Low-cost energy-efficient air quality monitoring system using sensor network

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Abstract: The air pollution has a significant impact on human's health and global environment. The air quality significantly decreased over the past few years. One of the methods for air pollution reduction is by installing green walls, green roofs or by implementing green buildings in urban areas as plants have capabilities to absorb the particulate matter through their leaves. The main goals of this paper are to present system for air quality monitoring using sensor network technology that can be easily deployed in polluted areas and to examine the influence of the experimental green wall setup to particulate matter more precisely PM10 and PM2.5 concentrations in Skopje, Republic of North Macedonia. Furthermore, the paper presents the preliminary results of the ongoing experiment developed to evaluate the impact of green walls in reduction of air polluting particles' concentrations. The air quality monitoring system can be easily replicated on other locations in the urban areas of Skopje.

Keywords: air quality monitoring system; green walls; sensor network; particulate matter.

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1 Introduction

Air pollution is one of the most dangerous environmental risks on human health. It can be result of harmful or excessive quantities of substances including gases, particulates and biological molecules. Air pollution may cause allergies, disease or even death on humans, also on other living organisms such as animals. Health problems such as asthma, cardiovascular disease and chronic obstructive pulmonary disease are result of excessive air pollution (Shah and Balkhair, 2011).

Common air pollutants include particulate matter (PM), sulphur dioxide (SO_2), ozone (O_3), nitrogen dioxide (NO_2) and carbon monoxide (CO). According to the Air Quality Guideline of the World Health Organization (WHO, 1999), in 2005, 89% of the world's population lived in areas with exceeded air pollution (Brauer et al., 2012). Particulate matter (PM10) is emitted from different heating sources and power plant, while fine particulate matter (PM2.5) are usually emitted from exhaust vehicles, burning wood and plastics (Shah and Balkhair, 2011).

Plants that are attached to a surface through various mechanisms making vegetated vertical surfaces are usually considered as green walls (Berardi, 2014; Bigazzi and Figliozzi, 2015). The plants filter the small particles (fine dust) from the air and nitrogen dioxide (NO_2). In the cities of the developing countries and industrialised nations these particles represent a very serious health problem. For air pollution improvement using various types of green infrastructure, the majority of studies have focused on pollutants such as the PM10 (Coma et al., 2017) and PM2.5 (Alberto et al., 2017) that have implications for the adverse health effects. Positive effect of the green walls consisted of hedera helix plant on air pollution mitigation is explored in (Ottelé et al., 2010). Rowe (2011) found that air pollution removal through green roofs applications is similar with mitigation effects of urban forest. They explored that 20% of adopted green roofs in Washington, D.C. can remove the same quantity of air pollution as 17,000 street trees, also they estimated that with conversion of 20% of all commercial roofs with green roofs the removal of NO2 per year is approximately 889 tonnes. In Manchester, England ground-level data on the impact of two green roofs were used to estimate the PM mitigation from 500,000 m^2 green roof strategy (Speak et al., 2012). They have concluded that 2.3% of PM concentrations can be removed per year. The study in Fahmy and Sharples (2011) examined that the annual energy consumption for interior heating and cooling can be reduced by using the green roofs. They are on average 15.5°C cooler than black roofs in summer (Currie and Bass, 2008).

The effect of green walls on adjacent air temperature compared to brick wall was analysed in Cameron et al. (2014). They explored that in the warmest period the air temperatures were 3°C cooler close to the vegetated walls, also the surface temperature was 9.9°C cooler behind the vegetated walls compared to the brick walls.

Cooling effects of small green urban areas on heat were also examined. Bowler et al. (2010) concluded that daytime air temperatures of green parks were approximately 1°C cooler than non-green urban areas. At the neighbourhood level, increased green space cover and high connectivity between neighbourhood-level green spaces are associated with cooler air temperatures and reduced urban heat island effects, particularly on hot days (Steeneveld et al., 2011).

The capital city of North Macedonia, Skopje also faces with the problem of the air pollution. The air quality in the city has dramatically decreased over the past few years. Few measurement stations located on different parts of the city have measured a high values of the PM concentrations especially in the winter period. This general air pollution problem was also analysed by a number of governmental agencies and non-governmental bodies, but so far, there is no definite list of responsible entities. The public pressure to provide appropriate solution is growing, so government and the city authorities are also investigating the possible sources of the pollution.

The goal of this paper is to present low-cost energy-efficient air quality monitoring system that uses sensor network technology (Pottie and Kaiser, 2008; Srbinovska et al., 2015). The system is developed to analyse the influence of the green wall on the air quality improvement. The paper presents results for evaluation of the impact of green walls for reduction of air polluting particles, more specifically the capability of the green wall to absorb PM10 and PM2.5 concentrations and other gaseous pollutants. In order to analyse the influence of the green wall structure, sensor nodes are located on different positions near the campus of the Faculty of Electrical Engineering and Information Technologies in Skopje, Republic of North Macedonia.

In Section 2 of the paper are described the development phases of the air quality monitoring system. Section 3 shows the maximum allowed values for various air pollutants according to the air quality index (AQI) values (Anon, n.d.).

In Section 4, the measurement results and the discussion of the monitoring data are given. At the end section, the conclusions are presented.

2 Development phases of the air quality monitoring system

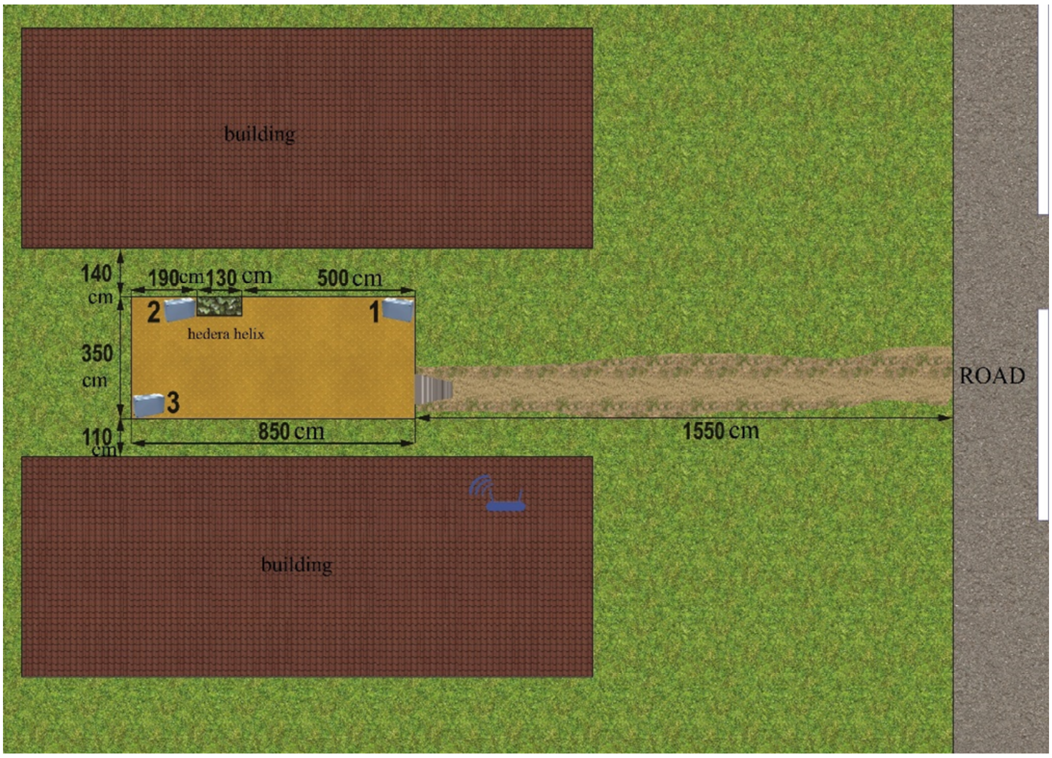
The first step in the implementation process was to select a proper location for installation of the monitoring system. It was chosen to be near the Faculty building where there is a small tree zone, consisted of deciduous trees and evergreens, on one side and one storey small buildings and a parking lot on the other side. The two buildings near the sensor network are used as classrooms, so there is a frequent movement of students. On the top of the platform where the nodes are located there is a system of photovoltaic (PV) cells that can be used as a renewable energies.

One of the sensor nodes was chosen to be near the small green area, the second one near the constructed green infrastructure and the third one near the parking as it is shown in Figure 1. The position of the nodes was selected to capture the effect of the green area, as well as to see the influence of the movement of people and vehicles.

The second step was to define the system architecture and hardware specification of the sensor nodes. Sensor nodes consist of four sensors measuring the following parameters: PM10, PM2.5 concentrations, NO_2 and CO. All sensors are integrated on single chip, including microcontroller and integrated Wi-Fi module for data transmission (De Vito et al., 2008).

SDS011 is the PM2.5 and PM10 sensing unit. The technology is based on laser diffraction theory, where particle density distribution is specified from the light intensity distribution patterns. The sensor contains a digital output and a built-in fan, which can measure the particle density distribution between 0.3 to 10 μm in the air. A built-in algorithm convert the particle density distribution into particle mass. The relative error is defined as maximum of ± 15% and ±10 μg/m^3.

Figure 1 Location of the sensor nodes near the faculty building (see online version for colours)



The main characteristics of the sensing elements are summarised in Table 1.

MiCS-4514 is a combined CO and NO_2 sensor. Some of the characteristics are low heater current, wide detection range, high sensitivity, two sensors in one SMD package with miniature dimensions. Detection of the polluted gases is achieved by measuring the sensing resistance of both sensors: RED (reduced) sensor in the presence of CO decreases the resistance and hydrocarbons, while OX (oxygen) sensor in the presence of NO_2 increases the resistance.

Table 1 Main characteristics of the SDS011 sensor

Measurement parameters	PM2.5, PM10
Range	0.0–999.9 $\mu g/m^3$
Power supply voltage	5 V
Maximum working current	220 mA
Sleep current	2 mA
Operating temperature	–20°C – 50°C
Relative error	Max of. ± 15% and ±10 $\mu g/m^3$
Minimum resolution of particle	< 0.3 µm

The controller unit is responsible for processing the acquired data before transmitting them to the network. ESP32-WROOM-32D is a powerful module that covers wide range of applications, from low – power sensor networks, to the most demanding tasks like voice encoding, music streaming. The main characteristics of the integrated sensors, microcontroller and the Wi-Fi module are explained in Velkovski et al. (2019). The Wi-Fi modules of the nodes send data to a router that is located in one of the buildings near the Faculty building. From that router, the collected data is uploaded on an open platform (Anon, 2020) and can be monitored online or downloaded for additional analyses.

The third phase was to construct and build the green wall structure. The green wall support construction is built of used materials (wooden boards and metal support structures from old furniture). Instead of using new plastic pots, old 6 L plastic water bottles are used. The green wall consists of hedera helix plant, because this type of plant is resistive on negative winter temperatures and different external conditions. The implemented construction is shown in Figure 2.

All the sensor nodes are protected in plastic boxes as it is shown in Figure 3. The whole design of the measurement system is made by the authors, so this solution is energy efficient and has a low price.

This system for air pollution monitoring can be easily replicated on other micro-locations on different parts of the city and compared with other monitoring stations that the government bodies have already installed (Jovanovski, 2020). Measurement stations covering different parts of the city can show that there is a significant variations in the presented measured values of PM concentrations that may differ for more than 20 to 50 $\mu g/m^3$ from one location to another, depending on the position of the sensor nodes at that parts of the city.

Figure 2 The green wall structure (see online version for colours)

Figure 3 Position of the sensor node near the hedera helix plant (see online version for colours)

3 Analysis of measurement data

Table 2 shows the maximum allowed values for various air pollutants (Anon, n.d.). The allowed values are on daily basis except for the parameter ozone (O_3), defined with average values for 8 h exposure. These values are used as comparison reference for the measurements at the experimental setup. The table also provides a reference for the AQI, which may be calculated using the methodology described in Heal et al. (2012).

Table 2 Overview of the maximum allowed values of gases and particulate matter

AQI category	*PM10 (μg/m³) (24 h)*	*PM2.5 (μg/m³) (24 h)*	*NO_2 (μg/m³) (24 h)*	*O_3 (μg/m³) (8 h)*	*SO_2 (μg/m³) (24 h)*
Good (0–50)	0–50	0–30	0–40	0–50	0–40
Satisfactory (51–100)	51–100	31–60	41–8	51–100	41–80
Moderately polluted (101–200)	101–250	61–90	81–180	101–168	81–380
Poor (201–300)	251–350	91–120	181–280	169–208	381–800
Very poor (301–400)	351–430	121–250	281–400	209–748	801–1,600
Severe (401–500)	430+	250+	400+	748+	1,600+

Source: Anon (n.d.)

Figure 4 PM2.5 concentration for 24-hour period from 13.01.2019 00:00–14.01.2019 00:00 (see online version for colours)

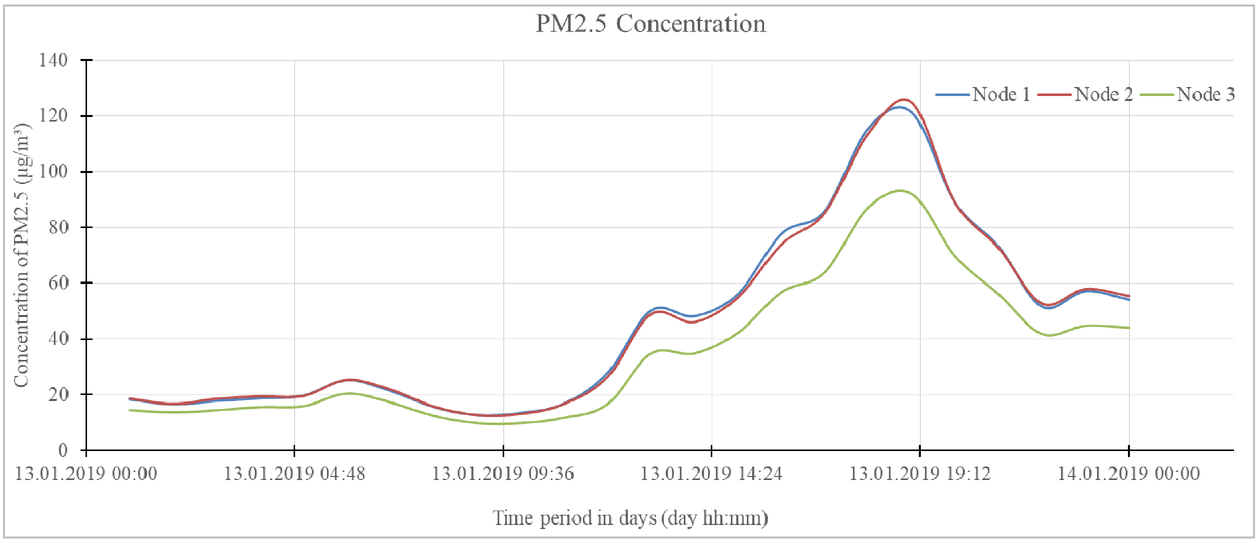
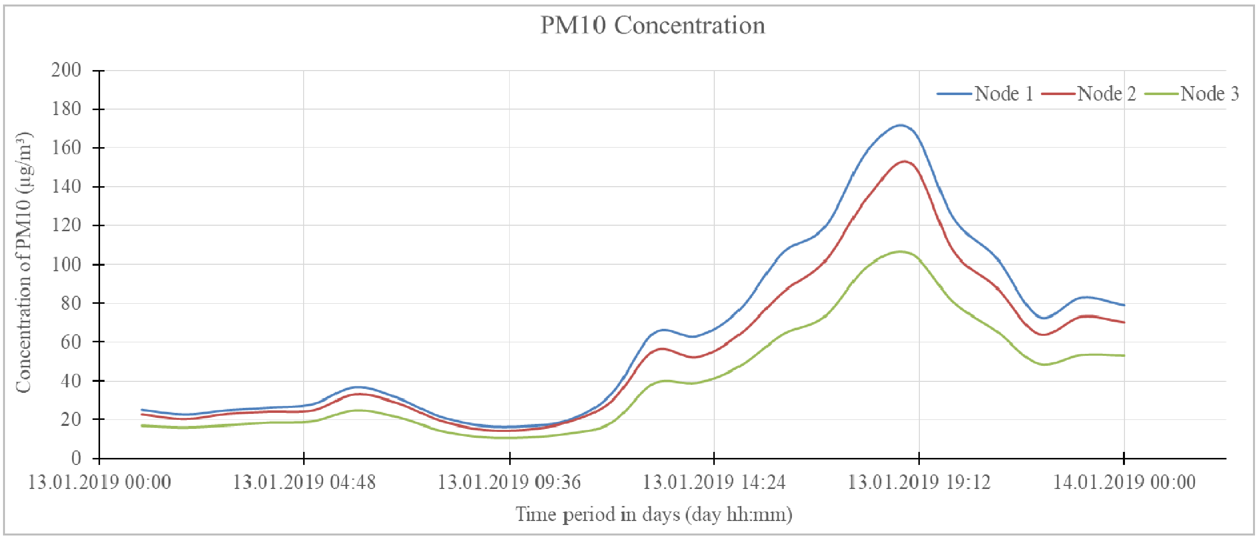


Figure 5 PM10 concentration for 24-hour period from 13.01.2019 00:00–14.01.2019 00:00 (see online version for colours)



As shown in Table 2, AQI values are divided into ranges, and each range is assigned with an adequate descriptor: good (minimal impact), satisfactory (may cause minor breathing discomfort to sensitive people), moderately polluted (may cause breathing discomfort to people with lung disease such as asthma, and discomfort to people with heart disease, children and older adults), poor (may cause breathing discomfort to people on prolonged exposure, and discomfort to people with heart disease), very poor (may cause respiratory illness to the people on prolonged exposure) and severe (may cause respiratory impact even on healthy people, and serious health impacts on people with lung/heart disease).

Figure 6 PM2.5 concentration for 24-hour period from 16.01.2019 00:00–17.01.2019 00:00 (see online version for colours)

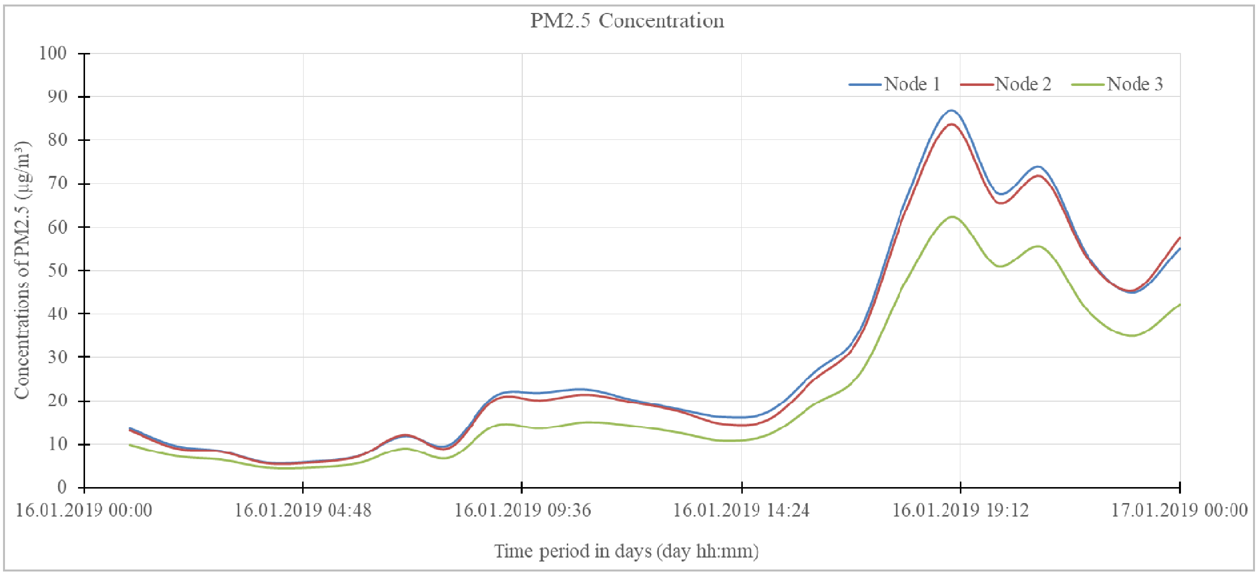
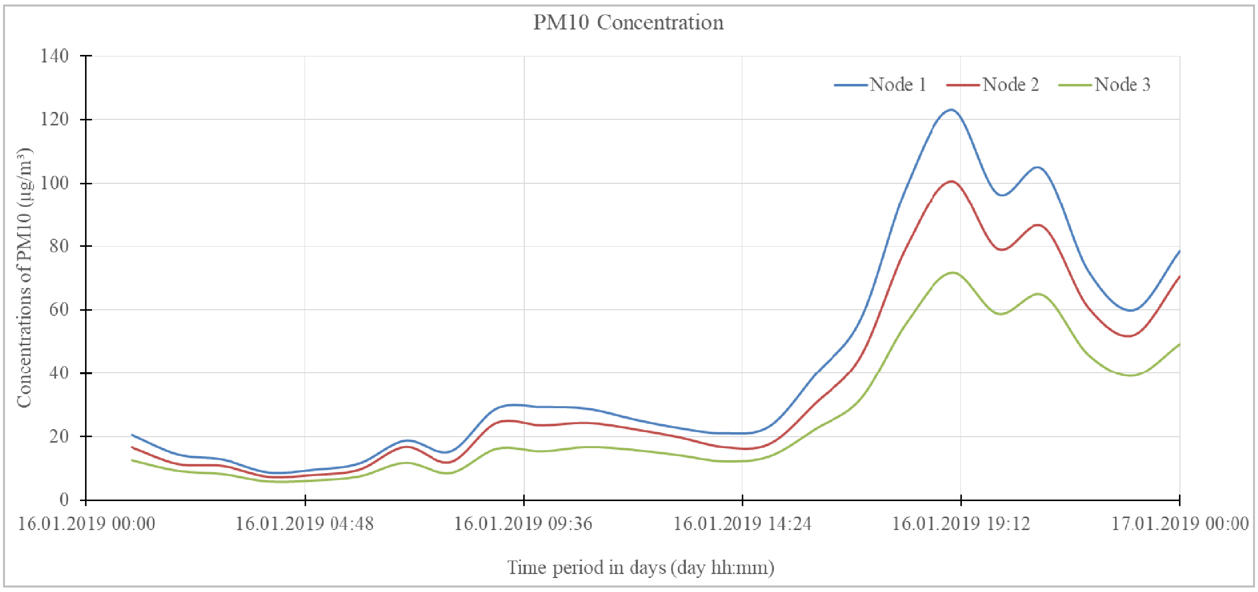


Figure 7 PM10 concentration for 24-hour period from 16.01.2019 00:00–17.01.2019 00:00 (see online version for colours)



These reference values can be used to compare the maximum allowed measured values of particulate matter with concentration of 10 micrograms or 2.5 micrograms. In Table 2 the presented data shows that the daily permitted values for PM10 concentrations is 50 micrograms per cubic meter, while the daily allowed values for PM2.5 concentration is 30 micrograms per cubic meter.

The values higher than this limit can be unhealthy for human's health.

4 Results and discussion

The implemented monitoring system started to log measurement data from May 2018. The quality of air in that period of the year is not as bad as during the winter months (Srbinovska et al., 2017). After the first equipment tests, the setup was used to provide continuous measurements of all four parameters. However, this paper presents the measurements of PM2.5 and PM10, as these parameters were critical for the air quality in Skopje, which is already described in Srbinovska et al. (2017). The experimental setup is designed in a manner that allows measurements to be taken near the green wall (sensor node 2) and in relatively short distance from the node 1 as it can be seen from Figure 1. The green area zone is closest to the node 3. The disposition of the sensor nodes allows to see the influence of the green area close to sensor node 3 and the benefit of the green wall near to sensor 2 on the quality of air on the micro-location where the experimental setup is positioned.

Figure 4 and Figure 5 present the measured data for PM2.5 and PM10 concentrations on a typical winter day. The obtained data shows average concentrations of PM2.5

and PM10 per hour respectively, but the measurements are taken with rate of one measurement per minute.

The PM2.5 concentration is higher than 30 µg/m3, being the relative concentration allowed in the air. It is clearly visible that the concentrations increase during the day, when there is more movement and are usually lower during the late night and early morning hours.

The highest peak for PM2.5 concentration on 13th of January 2019 is 121 µg/m^3 and it was measured around 7 PM. This value is above the allowed limit and is probably result of the household heating based on wood stoves or similar highly inefficient equipment.

Similar conclusions can be drawn from the graph presented in Figure 5. Namely, the concentrations of PM10 are higher than 50 µg/m^3, being the relative concentration allowed in the air. The highest peak for PM10 concentration on 13th of January 2019 is 170 µg/m^3 and it was measured also around 7 PM. These two values for PM2.5 and PM10 concentrations are measured at the sensor node 1, positioned near the road and frequent movement of people and vehicles. The analyses of the data indicate that the measurements at the sensor nodes 2 and 3 show relatively lower values than the sensor node 1, which is actually the one that is located furthest from the green area.

According to the maximum allowed parameters presented in Table 2 for PM2.5 and PM10 concentrations the measured data show moderately polluted values for people with discomfort breathing and lung disease such as asthma.

Figures 6 and 7 present average PM2.5 and PM10 concentrations also on a typical winter day. The presented measured data are chosen to be on 16th January 2019 showing also the highest values in the afternoon. The highest peak for PM2.5 concentration on 16th of January 2019 is 87 µg/m^3, while the highest peak for PM10 concentration on the same day is 123 µg/m^3 at 7 p.m. The cited values are for sensor node 1 which is further away from the green wall setup compared to nodes 2 and 3. The measurement data presented in Figures 6 and 7 also show that during the 16th of January the values of the PM2.5 and PM10 concentrations are above the allowed values for the PM2.5 and PM10 concentration.

Similar conclusions can be drawn as in Figures 4 and 5, the concentrations of PM2.5 and PM10 are increasing during the day and usually the peak of the concentrations are in the afternoon, when the household heating is turn on. Some local municipalities in Skopje does not have central heating, so one of the reasons for the bad air quality is the heating on wood stoves or highly inefficient equipment. From Figures 4, 5, 6 and 7, the concentrations of PM2.5 and PM10 are lowest early in the morning (00:00–08:00 AM) which is a result of low traffic, not frequent movement of people and other pollutants. Also in this period, the concentrations of PM2.5 and PM10 at sensor node 3 are constantly lower compared to the other two nodes.

Figures 4, 5, 6 and 7 show that there is a strong correlation between the PM2.5 concentrations and PM10 concentrations.

All the sensor nodes are placed on a platform near a PV installation. The sensor node 2 is placed near the PV cells. The node 2 is relatively close to the PV installation which may reduce the influence of meteorological factors in dust reduction to some extent.

The position of the nodes, the objects positioned near the nodes and the existence of the green area have an influence on the PM2.5 and PM10 concentrations, showing constantly lower values for the particulate matter at the sensor nodes located near the green areas compared to the node close to the pedestrian street and frequent movement of people and vehicles.

5 Conclusions

The main purpose of this paper is to present an experimental setup for air quality monitoring, to evaluate the measurement results and to analyse the influence of the green walls on air quality improvement on micro-locations.

Using only recycled materials and equipment in the design of the experimental setup makes this solution a low cost and easy to replicate on other locations. The acquired data can be used for online monitoring or off-line analyses.

Initial findings show that the highest values for the PM2.5 and PM10 concentrations usually occurred in the afternoon and are probably result of many factors, especially household heating. The measured values tend to be lower in the area nearer to the green zone and green wall structure. Although the presented measurement results are only for the winter months, the conclusion is similar also for the summer months, showing lower concentration of PM2.5 and PM10 nearer to the green area. The location of the green infrastructure in urban environments should be carefully planned in order to maximise its effect on air quality.

The project enables continuous monitoring of the PM2.5 and PM10 concentrations and gaseous pollutants. Using the IT technology and the sensor network shall provide a basis for analysis of the influence of the green wall in air quality improvement especially on PM concentration mitigation. Further considerations include analyses on how the weather conditions influence on the air pollution mitigation and defining a model that predicts the air pollution based on the weather data and the historical data about the pollution. The measured data for air pollution together with the weather information for temperature, humidity, wind speed, and wind direction could be combined to obtain the prediction model.

Further, the study will also reveal the economic benefits from the green walls through the provision of ecosystem services to society.

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