CEST 2017

15th International Conference on Environmental Science and Technology

Rhodes, Greece, 31 August to 2 September 2017

Indoor air quality and thermal comfort in a typical Mediterranean primary school with a green roof system

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Abstract

This paper presents experimental results from a typical school building in Athens equipped with a green roof system (GRS). The GRS covers 1/3 of the school's total area, while the rest is used for reference purposes. Environmental monitoring took place in six classrooms located under the concrete reference roof and the green roof sectors as well as in the immediate external environment during warm and cold periods of the year. Measurements of CO_2, VOCs, PM1, PM2.5, PM10, ambient temperature (T) and relative humidity (RH) were performed. Preliminary results highlight that during summer, the green roof reduces T in a classroom on the top floor by about 2.8 ^{0}C while RH is increased by 5.9 %, in comparison with respective classrooms under concrete roof. Amid winter, a reverse behavior occurs. Concentrations of PM1, PM2.5, PM10, CO_2 and VOCs levels were found to be elevated during class hours with average values of 0.85 μg m^{-3}, 3.11 μg m^{-3}, 22.68 μg m^{-3}, 589 ppm and 7.69 ppm respectively. The examination of the indoor/outdoor ratio of air pollutants, demonstrated that the outdoor meteorology affects only PM1 and PM2.5, as PM10 and VOCs are strongly affected by internal emitting sources and the activities of pupils.

Keywords: indoor air quality, thermal comfort, school building microenvironment, green roof, air pollutants

1. Introduction

Green roofs can mitigate building's thermal load, reduce local PM10 concentrations (Yang *et al.*, 2008) and improve the management of rainwater. A properly installed green roof system could have a lifespan of up to 20 years (Braeuner, 2006). It is a constructive innovation with many energy benefits which at the same time are accompanied by a considerable economic cost. Specifically, Kim *et al.*, 2012 and Hong *et al.*, 2012 highlight that economic aspect of maintenance, CO_2 emissions along with energy balance of the building should be considered for each case. Badiee *et al.*, 2015, report that white roofs have better results than conventional ones made of concrete but in cases of electric heating of the building, the green roof has the second best performance. In Mediterranean climates, green roofs cannot replace conventional insulation, but lead to remarkable improvement in proper cooling of the building, thermal comfort of the inhabitants and shading from sunlight (Perini *et al.*, 2013). Furthermore, the type of vegetation has a significant impact on the energy efficiency of a green roof and mainly on the emission of air pollutants. Best results are obtained, according to Ascione *et al.*, 2015, using vegetation with large leaf area index (LAI) and low stomatal resistance. The aim of this paper is to present the preliminary results of an experimental campaign that took place in a Greek primary school close to the center of Athens with an installed green roof system during summer of 2016 and winter of 2017. Measurements continue, up to summer of 2017.It should be noted that only a part of the total roof surface is covered by vegetation and the rest of it consists of cement which facilitates the direct comparison of results between the two types of roofs (reference area). Concentrations of the main air pollutants, as well as temperature and relative humidity were monitored within classrooms and on the roof. The effect of the green roof on the top floor classroom, which is located underneath the GRS is obvious in terms of indoor air quality and thermal comfort, compared to the classroom under the reference roof area. The seasonality is an additional parameter which strongly affects the results.

2. Methodology

This experimental campaign takes place in the 2nd Primary School of Nea Smyrni, which is located in the southern suburbs of the Attica basin, close to the coastline of the Saronikos Gulf. The total area of the Nea Smyrni municipality is 3487 km^2 and its population is 73076. It is a densely built area with busy streets. The sources of pollution are well distributed around the Nea Smyrni area combining traffic mainly from the central part of Athens (North) and port activities form the Southwest (port of Piraeus). There is no presence of factories or heavy industry within the area. The school is a two storey building, nearby a busy street with coordinates of 37 ° 56'19.8"N and 23 ° 42'57.8" E. The experimental campaign extended from June 2016 until today. The instrumentation consists of portable continuous recording equipment including T and RH sensors (Tinytag Plus2 thermohygrometers), mass particulate matter (PM10, PM2.5 and PM1) (Turnkey Osiris and Lighthouse Handheld 3016 continuous monitors) and concentrations of CO_2 and VOCs (IAQ Tongdy sensors). All parameters are measured on a 24hour basis at intervals of 15 minutes. Quality assurance of the equipment used was performed in several occasions during the experimental campaign. The measurements were obtained from 6 classrooms, 3 at each floor and under the two different types of roofs enabling a direct comparison beneath the green and the reference cement roof. All classrooms are naturally ventilated by window openings.

3. Results

3.1. Thermal comfort

The purpose of the campaign performed during the summer of 2016 while the school was not in operation, was to examine the temperature and relative humidity regimes of the classrooms. The results show that the type of roof strongly affects the internal conditions of the classrooms investigated. Table 1 demonstrates temperature, relative and absolute humidity for two classrooms of the 1st floor with the same orientation, which are adjacent to the roofs. It is important to note that the conversion of relative to absolute humidity was calculated according to the equation reported by Hall *et al*., 2016:

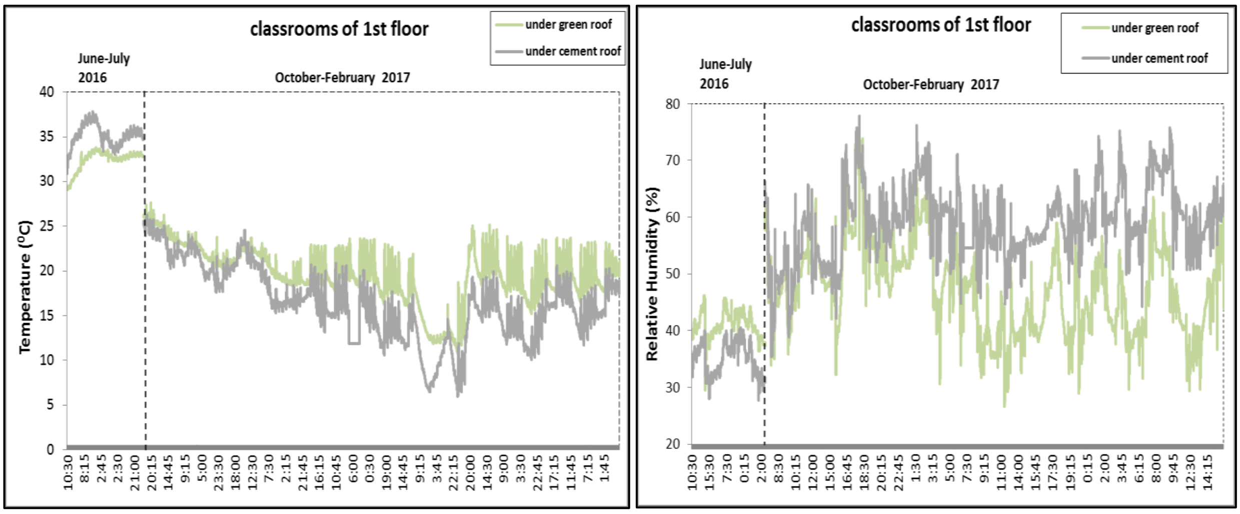
$$AH = \frac{6.112 \times e^{\frac{17.67\times T}{T+243.5}} \times RH \times 2.1674}{273.15 + T}$$

Where, T is the temperature in °C and RH is relative humidity in %. AH values are measured in g_{H2O} m^{-3}.

In summer, the average temperature of the classroom under the green roof is 32.4 ^{0}C while the respective beneath the concrete roof was found to be 35.2 ^{0}C. Thus, the green roof leads to a decrease of air temperature by about 2.8 ^{0}C. On the other hand, the relative humidity was increased by about 5.8%. This is possible related to the activation of the automatic watering system of green roof at regular periods. An important observation is that the absolute humidity has no significant fluctuations for both classrooms (14.2 and 14.0 g_{H2O} m^{-3}). Relative humidity strongly depends on temperature and absolute pressure of a system of interest. During the winter a reverse behavior occurs. The average internal temperature ranges from 19.7 ^{0}C under the green roof to 16.4 ^{0}C under the cement roof, while the average relative humidity ranges from 47.4% under the green roof to 59.2% under the cement roof. The automatic watering system of green roof operates less often amid winter than during summer. The school is centrally heated by a conventional oil combustion system. It is concluded that, during a cold season the green roof system creates a warmer and drier (in terms of RH) microenvironment. This observation is important, as thermal comfort in schools is currently evaluated in accordance to Fanger's model (ASHRAE Standard 55/2004, EN15251 / 2007, ISO Standard 7730, CIBSE Guide A) and the recommended temperature range lies between 20±1 ^{0}C and 24.5±2.6 ^{0}C depending on the season (Chatzidiakou *et al*., 2012). The absolute humidity does not differ for the two classrooms. The results of all measurements are summarized in Figure 1 (a) and (b).

3.2. Air quality

Concentrations of suspended particles were relatively low for all 6 classrooms of the school. The position of each classroom (ground floor or first floor, beneath green or concrete roof system) did not seem to affect the levels of particulate matter. Indicatively, the average concentrations of PM1, PM2.5 and PM10 were 0.85, 3.11 and 22.68 mg m^{-3} for the classrooms under the green roof, slightly higher than those of the respective classrooms under the reference cement roof (0.81, 1.80 and 19.03 g m^{-3}). The recorded differences between groups of measurements were tested for significance using the MannWhitney-U test. All p-values found to be <0.05 allowing to reject the null hypothesis that there is no significant difference between the ranks of two grouping variables. Furthermore, seasonality and meteorology play an important role to particle distribution. Mean in/out ratio (I/O) of PM10 during class hours (January-February), was found to be 1.97 and 2.89, respectively. On the contrary, amid summer while the school was not in operation, PM10 I/O ratio measured 0.60 in June and 0.46 in July.



(a) (b)

Figure 1. Time series of (a) T and (b) RH for classrooms under green and cement roof during two different periods.

Table 1. Results of T, RH and AH for classrooms under green and cement roof during two different periods.

		Classrooms of 1st floor					
		June-July 2016			October-February 2017		
		T (^{0}C)	RH (%)	AH (g_{H2O} m^{-3})	T (^{0}C)	RH (%)	AH (g_{H2O} m^{-3})
under green roof	average	**32.43**	**41.02**	**14.21**	**19.70**	**47.42**	**8.22**
	st.deviation	1.09	2.38	1.09	3.10	7.88	2.19
	minimum	29.09	29.45	10.64	10.81	26.60	3.72
	maximum	33.78	46.13	16.36	27.66	74.06	15.84
under cement roof	average	**35.20**	**35.14**	**14.04**	**16.40**	**59.17**	**8.45**
	st.deviation	1.21	2.94	.96	4.15	6.38	2.13
	minimum	30.90	27.71	10.67	5.97	35.40	3.84
	maximum	37.82	40.50	15.96	26.23	77.89	16.58

Thus, it is concluded that indoor PM10 concentrations are higher than those of the outdoor ones measured simultaneously. Activities of pupils, causing resuspension of these large particles are mainly responsible for the higher PM exposure in classrooms. The above statements are in agreement with previous published researches by Alves *et al.*, 2014 and Fromme *et al*, 2008. For the same period, I/O ratio of PM2.5 and PM1 is <1 which demonstrates the significant influence of external sources. Based on school location and wind direction these sources are the traffic from the city's Center (NNW) and emissions from the ships in the nearby port (SW) (Figure 2). It is noted that CO_2 concentrations in the indoor air is only an indicator for the air quality depending mainly on the number of persons in the room and ventilation (Myhrvold *et al.*,1996). According to Lee and Chang, 1999, the maximum occupancy in classroom environments recommended by ASHRAE Standard 62-1989 is 50 persons/100 m^2. Moreover, Shendell *et al.*, 2004 mention that a steady state indoor CO_2 concentration of 1000 ppm has been used as an informal dividing line between adequate and inadequate ventilation (ASHRAE, 2001). Within the classrooms of the experimental site, CO_2 levels range from 74ppm to 1997ppm. The values demonstrate strong variation for each classroom and as expected, tend to increase during class hours and to decrease at breaks and weekends. A remarkable observation is that on the first floor, the classroom under the green roof with 19 persons (70 m^2) and the respective one under cement roof with 27 persons (50 m^2), have about the same average CO_2 concentration, 768 and 763 ppm respectively. This is only an indication of the influence of the CO_2 released by the plants of the green roof on the indoor air quality, but further examination is required on the air exchange rate of each classroom. The first floor classroom beneath the concrete roof showed higher average concentrations of total VOCs (14.86 ppm) while the respective classroom under the green roof are lower by 50%. As far as the external measurements are concerned, VOCs in the green roof are slightly higher (9.50 ppm) than the respective measurements on the concrete roof (8.41ppm). Figure 3 (a) depicts the obtained results in the form of a violin plot in R language (Katavoutas, *et al.*, 2016) which presents advantages over the boxplot as an one dimensional scatterplot, thus enabling the user to assess the number of observations and estimating at the same time the explanatory power (Muthers and Matzarakis, 2010). The I/O ratio for all classrooms was found to be higher than 1 indicating that for VOCs, indoor concentrations exceeded outdoor levels and appeared to dominate personal exposures (Kinney *et al.*, 2002). Pegas *et al.*, 2010, state that the aromatic compounds benzene, toluene, ethylbenzene and the xylenes, followed by ethers, alcohols and terpenes, are usually the most abundant classes of VOCs. Terpenes are well known as substances emitted from cleaning products and room fresheners. Additionally, a-pinene is an intrinsic component of wood and furniture.

The first floor classroom under the green roof presents an I/O ratio of 0.8, and in combination with low concentrations, it seems that is strongly influenced by the VOCs released from the vegetation of the terrace. It is noted that plant foliage is an important source of natural VOCs emissions (Guenther., 1997). Figure 3 (b) demonstrates distributions and mean values of I/O ratio for VOCs of the classroom under cement roof and the respective beneath the green roof system.

4. Concluding Remarks

Preliminary results of an annual experimental campaign in a primary Greek school are presented in this paper. Part of the building has an installed green roof system and the rest of it consists of cement. We emphasize on the differences between classroom microenvironments in terms of thermal comfort and air quality depending on the roof type. Undoubtedly, the green roof has a positive thermal effect on the 1st floor classroom underneath compared to the respective classroom under the cement part. Internal temperature levels in the classroom underneath the GRS were lower during a warm period and higher in a cold one. The relative humidity in the same classroom was higher in the summer, by about 5-6% and slightly lower in the winter. Regarding air quality, differences between the two types of roofs do not seem to be significant. PM10 in both

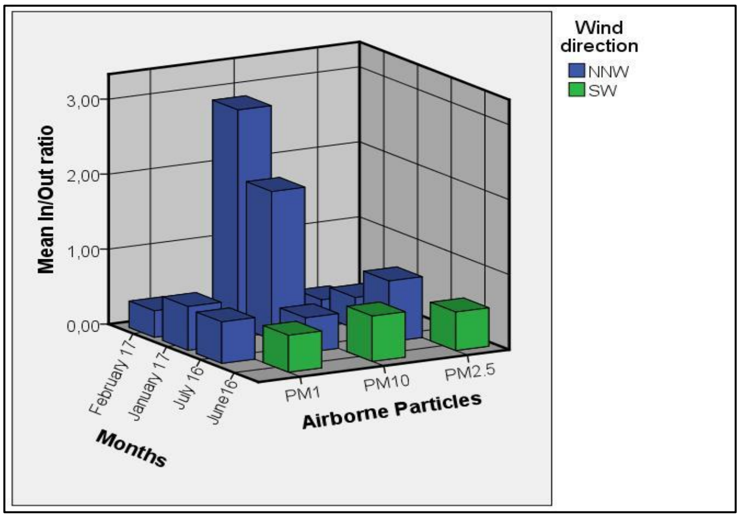
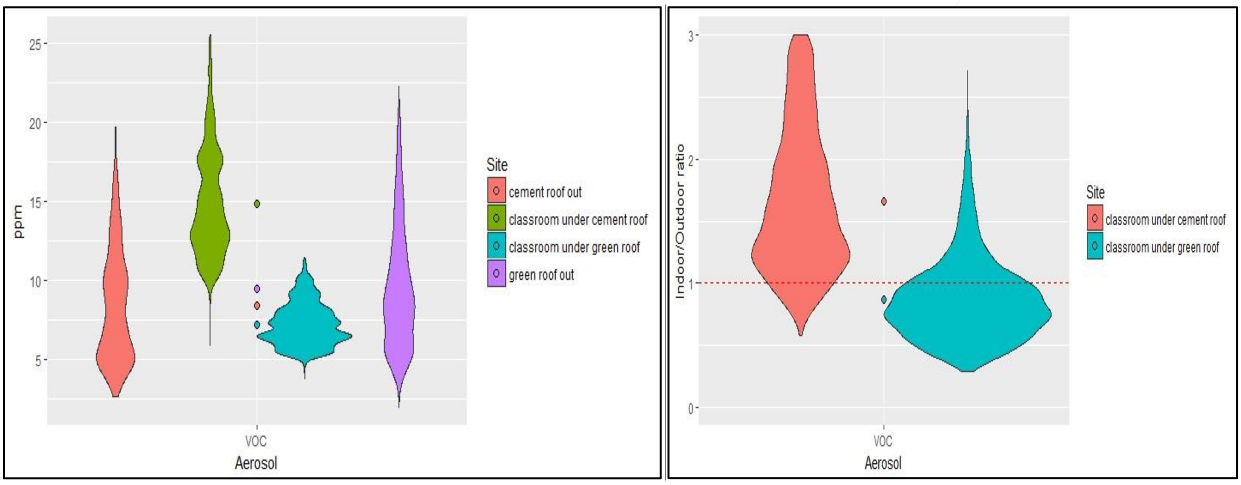


Figure 2. I/O ratio for all measured airborne particles during different months under the influence of wind direction.



(a) **(b)**

Figure 3. Indoor and outdoor VOCs distributions and mean values for (a) concentration and (b) I/O ratio at the main experimental sites of the school.

first floor classrooms have an I/O ratio > 1 demonstrating the internal emissions from anthropogenic activities. The I/O ratio of PM2.5 and PM1 is <1 which indicates that the indoor pollution mainly derives from external sources andis affected by seasonality and meteorology. On the other hand, there is an indication that the green roof slightly increases the CO_2 levels of the neighboring classrooms. This definitely requires further examination of the phenomenon with specific measurements. As for VOCs, they presented higher concentrations in the classroom under the cement roof with I/O ratio >1, indicating internal sources of emission. On the contrary, low VOCs concentrations in the classroom under the green roof seem to be affected by emissions from the plants (I/O <1). Overall, the green roof system in a school building within an urban area seems to have a positive influence on the students' thermal comfort while the air quality regime does not seem significantly affected.

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