1})
7	1963	Unit ventilator, steam AC	5/19–5/23 2003	71	MC	Y	186	566	100	22	36	691	513	947	92	12.3	0.4
				72	art	N	111	272	25	21	35	826	414	1531	280	3.3	0.35
				73	gen	Y	74	204	21	22	37	751	488	1150	190	5.1	0.47
				74	mus	N	111	204	25	24	35	776	468	1213	188	3.6	0.2
				75	gen	Y	74	204	25	23	39	937	433	1877	378	2.7	0.4
				76	gen	Y	74	204	25	26	37	801	489	1213	209	5.0	1.7
8	1954	Ceiling mounted radiant heat main fan, ducted distribution	5/27–5/30 2003	81	gen	Y	177	538	40	24	41	770	482	1203	188	2.3	0.2
				82	gen	N	70	255	26	22	45	1138	475	2113	374	1.9	0.5
				83	gen	Y	74	226	25	23	44	1061	575	1727	295	3.5	0.3
				84	gen	Y	74	226	23	22	45	845	521	1393	245	6.3	0.26
				85	gen	Y	79	241	14	22	46	1142	537	1702	393	1.8	0.35
				86	gen	Y	79	241	22	23	41	837	500	1958	320	4.4	0.2
				87	gen	Y	70	255	22	21	52	–	–	–	–	–	–
				88	gen	Y	70	255	23	22	46	822	486	1699	423	1.3	0.3
				89	off	Y	11	27	1	21	51	–	–	–	–	–	–
9	1969	Roof mounted HVAC forced air AC	6/2–6/7 2003	91	gen	N	76	185	20	23	38	713	498	1156	147	6.0	0.3
				92	gen	N	76	185	21	22	40	795	444	1285	190	3.6	0.3
				93	gen	N	76	185	23	22	41	–	–	–	–	–	–
				94	gen	N	16	40	3	22	36	647	468	840	78	6.7	0.28
				95	gen	N	76	185	20	23	40	749	444	1197	164	4.1	0.3
				96	gen	N	76	185	20	22	40	783	489	1159	158	4.0	0.9

Notes: (1) Room type: gen = general classroom, sci = science classroom; mus = music classroom; HE = home economics classroom; art = art classroom; SE = special education classroom; MC = media center; off = office; (2) Openable windows: Y = yes; N = no; (3) estimate; NA = not applicable. Schools 1–5 were middle schools and 6–9 were elementary.

contaminants, building drainage, roof, attic and interior inspection, maintenance, combustion appliances, room area and volume, carpets, animals, special facilities, space usage, and other factors. Photos of each room were taken. Floor plans and other information regarding the school were obtained.

Air exchange rates

Using CO_2 as a tracer, air exchange rates (AER) were estimated using two methods. The 'steady-state' AER_{ss} (h^{-1}) was calculated as

$$AER_{ss} = nS/[V(C_{max} - C_{min})] \quad (1)$$

where n is the number of persons in the room; S is the CO_2 emission rate per person, taken as 0.3 l min per person (ASHRAE 62-2001, 2001); V is the room volume estimated from floor dimensions and room height; C_{max} is the maximum sustained indoor CO_2 concentration; and C_{min} is the estimated minimum concentration. C_{max} was generally taken as a 2-h average mid-day concentration (~11:00 to 13:00), and C_{min} was the lowest concentration observed during the monitoring period. Because ventilation was turned off in the late afternoon, CO_2 levels generally did not fall to outdoor levels (~370 ppm), but remained slightly elevated (420–450 ppm). AER_{ss} was determined for each study day by examining the trendline of the CO_2 concentration to select time periods when steady state was achieved; an average of 3–5 days is reported. AER_{ss} is a mid-day measurement obtained when ventilation systems were fully operating and after CO_2 levels had stabilized, and relatively high rates were expected.

The second AER estimate fitted the decay in CO_2 levels measured at the end of the school day to a first-order model:

$$C_t = C_0 \exp(-AER_{DECAY}t) + C_{min} \quad (2)$$

where C_t is the observed CO_2 concentration at time t; C_0 is the estimated initial concentration; AER_{DECAY} is the estimated decay rate; and C_{min} is the minimum concentration. Parameters were estimated by regressing the logarithm of concentrations against time using the afternoon period just after children left the room (typically 14:30 to 16:30). AER_{DECAY} was determined for each study day, and the reported value is averaged over 3–5 days. Most AER_{DECAY} estimates were robust, i.e., regressions achieved high R^2 and the day-to-day variation was small. AER_{DECAY} represents the period immediately following occupancy, often when ventilation systems were turned off and windows were closed, thus low rates were expected.

Statistical analysis

For VOCs, detection probabilities (fraction of observations above LODs) were calculated. VOC distributions were asymmetric and non-normal, therefore, log-transformations were used in hypothesis testing, and Spearman rank correlations were used (Zar, 1999). Only VOCs with detection probabilities >50% were selected for correlations, scatter plots, ANOVA, factor analyses, and multiple linear regression. Differences in average concentrations between middle and elementary schools were tested using Student's t and Mann-Whitney tests. To control for intraclass correlations for elementary and middle schools and for the dependencies of measurements taken in a given school building, within- and between-school variability was evaluated using mixed linear models. The significance of between-school variability was determined using log likelihood ratio tests (Verbeke and Molenberghs, 2000). Excel, Access (Microsoft, Seattle, WA), SAS v. 9 (SAS Institute, Cary, NC, USA), and Systat v.10 (SPSS Corporation, Chicago IL, USA) were used to manage data, provide QA/QC checks, and generate statistics.

Linear regression models were used to assess effects of building environmental factors on measured concentrations of selected indoor air contaminants, specifically, VOCs and bioaerosols that had detection probabilities exceeding 50%. Initially, predictor variables included building factors that had statistically significant correlation coefficients with the contaminants. Subsequently, stepwise regression was used to develop multivariate models (SAS Institute).

Results

Sixty-four rooms in five middle and four elementary schools were sampled, with 47 (73%) having openable windows (Table 1). Nearly half (31 rooms, 48%) were general classrooms of which 23 (74%) had openable windows. The rest of the rooms were science (10, 16%), offices (7, 11%), music (5, 8%), or other (11, 17%) rooms.

VOC concentrations, correlations, and sources

The most prevalent VOCs in schools were benzene, ethylbenzene, toluene, xylene, α-pinene, and limonene, and, as expected, indoor concentrations usually exceeded outdoor levels (Table 2, Figure 1). Target compounds constituted 36 ± 19% of TVOC in the 50 permanent classrooms, and 34 ± 12% of TVOC in the three portable classrooms. With the exception of α-pinene and limonene, VOC levels were lower than levels reported previously in schools (e.g., Shendell et al., 2004a). TVOC levels also were comparable or lower than that found in the other studies. Concentrations of limonene, α-pinene, toluene, and *m,p*-xylene across the 64 rooms were significantly correlated ($r =$ 0.30–0.56) with TVOC (Table 3). In contrast, benzene was negatively, but not significantly, correlated with most other VOCs except naphthalene ($r = 0.22$);

Table 2 Summary statistics of volatile organic compounds (VOC) and bioaerosol concentrations in schools and outdoors

	Classrooms				Outdoors			
VOCs	Mean (μg/m^3)	90th (μg/m^3)	Max (μg/m^3)	Det. Freq (%)	Mean (μg/m^3)	90th (μg/m^3)	Max (μg/m^3)	Det. freq (%)
Aromatics								
Benzene	0.09	0.2	1.6	62	0.06	0.1	0.1	70
Ethylbenzene	0.24	0.7	2.8	37	<0.01	0.0	0.0	0
Toluene	2.81	3.6	74.6	100	0.52	1.0	1.0	90
p,m-Xylene 0.83	2.3	10.2	63	0.03	0.0	0.2	10	
o-Xylene	0.24	0.6	3.8	32	<0.01	0.0	0.0	0
Styrene	0.04	0.0	1.4	23	<0.01	0.0	0.0	0
1,3,5-Trimethylbenzene	0.02	0.0	0.2	11	<0.01	0.0	0.0	0
1,2,4-Trimethylbenzene	0.14	0.4	1.5	51	0.01	0.0	0.0	10
p-Isopropyltoluene	0.02	0.0	0.6	6	<0.01	0.0	0.0	0
Chlorinated					<0.01			
1,3-Dichlorobenzene	0.02	0.0	0.4	2	<0.01	0.0	0.0	0
1.2.3-Trichlorobenzene	0.01	0.0	0.3	2	<0.01	0.0	0.0	0
1.2.4-Trichlorobenzene	0.07	0.0	3.9	2	<0.01	0.0	0.0	0
Chloroform	0.09	0.1	2.5	15	<0.01	0.0	0.0	0
Trichloroethylene	0.02	0.0	0.3	3	0.01	0.0	0.1	10
Tetrachloroethylene	0.02	0.0	0.3	2	<0.01	0.0	0.0	0
1,2,3-Trichloropropane	0.01	0.0	0.1	2	<0.01	0.0	0.0	0
Other					<0.01			
2-Butanone	0.24	0.9	3.0	38	<0.01	0.0	0.0	0
Tetrahydrofuran	0.16	0.0	3.8	8	<0.01	0.0	0.0	0
Methyl isobutyl ketone	0.46	1.0	8.2	40	0.02	0.0	0.1	10
Phenol	0.61	1.5	12.1	37	0.13	0.1	1.2	10
α-Pinene	1.35	1.9	35.2	72	0.11	0.5	0.6	20
Limonene	4.41	8.2	45.1	100	0.29	1.2	1.6	20
Naphthalene	0.82	1.8	10.3	42	0.10	0.1	0.9	10
Total VOCs	58.0	84.9	384.2		10.44	15.1	27.5	

	Classrooms				Outdoors			
Bioaerosols	Median (CFU/m^3)	90th (CFU/m^3)	Max (CFU/m^3)	Det. Freq. (%)	Median. (CFU/m^3)	90th (CFU/m^3)	Max (CFU/m^3)	Det. Freq (%)
Mold spores								
Agrocvbe/Coprinus	0	0	0	0	0	254	726	30
Alternaria	0	0	75	4	0	89	161	30
Aspergillus/Penicillium	484	1735	6370	98	868	1992	2820	100
Bipolaris	0	81	403	13	61	484	484	50
Cladosporium	0	121	726	27	484	13610	37100	90
Immature/unidentified	0	81	161	18	20	141	323	50
Hyphae	0	0	81	2		00	0	0
Total mold spores	505	1937	6370	98	2461	15879	40894	100
Other								
Pollen	0	0	75	4	0	173	282	20
Fiberglass	0	0	38	2	0	8	81	10
Insect fragments 0	0		38	4	0	0	0	0

Note: For VOC, $n = 65$ indoors and 10 outdoors; for bioaerosols, $n = 56$ indoors and 10 outdoors.

however, benzene levels were very low (average < 0.1 μg/m^3). Outdoor concentrations of VOCs were low (generally <1 μg/m^3 for individual compounds), reflecting the residential and suburban areas sampled. None of the schools were close to highways, and the community is largely free of strong industrial sources.

The high indoor/outdoor ratios (I/O $>$ 10) for ethylbenzene, xylene, 2-butanone, methyl isooctane, α-pinene, and limonene, and the moderate I/O ratios (>4) for toluene, styrene, 1,2,4-trichlorobenzene, chloroform, phenol, and naphthalene suggest indoor sources for these VOCs. In contrast, the I/O ratio for benzene (1.4), indicates that outdoor sources were the primary contributors.

Each middle school showed traces of chloroform, trichloroethylene and 1,2,3-trichlorobenzene (mean $<$ 0.1 μg/m^3, maximum $<$ 4 μg/m^3), and each had an indoor swimming pool. Additional sampling at three locations in the distribution ducts of the ventilation system of one of the middle schools showed that the pools were a chloroform source, likely a by-product of chlorine disinfection. These compounds were rarely detected in the elementary schools, which did not have pools. A primary school art room (room 72) had the highest concentrations of toluene, methyl isobutyl

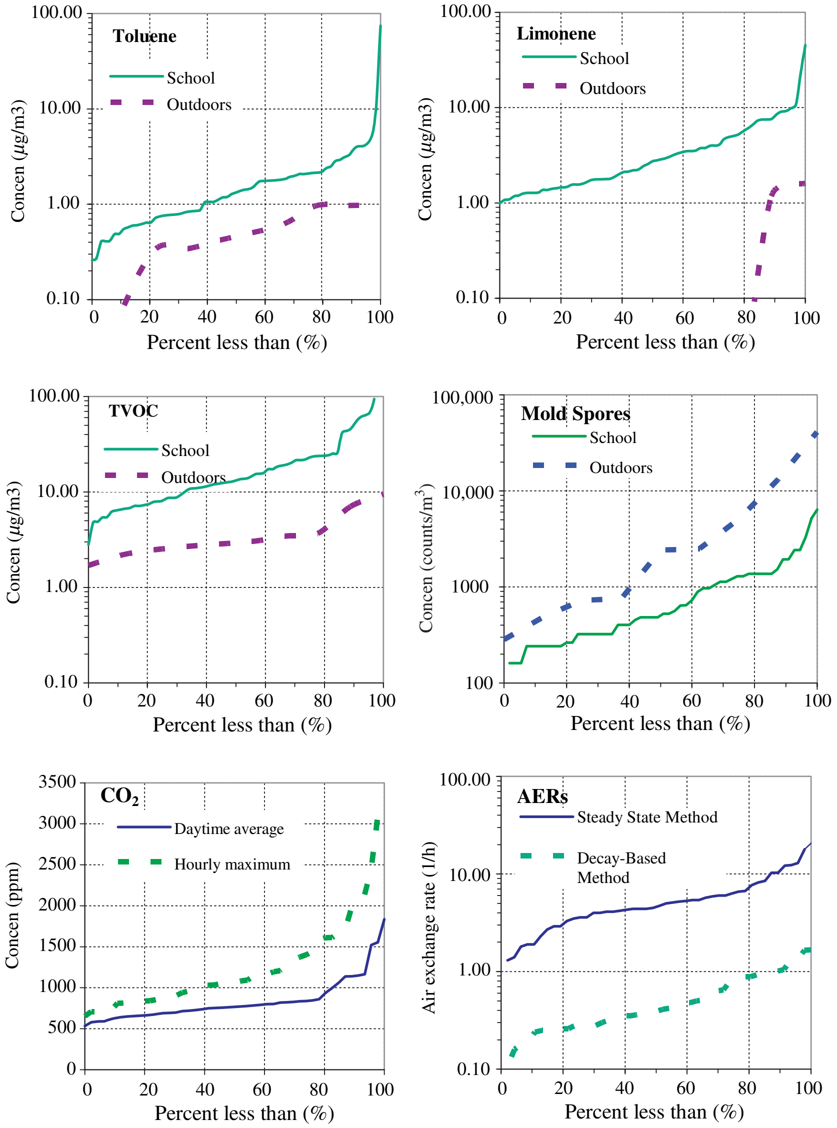

Fig. 1 Distributions of toluene, limonene, benzene, total volatile organic compound concentrations in 65 school rooms and 10 outside locations; total mold spore concentration in 56 school rooms and nine outdoors; maximum and average CO_2 in 47 school rooms; and air exchange rates in 47 and 48 rooms for steady-state and decay-based methods, respectively

ketone, and phenol (9.8, 8.2, and 12 $\mu g/m^3$, respectively), while a middle school art room (room 43) had high levels of chlorinated VOCs (chloroform and 1,2,4-trichlorobenzene at 2.5 and 3.9 $\mu g/m^3$, respectively). This room was close to the pool, the likely chloroform source. Science rooms showed the highest concentration of naphthalene (10 $\mu g/m^3$ in room 56, and 7.3 $\mu g/m^3$ in room 21); another science room had high levels of α-pinene (35 $\mu g/m^3$ in room 44), a component used in many cleaning products. Levels of other VOCs in science rooms were typical. One of the three portables (room 26) tested had the highest levels of styrene and limonene (1.4 and 45 $\mu g/m^3$, respectively), and the second highest levels of α-pinene (5 $\mu g/m^3$). Compared with conventional classrooms, portables also had higher levels of styrene (0.54 vs. 0.02 $\mu g/m^3$), α-pinene (2.6 vs. 1.4 $\mu g/m^3$), and limonene (16.9 vs. 4.0 $\mu g/m^3$), but lower levels of *m,p*-xylene (0.15 vs. 0.85 $\mu g/m^3$). While levels of most VOCs appear to be higher in portable classrooms, this result should be interpreted cautiously as only three portables at one school were sampled.

The multiple regression models showed that daytime average CO_2, AER_{SS} (i.e., daytime ventilation rate) and floor type (i.e., tile, tile/carpet, and fully carpeted) were statistically significant predictors of toluene, *m,p*-xylene, α-pinene, limonene, and TVOC concentrations. For toluene, daytime average CO_2 had a standardized coefficient (STB) of 0.27 but the adjusted multiple coefficient of determination was very small ($R^2 = 0.04$). For *m,p*-xylene, AER_{SS} ($STB = -0.35$) and carpeting ($STB = -0.34$) made significant contributions ($R^2 = 0.21$). Similar results were obtained for α-pinene with AER_{SS} ($STB = -0.35$) and carpeting

Table 3 Spearman rank correlation coefficients for frequently detected (>50%) indoor volatile organic compounds (VOC) and bioaerosols, CO_2, ventilation rates, and school room factors

	Benzene	Toluene	*m*-, *p*-xylene	α-Pinene	Limonene	Total VOCs	*Aspergillus*	Total bioaerosols	Openable windows	Carpeting	Steady state AER	Weighted mean AER	Decay-based AER	Schoolday avg. CO_2	Daytime hourly max. CO_2	No. of occupants
Benzene	1															
Toluene	−0.06	1														
m-,*p*-xylene	−0.13	0.38*	1													
α-Pinene	−0.30*	0.15	0.45*	1												
Limonene	−0.21	0.32*	0.27*	0.36*	1											
Total VOCs	−0.29*	0.56*	0.20	0.30*	0.37*	1										
Aspergillus	0.13	0.02	−0.30*	−0.40*	0.07	0.00	1									
Total bioaerosols	0.13	0.09	−0.27	−0.39*	0.11	−0.02	0.97*	1								
Openable windows	0.07	0.15	−0.29*	0.02	−0.18	0.09	−0.03	0.03	1							
Carpeting	−0.21	0.16	−0.08	−0.13	0.06	0.01	0.46*	0.45*	0.16	1						
Steady state AER	0.16	−0.27	−0.40*	−0.37*	−0.42*	−0.30*	−0.05	−0.03	0.07	0.07	1					
Weighted mean AER	0.12	−0.31*	−0.47*	−0.41*	−0.47*	−0.33*	0.07	0.08	0.15	0.14	0.94*	1				
Decay-based AER	0.08	−0.30*	−0.42*	−0.19	−0.33*	−0.19	0.40*	0.34*	0.22	0.26	0.14	0.38*	1			
Schoolday avg. CO_2	−0.06	0.45*	0.28	0.32*	0.42*	0.55*	0.02	0.00	0.14	0.01	−0.56*	−0.48*	−0.18	1		
Daytime hourly max. CO_2	0.08	0.50*	0.30	0.15	0.30	0.47*	0.13	0.12	0.09	0.00	−0.50*	−0.50*	−0.38*	0.82*	1	
No. of occupants	0.15	0.03	−0.18	−0.14	−0.30*	0.13	0.04	−0.02	0.20	0.17	0.28*	0.31*	0.14	0.17	0.12	1

*statistically significant. Notes: $n = 58$ for VOC, no. of occupants and openable windows; $n = 56$ for floor area/no. of occupants; $n = 50$ for bioaerosols; $n = 46$ for decay-based air exchange rate (AER_{DECAY}); $n = 45$ for school-day average CO_2 and steady-state AER (AER_{SS}); $n = 39$ for daytime hourly max CO_2.

(STB = −0.35), which gave a slightly higher fit ($R^2 = 0.26$). Limonene was predicted using daytime average CO_2 (STB = 0.33) and AER_{SS} (STB = −0.31) with a comparable fit ($R^2 = 0.29$). A single variable, daytime average CO_2 (STB = 0.58), provided the best fit for TVOC ($R^2 = 0.32$).

VOC concentrations tended to differ significantly between elementary and middle schools as shown by both parametric (Student's *t*) and nonparametric (Mann-Whitney *U*) tests (Table 4). Toluene, *m*,*p*-xylene, and limonene were higher in elementary schools, while benzene, α-pinene, and napthalene were higher in middle schools. Average TVOC concentrations did not differ significantly between elementary and middle schools. Mixed regression models controlling for school type showed that concentrations of α-pinene and limonene varied more within schools (expressed as a percentage of the total variation) than between schools, while toluene and *m*,*p*-xylene showed the opposite trend (Table 5). For example, Figure 2 shows that limonene levels at most varied over an order of magnitude, and generally schools with higher concentrations also showed greater variability. For the summary measure TVOC, the majority (57%) of the variation was owing to between-school variation.

Table 4 Comparison of average indoor air concentrations between elementary and middle schools

	Elementary			Middle			*P* value	
Variable	*n*	Mean	Median	*n*	Mean	Median	Student's t	Mann-Whitney u
VOCs (μg/m^3)								
Benzene	26	0.03	0.01	29	0.15	0.07	0.00	0.00
Toluene	26	2.05	1.79	29	1.20	1.04	0.01	0.02
m,*p*-Xylene	26	1.64	1.20	29	0.15	0.02	0.00	0.00
α- Pinene	26	0.86	0.72	29	1.84	0.51	0.04	0.02
Limonene	26	5.45	4.35	29	2.65	1.78	0.00	0.00
Naphthalene	26	0.11	0.01	29	0.97	0.01	0.02	0.03
Sum target VOCs	26	18.67	14.73	29	24.11	9.02	0.36	0.14
Total VOCs	26	45.88	39.91	29	59.00	34.77	0.45	0.93
Bioaerosols (counts/m^3)								
Aspergillus	23	1115	1050	27	563	403	0.59	0.23
Cladosporidium	23	21	0	27	73	0	0.16	0.18
Immature/ unidentifed	23	14	0	27	18	0	0.91	0.87
Total bioaerosols	23	1168	1050	27	6661	484	0.66	0.19

Notes: Elementary schools: $n = 26$ for volatile organic compounds (VOC), $n = 23$ for bioaerosols. Middle schools: $n = 29$ for VOC, $n = 27$ for bioaerosols. Student's *t*-test used log-transformed data. *P* values indicate significance of difference between middle and elementary school means.

Table 5 Within- and between-school variation in indoor air quality (IAQ) parameters and tests of differences using log-transformed data Note

		Percent of variation (%)		
Variable	*n*	Within schools	Between schools	*P*
Toluene	58	47	53	0.00
m,*p*-Xylene	58	44	56	0.00
α-Pinene	58	52	48	0.00
Limonene	58	83	17	0.06
Sum Target VOCs	58	65	35	0.00
Total VOCs	58	43	57	0.00
Aspergillus	53	72	28	0.00
Total bioaerosols	53	78	22	0.02
Daytime average CO_2	46	76	24	0.03
Hourly maximum CO_2	45	77	23	0.03
AER_{DECAY}	46	70	30	0.01
AER_{SS}	47	69	31	0.02

H_0: no significant between-school difference. Between-school difference of all variables were statistically significant at $P \leq 0.05$ except limonene ($P = 0.06$). Benzene was not included because very low concentrations provided inadequate data for analyses.

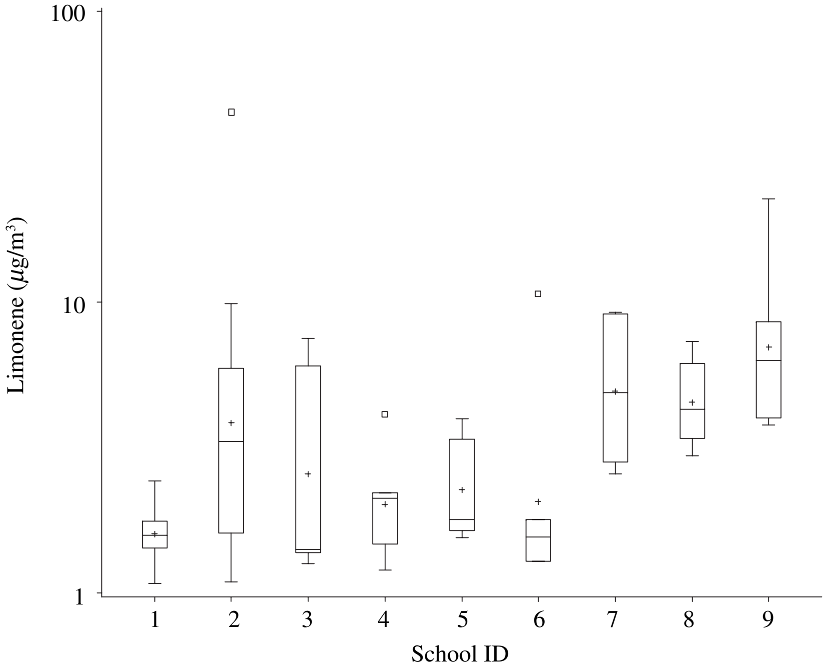

Fig. 2 Box plot of limonene concentration by school. Symbol '□' designates outliers, '+' identifies means. Schools 1–5 are middle schools and 6–9 are elementary

Carbon dioxide

CO_2 levels ranged widely and exceeded 1000 ppm in at least one room at each school except school 4 (Figure 1, Table 1). Peak levels reached 2700 and 3330 ppm in a nonportable and portable classrooms, respectively (rooms 53 and 28). High CO_2 levels were found in all three portable classrooms. Maximum CO_2 levels should be interpreted cautiously as they may reflect events such as occupants clustering around and/or breathing on the sensor. Average CO_2 levels, which are robust as they represent school-day periods averaged over 3 or 4 days, ranged from 533 to 1522 ppm in individual nonportable classrooms and from 1148 to 1836 in the three portables (rooms 26, 27, and 28). Both daytime average and hourly maximum CO_2 levels showed much greater within-school variability (76–77%) than between-school variability (23–24%, Table 5).

Bioaerosols

Five mold genera were detected in schools, of which *Aspergillus/Penicillium* was by far the most common and found in all indoor and outdoor samples. *Cladosporium* was the next most common, found in 27% of indoor samples and 90% of outdoor samples (Table 2). Mildew, *Chaetimium*, *Curvularia*, *Ganoderma*, *Periconia*, and *Stachybotrys* were not detected. Identified genera were found both indoors and outdoors, i.e., none was present exclusively indoors or outdoors. Pollen, fiberglass, and insect fragments were detected at a few sites, especially in school 1. The total mold spore concentrations ranged widely (Figure 1). For most species and schools, outdoor levels (median = 2461 counts per m^3, $n = 10$) exceeded indoor levels (median = 527 counts per m^3, $n = 74$). The exception was *Aspergillus/Penicillium*, for which schools 2, 3, 7, and 9 had average I/O ratios of 3.5, 3.2, 6.9, and 1.4, respectively. I/O ratios at schools 2, 3, and 7 were affected by low outdoor levels (121 to 323 counts per m^3); outdoor levels at school 9 were typical (928 counts per m^3). These results suggest possible indoor sources of *Aspergillus* and/or *Penicillium* at school 9. Portable classrooms had higher bioaerosol concentrations than conventional classrooms (e.g., median levels of *Aspergillus/Penicillium* of 1610 vs. 443 counts per m^3, respectively); however, as mentioned with regards to VOCs, this comparison is based on only three portables. A total mold spore concentration of 1000 counts per m^3, sometimes used as a guideline (e.g., Bush and Portnoy, 2001; Lee and Chang, 2000;), was exceeded in 22 rooms (31%). However, mold infestation appears unlikely given that indoor levels were generally lower than outdoor levels, bioaerosol compositions were similar both indoors and outdoors, humidity levels were not excessive, and no school showed evidence of water damage or other causative factors in the walk-through inspections. Total bioaerosols were weakly but significantly negatively correlated with α-pinene (Table 3), possibly reflecting recent or increased use of cleaning products in rooms with higher mold concentrations. Multivariate models showed that only the number of occupants (STB = 0.31) and the presence of carpeting (STB = 0.58) were associated with

Aspergillis concentrations ($R^2 = 0.19$), the only bioaerosol detected in >50% of the classrooms. Carpeting (STB = 0.41) was the only significant predictor for total bioaerosol concentrations ($R^2 = 0.15$). Bioaerosol concentrations in elementary and middle schools did not differ (Table 4), and within-school variability was much greater than between-school variability.

Air exchange rates

Estimated AER are listed in Table 1, and the distribution of AER is shown in Figure 1. Rates were much higher during the occupied period (average $\mathrm{AER_{SS}} = 6.2 \pm 3.1$ per hour, $n = 48$), as compared with late afternoon when HVAC systems are shut down to conserve energy and windows are closed (average $\mathrm{AER_{DECAY}} = 0.6 \pm 0.3$ per hour, $n = 47$). The average school-day $\mathrm{AER_{SS}}$ in classrooms with openable windows was slightly but not statistically lower (4.4 ± 1.9 per hour, $n = 28$) than rooms with fixed windows (5.0 ± 4.6 per hour, $n = 14$, $P = 0.80$, *t*-test). Possibly infrequently or only partially opened windows, and differences in the amounts of outside air provided by the HVAC system may have obscured the expected difference. However, a small but statistically significant difference was seen in the afternoon when classrooms with operable windows had a higher $\mathrm{AER_{DECAY}}$ (0.64 ± 0.41 per hour) than rooms with fixed windows (0.38 ± 0.27 per hour) ($P = 0.04$, *t*-test). Rooms with operable windows may be 'leakier' than rooms with sealed or no windows, but this can only be observed when the HVAC system is off. Within-school variability for $\mathrm{AER_{SS}}$ and $\mathrm{AER_{DECAY}}$ was much larger than between-school variability, suggesting the importance of room effects (e.g., window and door opening).

Temperature and humidity

School-day temperatures in classrooms averaged 23 ± 3°C and the RH averaged 38% ± 9%, and all but two classrooms achieved the comfort range (20 to 26°C and 20% to 60% RH) as per the recommendations of ASHRAE (1993). Temperatures rose steadily over the study period, averaging 14.5 ± 9.5°C in April, increasing to 18.2 ± 3.3°C in May, then stabilizing in mid-June to 17.3 ± 3.6°C. Indoor and outdoor RH also increased over the study period (indoors levels were 30% ± 4%, 39% ± 6%, and 43% ± 6% in April, May, and June, respectively; outdoors levels were ~17% higher). None of the classrooms were humidified.

Discussion

Contaminant levels

TVOC levels measured in this study fell in the range reported in previous studies. However, comparisons of TVOC levels across studies can be problematic owing to differences in definition, measurement, and analysis (Andersson et al., 1997), and examination of specific VOC species is often more informative. Only two studies in the recent peer-reviewed literature gave concentrations of specific VOCs other than formaldehyde in schools. Shendell et al. (2004a) reported higher concentrations of benzene, toluene, and *m,p*-xylene (1.7, 9.5, and 2.7 μg/m^3, respectively) in main building classrooms than found here, but lower levels of α-pinene and limonene (0.4 and 1.7 μg/m^3, respectively; $n = 3$), while Norback (1995) reported higher toluene and limonene concentrations (averaging 16 and 13 μg/m^3, respectively, $n = 6$). Given the paucity of VOC measurements in schools, we compare concentrations in schools with those reported in office buildings. Schools have swimming pools, science and art rooms, and so on, at higher concentrations of certain VOCs (e.g., chlorinated VOCs, aromatics) might be expected. Nontheless, compared with the large BASE study of office buildings (US EPA, 2005), maximum VOC levels in schools were low with the exceptions of α-pinene (office and classroom maxima were 8.4 and 35 μg/m^3, respectively) and naphthalene (office and classroom maxima of 9.7 and 10.3 μg/m^3).

VOCs in schools likely originated from a combination of building sources, occupant activities, and outdoor sources. We saw no clear association of VOCs with openable windows and floor area. However, the regressions were consistent in showing effects related to ventilation and the presence of carpeting, although these models provided only modest explanatory power. Excluding the model for toluene owing to its very low R^2, the standardized regression coefficients for ventilation and CO_2 concentration indicated that increased ventilation was associated with decreased VOC concentrations. These results, the room-to-room variability, and the low outdoor levels suggest local (classroom) sources rather than building-wide or outdoor sources. Art and science rooms had some of the highest levels measured for certain VOCs (e.g., toluene and naphthalene, respectively). The passive sampling method provides an integrated sample for both occupied and unoccupied periods, thus, concentrations may not be representative of occupant exposure levels. Depending on the nature of the source and the ventilation, passive sampling may either over- or underestimate occupant exposures, especially for VOCs closely associated with occupant activities.

Median indoor bioaerosol concentrations were below 1000 counts per m^3, which is comparable or lower to published levels measured in nonproblem buildings (Scheff et al., 2000b; Smedje and Norback, 2000). Multiple regression analyses showed concentrations of commonly detected bioaerosols were positively associated with carpeting, suggesting that carpeting may be a source of bioaerosols. As the measurements included both viable and nonviable particles, viable concentrations (i.e., CFU/m^3) would be lower. Unlike (Santilli, 2002) who found *Alternaria*, *Boytrytis*, *Curvularia*, *Episoccum*, and *Stachybotrus* exclusively indoors and at high concentrations in three 'problem schools', we found no genera that were similarly exclusive and concentrations were low. Indoor bioaerosol concentrations can be highly variable and influenced by many factors, e.g., the life cycle of the organism, season, humidity, window opening, HVAC maintenance, and air filtration. Thus, the short-term bioaerosol samples reflect concentrations only for the day the samples were taken and may not be representative of long-term exposures.

Adequacy of ventilation

Ventilation was inadequate in many of the school rooms, reinforcing earlier studies (e.g., Daisey et al., 2003; Scheff et al., 2000a; Shendell et al., 2004b). Based on AER_{SS}, only 27% of the classrooms achieved an AER of 3/h or more needed to achieve the ASHRAE standard of 8 l/s per person for classrooms (Daisey et al., 2003). Based on a 1000-ppm CO_2 limit (ASHRAE 62-2001, 2001) and using school-day averages, 17% of the classrooms were inadequately ventilated. Ventilation in portable school rooms was notably worse than in main school buildings, also noted by Shendell et al. (2004b).

The differences found between steady-state and decay-based AER appear largely owing to differences in HVAC operation during occupied and unoccupied periods. The former were estimated for occupied periods when HVAC systems were operating, while the latter were determined when most individuals had left the building and HVAC systems were turned down or shut-off to conserve energy. The estimated steady-state AER exceed levels reported in recent studies, while the decay-based AER were comparable with the lowest values reported. For example, (Kinshella et al., 2001) reports a high of 3.4/h (range of 0.4–7.5/h), while Liu et al. (2000) reports the lowest value, 0.66/h (range of 0.3–2.5/h). The studied school district had recently engaged in a system-wide building and HVAC assessment and preventative maintenance program which, according to district staff, had resulted in improved operation. Seasonal differences might explain some of the results as windows and doors may have been opened more during occupied periods when the weather was warmer, near the end of the study. However, AER during occupied periods between rooms with and without operable windows were comparable. The different methods used to determine AER during occupied and unoccupied periods might explain some of the differences, though no specific biases are expected.

Spatial variation

Room-by-room variation seen for limonene, α-pinene, bioaerosols, AERs, and CO_2 suggests that differences in indoor emission sources and activities affecting pollutant levels affected measurements more than any common school factor, e.g., location, HVAC system type, and building-wide cleaning/maintenance practices. Schools contain a variety of spaces serving different activities, potentially different contaminant sources (e.g., classrooms, offices, gymnasiums, pools, art, science, wood, jewellery and metal shops, libraries, kitchens, and cafeterias), and many schools employ unitary air handlers that limit mixing with other spaces in the school. Consequently, multiple locations should be measured to characterize IAQ parameters in schools.

Limitations

The 64 classrooms in nine public school buildings sampled likely reflect IAQ and ventilation parameters in the Michigan school district; however, results may not be representative of school districts elsewhere for several reasons: (i) the tested schools were in a relatively affluent district which has active IAQ and preventative maintenance programs; (ii) schools in other climatic regimes, especially in hot and humid areas, often are dependent on air conditioning and have a greater chance of poorer ventilation, higher humidity, and mold problems; (3) the tested schools, all sited in suburban areas with generally good ambient air quality (in terms of VOCs and bioaerosols), may not reflect air quality in schools near highways, agriculture, or industry; (4) schools were monitored during the spring, a period when outdoor conditions are moderate but highly variable. Monitoring during other seasons is necessary to evaluate seasonal effects, e.g., ventilation may be further reduced during very cold and very warm seasons.

The IAQ characterizations used instruments, indicators, averaging times, and analysis methods that may differ from those used in other studies. This is especially likely for bioaerosol and VOC measurements. In contrast, CO_2 measurements are generally comparable, which should improve the study comparability, though again averaging times for CO_2 measurements vary. Also, monitoring did not include several potentially important contaminants (e.g., formaldehyde, particulate matter, and bacteria) and several 'microenvironments' that may provide considerable exposure, e.g., swimming pools, kitchens, and industrial arts shops. While care was taken in monitoring site placement, some measurements may not be representative, e.g., the highest CO_2 concentrations might have resulted from persons breathing on the instruments.

Conclusions

The 64 rooms monitored in nine schools in the suburban school district showed generally low levels of VOCs and bioaerosols, acceptable ranges of temperature and humidity, but often deficient rates of ventilation. The within-school variability of most IAQ parameters (most VOCs, bioaerosols, and CO_2) was comparable with or exceeded the variability between schools, suggesting the influence of local (in-school) emissions, activities, or building features, and the need for multiple monitoring sites to characterize IAQ in schools. For VOCs, identified sources included activities in art rooms, science rooms, and indoor pools; therefore, we recommend that school buildings be designed to prevent migration of potentially contaminated air from these types of special-use areas into the rest of the building. This may be accomplished by, e.g., pressure gradients, dedicated ventilation systems, or in extreme cases standalone structures. Bioaerosols were positively associated with the presence of carpeting, suggesting that carpeting may be a source of bioaerosols in the study schools and thus should be cleaned regularly and monitored for signs of dampness and/or moisture damage. Walkthrough inspections revealed no obvious problems with HVAC systems, water damage, mold infestation, and so on, and buildings appeared to be well maintained. Nonparametric statistical methods produced very similar results to parametric methods conducted on log-transformed data.

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