

Original article

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Indoor carbon dioxide concentrations in Croatian elementary school classrooms during the heating season

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Aware that exposure to stuffy indoor air with high levels of carbon dioxide (CO₂) is associated with higher absenteeism and reduced academic performance in school pupils, the World Health Organization (WHO) Regional Office for Europe initiated indoor air quality surveys in schools, including CO₂ monitoring, to assess ventilation and exposure to stuffy air. Here we report the findings of the first such survey in Croatia. It was conducted in 60 classrooms of 20 urban and rural elementary schools throughout the country during the heating season. Measurements of CO₂ levels showed that all 60 classrooms exceeded the international guidelines of 1938 mg/m³. Mean CO₂ concentrations ranged from 2771 to 7763 mg/m³. The highest concentration measured in urban schools was 7763 mg/m³ and in rural schools 4771 mg/m³. Average CO₂ levels were higher in continental schools (3683 mg/m³) than the coastal ones (3134 mg/m³), but all demonstrate poor ventilation during the heating season all over Croatia.

KEY WORDS: CO₂; indoor air quality; ventilation

Children belong to the most vulnerable social groups to a variety of air pollutants (1). In contrast to adults, their organs are still maturing, they inhale more air per body weight, and are less resistant to environmental factors that may impair their health and cognitive performance in the long run (2–4).

After homes, schools are the second most important place of child exposure to indoor pollutants, and the level of exposure is directly associated with classroom ventilation, which, in turn, is closely associated with health (5–7). According to the World Health Organization (WHO) Regional Office for Europe report (8), CO₂ concentrations in classrooms serve as a proxy for ventilation rates and recommendations for maximum values vary from 1938 to 2907 mg/m³ (1000–1500 ppm). Health effects of poor ventilation ("stuffy air") in classrooms range from headaches and respiratory infections, which result in absenteeism, to lower cognitive performance and learning

(9–12). Satish et al. (13) found that cognitive performance was slightly worse at CO₂ concentrations of 1938 mg/m³ and substantially worse at 4845 mg/m³. According to Janssen et al. (14), the quality of indoor air environment in schools can be affected by insufficient ventilation, especially in winter, presence of indoor emission sources, such as furniture and building materials, and crowded classrooms.

In educational facilities, indoor CO₂ concentration serves as an indicator of indoor air quality (15), and several studies have assessed CO₂ concentrations in indoor school environment and children's exposure to indoor pollution (16–20).

In line with the commitment to prevent diseases in children by improving outdoor and indoor air quality set out in the Parma Declaration (21), the WHO European Centre for Environment and Health (ECEH) and its partner institutions developed standardised methodology for comprehensive assessment of exposures in the school environment (22).

In 2012, WHO ECEH and the Public Health Institute of the Osijek-Baranja County set up a pilot project in the

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schools of Osijek (Eastern Croatia) to implement standard WHO data collection tools to Croatian settings (23), which then gave way to a comprehensive survey at the national level (24). Here we report the results of this national survey.

MATERIALS AND METHODS

The survey was conducted in 20 randomly selected schools in 10 counties across Croatia from February to May 2014 (Figure 1) and involved monitoring of 60 classrooms (3 classrooms per school) during one school week, Monday morning to Friday evening, for 24 h a day, to obtain daily fluctuations CO₂ in real-life settings. The schools were selected to cover all geographic locations and socioeconomic environments (rural, urban, coastal and continental). Nine of twenty selected schools were located in rural areas; six schools were located in the coastal region. Only one school had a mechanical ventilation system, while others were ventilated by opening doors and windows.

Carbon dioxide levels, temperature, and relative humidity were measured with compact Kistock KTH-CO₂ (Kimo, Rennes, France) monitors with data loggers and memory sufficient to retain 20,000 recordings. Carbon dioxide was recorded at one-minute intervals with the upper limit of quantitation of 9689 mg/m³ and accuracy of $\pm (96.9 \text{ mg/m}^3 + 3 \% \text{ of the measured value})$. Relative

humidity and temperature were recorded continuously with the accuracy of $\pm 2 \%$ for relative humidity and $\pm 0.5 \text{ }^\circ\text{C}$ for temperature (both at temperatures from 15 $^\circ\text{C}$ to 25 $^\circ\text{C}$). The monitors were calibrated for each parameter using a two-point adjustment method, in which a new slope and a new offset are automatically calculated based on high and low calibration values (25).

Statistical analysis

For statistical analysis we used the Statistica software v. 7.1 (StatSoft Inc., Tulsa, OK, USA). Numerical data are reported descriptively as medians and interquartile ranges. Normality of distribution was tested with the Kolmogorov-Smirnov test. Between-group differences were assessed with the Mann-Whitney U test. Hierarchical clustering using the complete linkage method with Euclidean distance was applied according to our hypothesis that different schools could be clustered by similar features. P values of less than 0.05 were considered statistically significant.

RESULTS AND DISCUSSION

School characteristics

The school sizes ranged from 103 to 767 pupils. Classroom volumes varied from 60 to 334 m³. The average



Figure 1 Locations of schools participating in indoor air monitoring

Table 1 Indoor air parameters and main characteristics of 20 schools (averages from three classrooms)

No.	Type	Location	TFA (m ²)	NP	RV (m ³)	FAP (m ² /pupil)	T (°C)	RH (%)	CO ₂ (mg/m ³)
1	Urban	Continental	4750	586	162	8.10	21.3	49.2	4690
2	Rural	Continental	3500	636	180	5.50	22.7	37.7	3521
3	Urban	Continental	1553	705	231	2.20	21.8	39.3	3180
4	Rural	Continental	1600	205	144	7.80	21.8	43.6	3616
5	Urban	Continental	1400	531	152	2.63	21.9	31.2	3583
6	Rural	Continental	837	103	123	8.12	20.8	60.2	3612
7	Urban	Continental	3000	504	117	5.95	22.9	54.7	3819
8	Rural	Continental	1390	217	215	6.40	21.9	45.9	4224
9	Urban	Continental	3100	738	210	4.20	23.2	42.3	4213
10	Urban	Continental	3000	378	334	7.93	20.3	54.8	5346
11	Urban	Continental	6000	767	192	7.82	20.9	47.5	3841
12	Rural	Continental	1542	328	308	4.70	21.4	34.6	4036
13	Urban	Continental	2338	377	210	6.20	22.5	49.8	3695
14	Rural	Continental	3600	186	130	19.35	20.1	50.2	4209
15	Rural	Coastal	2100	273	173	7.69	21.6	45.3	3302
16	Urban	Coastal	2600	570	262	4.56	21.4	54.2	3515
17	Rural	Coastal	360	205	162	1.75	21.6	49.7	3486
18	Rural	Coastal	1158	130	134	8.90	20.7	40.8	2951
19	Rural	Coastal	2200	521	60	4.22	20.6	43.4	3428
20	Urban	Coastal	3750	524	70	7.15	20.8	42.1	3593

TFA – total floor area; NP – number of pupils; RV – room volume; FAP – floor area per pupil; T – temperature; RH – relative humidity

classroom temperature varied from 20.1 to 23.3 °C, and relative humidity from 31.2 to 60.2 %.

CO₂ concentrations

The mean CO₂ concentration for all 60 classrooms was 3767±1393 mg/m³ (median 3339 mg/m³), and the measurements ranged from 901 mg/m³ to the upper limit of quantitation of 9689 mg/m³. All the 60 classrooms had mean CO₂ levels above the recommendations from WHO report of 1938 to 2907 mg/m³ (8).

Maximum CO₂ concentrations coincided with the school day between 8 am and 6 pm, as the classes were organised in two shifts in all schools. Classrooms were not ventilated after the school day. Overnight, CO₂ dropped to concentrations between 1938 mg/m³ and 3876 mg/m³.

Rural (N=27; 3381 mg/m³) and urban (N=33; 3629 mg/m³) schools did not significantly differ in mean CO₂ concentrations (P=0.242), even though their respective average ranges of 2965-4771 mg/m³ and 3062-7763 mg/m³ suggest so. However, continental schools (N=42, 3683 mg/m³) had significantly higher CO₂ levels (P<0.001) than coastal schools (N=18; 3134 mg/m³), which could be related to warmer weather conditions and therefore better natural ventilation in the coastal area.

Cluster analysis shows that, with the exception of one school in the Osijek area (school No. 1 with the highest mean concentration of 4691 mg/m³ and a completely

different CO₂ profile), elementary schools did not form any distinct geographical clusters with respect to CO₂ levels (Figure 3).

From the moment pupils entered the classroom at 7.55 am, CO₂ concentration sharply rose (Figure 4). Slight decreases in CO₂ concentration occurred during breaks between classes, probably due to brief ventilation caused by door opening. When classrooms were unoccupied between morning and afternoon shifts, the CO₂ concentrations dropped and started to rise again as afternoon classes began.

All schools had a similar CO₂ concentration profile but differed in daily morning and afternoon shift maxima. Similar variations have also been reported elsewhere (20). Like in Portuguese schools (17), the classrooms were poorly ventilated due to noise, rain, and cold weather. Furthermore, windows were not opened for ventilation overnight for security reasons. During the night hours, CO₂ dropped to concentrations between 1938 mg/m³ and 3876 mg/m³. Even in the early morning hours before classes began on Monday, the initial CO₂ concentration in 30 % of the classrooms ranged from 2132 to 4651 mg/m³, probably due to overheating.

Particularly high CO₂ levels (going over the upper quantification limit of 9689 mg/m³) were found in computer classes. Similar findings reported earlier (26–28) indicate that low air quality in computer classes could be a result of

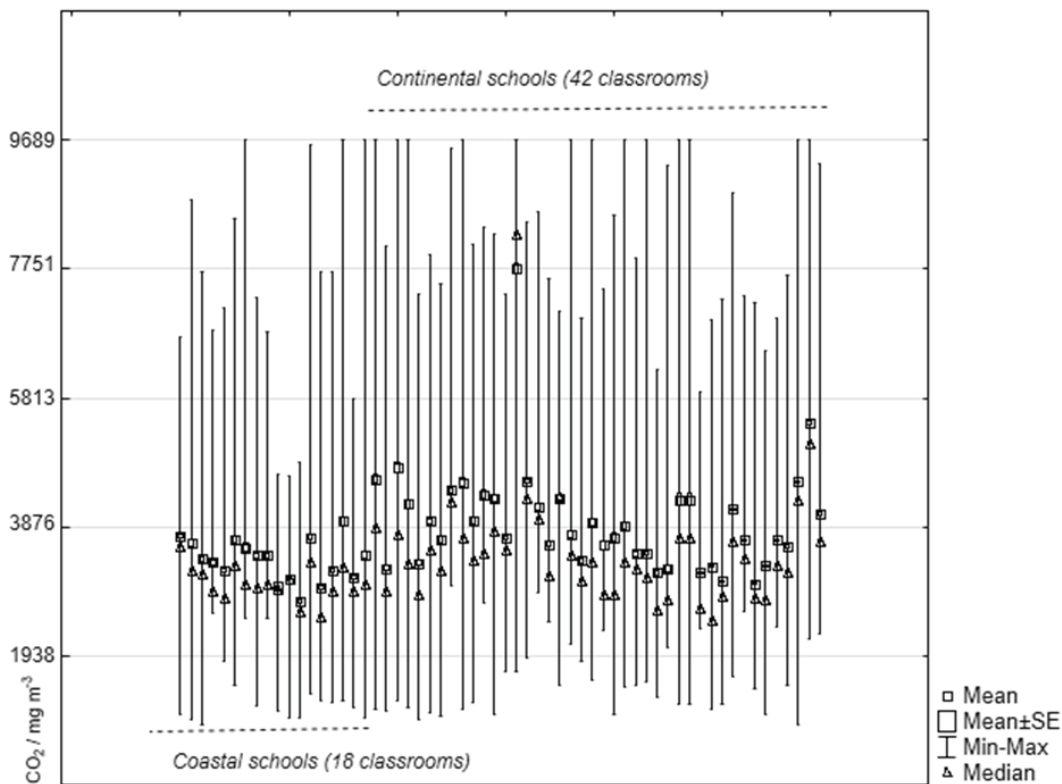


Figure 2 CO₂ concentrations in classrooms during one school week (Monday to Friday)

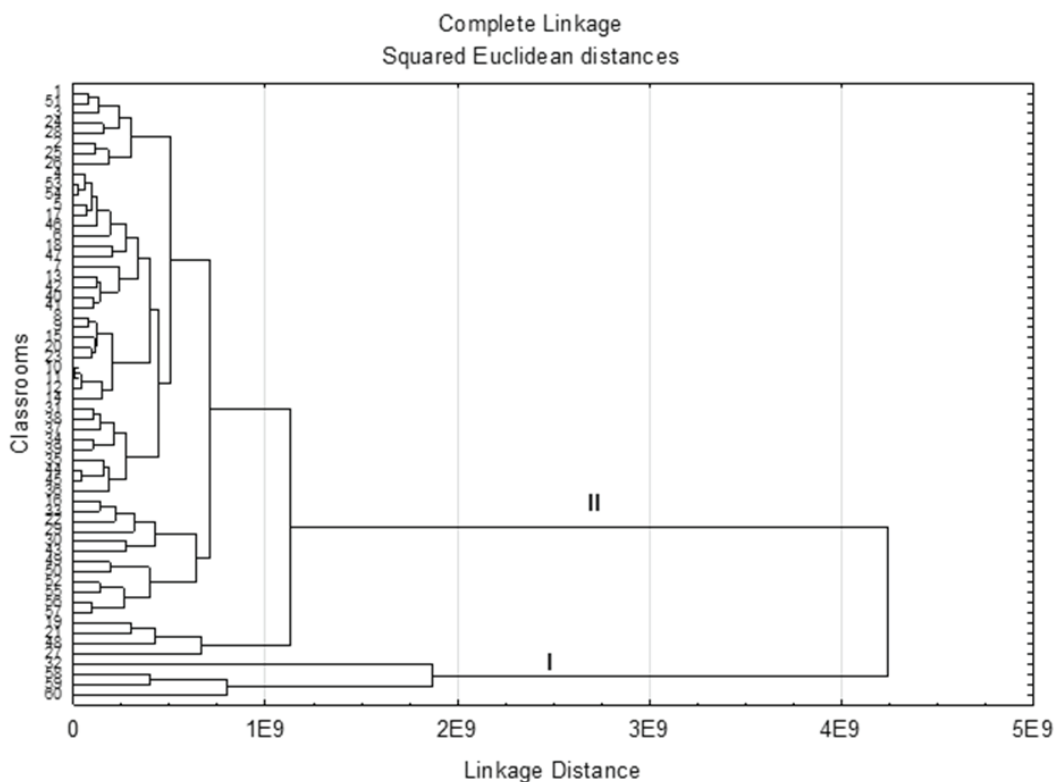


Figure 3 Cluster analysis dendrogram of all 60 classes included in the study. At higher distances two clusters can be observed: a three-member cluster (I) corresponding to classes in one urban school located in the eastern part of Croatia (Osijek) and a complex mixed (rural/urban) cluster (II) which at lower distances split into clusters showing the remaining schools

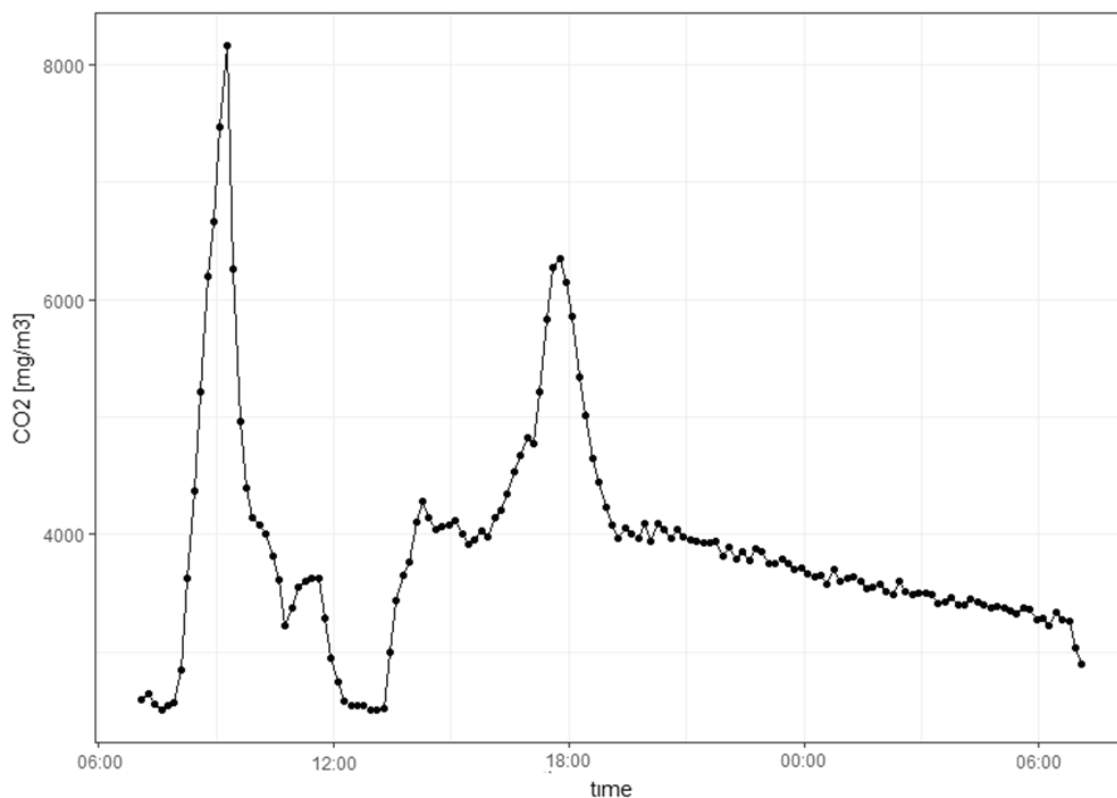


Figure 4 An example of 24-hour fluctuations of CO₂ in a classroom

poor air ventilation. During the night, CO₂ concentrations in vacant computer classrooms were very high and stable.

In our study, CO₂ concentrations in the classrooms were higher than those reported in Serbia (19) and Portugal (17), where mean values ranged from 2093 to 2484 mg/m³, but are consistent with another Serbian study (20) conducted in five rural and urban elementary schools during the heating season, with mean values going up to 3627 mg/m³. Similar to ours were also the results of a study conducted in Albanian schools during the cold season, which often exceeded 1938 mg/m³ at the beginning of the first morning class and ranged between 3225 and 9069 mg/m³ (18).

Three years after our study was conducted, the Sixth Ministerial Conference on Environment and Health convened in Ostrava, Czech Republic, in 2017 to review developments since the 2010 Parma conference (29). The resulting Ostrava Declaration on Environment and Health set improving indoor and outdoor air quality as one of major priorities (30) and has been used as a platform for the implementation of environmental and health goals and targets of the 2030 Agenda for Sustainable Development (31, 32).

CONCLUSION

This observational study measured CO₂ concentrations in a real-life setting but did not measure the direct effects of increased CO₂ on pupils. With CO₂ concentrations consistently above the recommended maximum of

1938 mg/m³ in all 20 schools, it clearly points to poor classroom ventilation, which remains an issue to be addressed by further multidisciplinary research and solutions that would improve indoor air conditions in schools to become more beneficial for students.

Acknowledgements

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Conflicts of interests

None to declare.

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Koncentracije ugljikova dioksida u učionicama hrvatskih osnovnih škola tijekom sezone grijanja

Izloženost zagušljivom zraku u zatvorenom prostoru s visokim razinama ugljikova dioksida (CO₂) povezano je s izostancima s nastave i lošijim uspjehom u školi. Regionalni ured Svjetske zdravstvene organizacije (WHO) za Europu razvio je provedbu istraživanja o kvaliteti zraka u zatvorenim prostorima u školama, uključujući praćenje CO₂ kako bi se procijenila ventilacija i izloženost zagušljivom zraku. Ovo je bilo prvo istraživanje o kvaliteti zraka u zatvorenim prostorima u hrvatskim osnovnim školama uz praćenje CO₂ kao pokazatelja kvalitete zraka i ventilacije. Istraživanje je provedeno u 60 učionica u 20 urbanih i ruralnih osnovnih škola diljem zemlje tijekom sezone grijanja. Razine CO₂ mjerene su s intervalom od jedne minute tijekom jednoga školskoga tjedna u svakoj učionici. Međunarodne smjernice od 1938 mg/m³ premašene su u svih 60 učionica. Srednje koncentracije CO₂ tijekom nastave bile su u rasponu od 2771 do 7763 mg/m³. Najveća srednja koncentracija u urbanim školama iznosila je oko 7763 mg/m³, a najveća srednja koncentracija CO₂ u ruralnim školama oko 4771 mg/m³. Prosječne razine CO₂ bile su veće u školama u kontinentalnim područjima (3683 mg/m³) u usporedbi s obalnim područjima (3134 mg/m³). Rezultati upozoravaju na slabu ventilaciju u učionicama tijekom hladne sezone kao široko rasprostranjen problem u Hrvatskoj.

KLJUČNE RIJEČI: Hrvatska; kvaliteta zraka u zatvorenom prostoru; učionice; ventilacija