Low-Cost Energy-Efficient Air Quality Monitoring System Using Sensor Network

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Abstract – **The air quality in urban areas is a major concern in modern cities due to significant impacts of air pollution on human health and global environment. Implementation of green walls is one of the methods for decreasing air pollution in urban areas as plants absorb the particulate matter through their leaves and growing medium. The objective of the paper is two-fold: 1) to present an implementation of a low-cost and energy-efficient air quality monitoring system using sensor network that can be easily deployed in highly polluted areas; and 2) to examine the influence of experimental green wall setup to particulate matter concentrations in the air in an urban area in Skopje. 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.**

Keywords – **Sensor network, Air quality improvement, vertical green walls.**

I. Introduction

The air quality in many countries has been adversely affected over the past years due to continuous economic and industrial development. The increasing level of air pollution from vehicles exhausts, chemical discharge from industries, dust and particulate matter from various sources and toxic gas leakage are affecting the citizens' health and ecosystems. With the aim to respond to the existing environmental issues, new methods for improving air quality in both indoor and outdoor environments are being developed. According to the World Health Organization (WHO), more than one million people worldwide die from the consequences of polluted air every year [1]. United States Environmental Protection Agency [2] defines the air quality by measuring specific gases that have the most significant effect on human health, including: ground – level ozone (O_3), carbon monoxide (CO), nitrogen oxide (NO), particulate matter (PM10). Other pollutants also include carbon dioxide (CO_2), various nitrogen and sulfur oxides, hydrogen sulfide (H_2S), volatile organic compounds, smog and other particulate matters. The measurement of these gases is related to the specifics of each gas as well as of the equipment that is used.

The problem of air quality is increasing around the world. The growing economies of Asia have had this problem during the past decade [3, 4, 5, 6] and some European countries have been tackling this problem as well [7].The air quality in Skopje has decreased significantly over the past years. Data from several measurement stations throughout the city have shown high levels of particulate matter [8], especially during the winter months. These levels a few times higher than normally acceptable and are cause of serious concerns of citizens and authorities. A few governmental agencies and non-governmental bodies examine the reasons, but so far, there is no definite list of responsible entities. The general reasons lay into fast urbanization that "attacks" every free inch of space. Furthermore, the city has been developing for use of cars rather than other means of transportation, although it has a good disposition for using bikes. Other problems are the unauthorized landfills, use of various fossil fuels for heating. Although steps are being taken to solve this problem, public pressure to provide solutions is growing. Therefore, the existing problem of air pollution and the possible ways to solve it is the main motive to start our work on the air quality measurement project.

Green walls are vegetated vertical surfaces where plants are attached to the surface through various mechanisms. Green walls allow for high density and high diversity vegetation on vertical areas [9]. The plants filter nitrogen dioxide (NO_2) and microscopically small particles (fine dust) from the air. Both represent a very serious health problem in the cities of both industrialized nations and developing countries. For air pollution improvement using various types of green infrastructure, the majority of studies have focused on pollutants such as the PM10[10], PM2.5[11] that have implications for the adverse health effects.

II. Literature review

Research shows significant influence of green walls on various environmental problems. Authors in [12] investigate the potential of green walls and facades for saving energy. Furthermore, the research presented in [13] describes the potential for energy savings in buildings using green walls and double-skin green facades. Classification and technical aspects of the green roofs are explained in [14]. The study showed that green roofs could reduce annual energy consumption for interior heating and cooling. Among the reasons for this is that they are on average 15,5 °C cooler than black roofs in summer [15]. Buildings in northern climates, with high temperature extremes and shorter growing seasons, distinctly show the energy advantages of green roofs.

The aim of this paper is to present a low - cost energy-efficient system for air quality monitoring in order to analyze the influence of the green wall on air quality improvement. The

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paper presents results for evaluation of the impact of green walls for reduction of air polluting particles, more specifically the influence of the air flow through the green wall and the capability of the green wall to absorb particulate matter. Therefore, the investigated system uses sensor network for measurement of particulate matters (PM10, PM2.5), CO and NO_2.

III. Development phases

The first phase in the implementation process was to select a proper location for installation of the system. The experimental location is near the building of FEEIT and a parking lot with frequent movement of people and vehicles. Before the installation of the sensor nodes, continuous measurements for air quality monitoring were done using reference measurement instrument. The second step was definition of system architecture and hardware specification. The process was followed by equipment procurement. The third step was related to the green surface construction and installation of the WSN. The aim was to construct the green wall and to install the sensor nodes for measurement that will provide information for the important parameters related to air quality (PM2.5, PM10, CO, NO_2).

A. Hardware setup

The sensor modules deployed in the experimental setup consist of two major hardware components – sensors and controller. The sensor nodes are the primary data collecting elements in the network. They consist of four sensors measuring the following parameters: PM2.5, PM10, CO and NO_2, which feed data to the Wi-Fi module for transmission.

Table I
Main characteristics of the SDS011 sensor

Measurement parameters	PM2.5, PM10
Range	0.0-999.9 µg/m3
Power supply voltage	5V
Maximum working current	220 mA
Sleep current	2 mA
Operating temperature	-20 °C-50 °C
Minimum resolution of particle	<0,3µm

SDS011 [16] is the PM2.5 and PM10 sensing unit. It uses the principle of laser scattering and can get the particle concentration between 0.3 to 10µm in the air. This sensor with the digital output and built-in fan is stable and reliable. Some of the characteristics of this sensor are: accurate and reliable, it has quick response with response time less than 10 seconds when the scene changes, easy integration with universal asynchronous receiver-transmitter (UART) output, and high resolution of 0.3µg/m^3. The main characteristics of the sensing elements are summarized in Table I. MiCS-4514 [17] is combined CO and NO_2 sensor. Detection of the polluted gases is achieved by measuring the sensing resistance of both sensors: RED (reduced) sensor resistance decreases in the presence of CO and hydrocarbons, OX (oxygen) sensor resistance increases in the presence of NO_2.

The main characteristics of the sensing elements are summarized in Table II.

Table II
Main characteristics of the MiCS-4514 sensor

Measurement parameters	CO, NO_2
Maximum heater power dissipation	88 mW (RED sensor) /50 mW (OX sensor)
Voltage supply	4.9 V - 5.1 V
Relative humidity range	5 % - 95 %
Ambient operating temperature	-30 °C - 85 °C
CO detection range	1 ppm - 1000 ppm
Sensing resistance in air	100 kΩ - 1500 kΩ
NO2 detection range	0.05 ppm - 5 ppm
Sensing resistance in air	0.8 kΩ - 20 kΩ

ESP32-WROOM-32D [18] 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. At the core of the module is the ESP32-D0WD chip.

The controller has integrated on-board antenna and Wi-Fi module, that allows large physical range and direct connection to the internet through Wi-Fi router. The current of the ESP32 chip in sleep mode is less than 5 µA, which makes this module suitable for battery powered and wearable electronics applications. The main characteristics of the controller are presented in Table III.

Table III
Main characteristics of the EPS controller

Controller	EP32
Power supply	2.7 V - 3.6 V
Operating temperature range	-40 °C - 85 °C
Operating current	80 mA
On-chip sensor	Hall sensor
On-board clock	40MHz crystal
Module interface	SD Card, UART, SPI, I2C, Motor PWM
Wi-Fi frequency range	2.4 GHz - 2.5GHz

B. Experimental setup

For the experimental setup we used old materials for the hedera helix construction in order to build a simple, cheap and easy to replicate system and to contribute to waste reduction. 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 implemented construction is shown on Figure 1. Wires that connect the wooden boards are used to support the growing hedera helix plants. It is chosen to be near the Faculty building, which faces a Faculty parking lot, between two smaller classroom buildings. Students and staff frequent this location quite often.

The sensor network consists of 4 sensor nodes. As shown in Fig. 2, all sensor nodes are cased in plastic boxes. One of the sensor nodes is placed near the green wall construction, while the other three are placed near the parking zone and the classroom buildings. The fourth sensor is positioned to face the parking side, where a lot of cars and vehicles commute on daily bases. The measurement data from all the sensor nodes are uploaded to an open platform [19] and are available for online

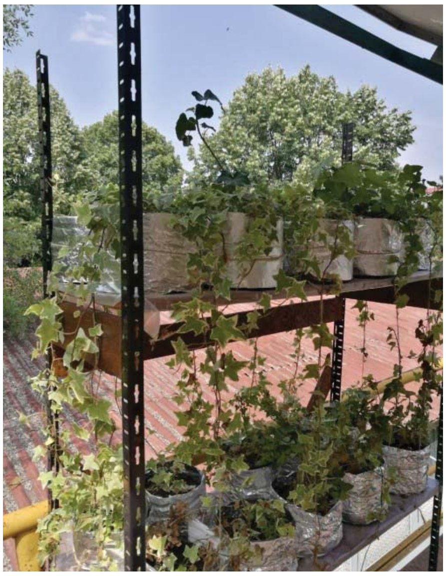

Fig. 1. Hedera helix green wall structure

Fig. 2. Sensor node box

monitoring and extraction for further analyses.

IV. Analysis of measurement data

Table IV shows the maximum allowed values for various air pollutants [20]. These values are used as comparison reference for the measurements at the experimental setup. The table also provides a reference for the Air Quality Index (AQI), which may be calculated using the methodology described in [7]. As shown in Table IV, AQI values are divided into ranges, and each range is assigned with an adequate descriptor.

The experimental setup is designed in a manner that allows measurements to be taken near the green wall (sensor node 2) and in relative distance of few meters from the setup (nodes 1, 3 and 4). Node 4 faces the parking lot and is the most distant node from the experimental green wall. The disposition of the sensor nodes allows assessment of the influence of the green wall on the quality of air on the micro-location where the experimental setup is positioned.

Table IV

Overview of the maximum allowed values of gases and particulate matter [20]

PM10 (µg/m³)	CO (µg/m³)	SO^2 (µg/m³)	NO_2 (µg/m³)	AQI	
0-50	0.0-10.0	0.0-350	0.0-200	0-50	Good
51-150	10.01-20.0	351-1500	201-400	51-100	Moderate
151-250	20.01-30.0	1501-2500	401-800	101-150	Unhealthy for sensitive group
251-350	30.01-45.0	2501-3500	801-1200	151-200	Unhealthy
341-450	45.01-70.0	3501-6500	1201-2400	201-300	Very unhealthy
420-500	70.1-100.0	6501-8500	2401-3200	301-400	Dangerous
501-600	100.01-120	8501-10000	3201-4000	401-500	Very Dangerous

V. Results

The new series of measurements started in May 2018. The air pollution in this period of the year is not as high as during the winter months. 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 [3].

The values shown on Fig. 3 and Fig. 4 represent average concentrations of PM2.5 and PM10 per hour respectively, but the measurements are taken with rate of one measurement per minute. The sensor nodes are numbered as described above, node 2 being the closest and node 4 being the furthest positioned node from the green wall. The PM2.5 concentration is well below 25 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.

Similar conclusions can be drawn from the graph presented on Fig. 4. Namely, the concentrations of PM10 are lower than the reference in Table IV and the distribution of values follows similar pattern.

The graphs depicted in Fig. 3 and Fig. 4, show a typical cases during the winter months in Skopje. The graphs depict measurements of PM2.5 and PM10 concentrations respectively and are taken in a period of 24 hours, starting at 00:00 on 10.11.2018 until 00:00 on 11.11.2018.

First and foremost, it can be seen that the particular matter concentration values from nodes 2 and 3 are constantly

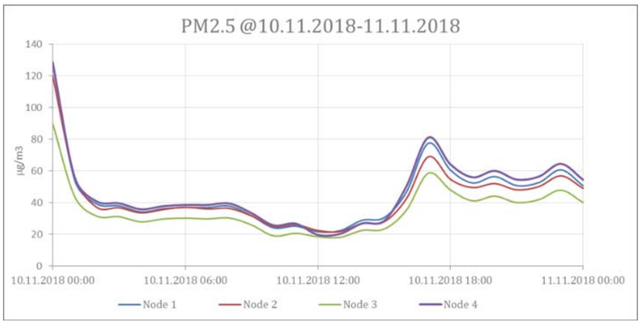

Fig. 3. PM2.5 concentration measurement for the 24-hour period from 10.11.2018 00:00 – 11.11.2018 00:00.

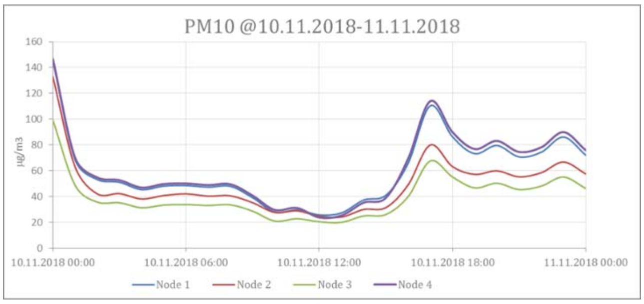

Fig. 4. PM10 concentration measurement for the 24-hour period from 10.11.2018 00:00 – 11.11.2018 00:00

relatively lower than those from node 1 and 4 which are furthest away from the green wall setup of the three nodes. This is observed in Fig. 3 and Fig. 4 and confirms the preliminary findings presented in [3] that the green wall contributes to lowering the levels of particulate matter in the surrounding air.

VI. Conclusion

The goal of this paper is to describe an experimental green wall setup and to present preliminary measurement results from an ongoing experiment designed with the aim to evaluate the influence of green walls on air quality on micro locations.

The presented experimental green wall setup is a low cost design, using over the counter and recycled materials and equipment. The collected data is available for online monitoring as well as off-line analyses.

The measurement results from a longer period of about 6 months indicate that particular matter concentrations tend to be constantly lower in the area nearer to the green wall structure.

The experimental green wall project enables continuous measurements of gaseous pollutants and PM concentrations. A continuous measurement campaign, using the WSN measurements, shall provide basis for analysis of the influence of the green wall in improving air quality, especially in terms of mitigating PM10 concentrations. Further considerations include analyses on how the size of the green wall structure impacts the scale of reduction of the particular matter concentration and the size of the area it affects positively.

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