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INFLUENCE OF VERTICAL GARDENS ON THE AIR QUALITY OF A CITY HISTORIC CENTER

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Quito is an Andean city with 2.7 million inhabitants that regularly exceeds the WHO air quality guidelines for O_3, SO_2, $PM_{2.5}$, and PM_{10}. Within the historic center in an area of 920.000 m^2, only 4% is green space. However, 14.000 m^2 of vertical walls exist that could potentially host vertical gardens. The present study evaluates the ability of four vertical gardens to improve air quality and quantifies the area of viable spaces to host vertical gardens in the Historic Center. The air quality was monitored with continuous measuring systems near each vertical garden and in areas outside the area of influence. The capacity for retention of gaseous emissions from an internal combustion engine in an active garden was also evaluated. The results were a mixture of advantages and uncovering possible myths: a) the presence of vertical gardens causes a significant decrease in O_3 (up to 99%), NO_2 (up to 80%), SO_2 (up to 83%), $PM_{2.5}$ (up to 79%) and PM_{10} (up to 85%); b) however, a poor choice of plant species in vertical gardens may increase the formation of O_3; and c) in the case of exposing an active vertical garden to emissions injected directly into the garden by a combustion engine, the particle size distribution influences its removal, being more efficient with a size greater than 4 μm but not effective for smaller diameters.

Keywords: Air pollution, Retention of gaseous emissions, Combustion engine, Quito.

1 INTRODUCTION

The World Health Organization (WHO) recognizes the importance of air quality for health (WHO 1990). Simoni *et al*. (2004) proved that there is an association between particles with a diameter of less than 2.5 µm ($PM_{2.5}$) and bronchitis and asthmatic symptoms, and an association between nitrogen dioxide (NO_2) with acute respiratory symptoms. Air pollution also contributes to a higher incidence of dementia and may accelerate Alzheimer-related issues (Cacciottolo *et al*. 2017). The WHO has identified that over 90% of the world population lives in cities where pollutant levels exceed the set limits and that 4.2 million yearly deaths are attributed to the exposure to the outside air (WHO 2018). In Quito, pollutant levels exceed the limits set forth by the WHO in regard to ozone (O_3), particles with a diameter of less than 2.5 µm ($PM_{2.5}$) and less than 10 µm (PM_{10}), as well as sulpher dioxide (SO_2). Prior studies have shown that green infrastructures may contribute to the decrease of air pollutants (Vailshery *et al*. 2013). The implementation of trees and green walls or roofs is an affordable pollutant-removal method (Rowe 2011, Abhijith *et al*. 2017). Furthermore, pollutants such as NO_2, PM_{10}, ozone (O_3), and

SO_2 are removed with higher efficacy than $PM_{2.5}$ (Yang *et al*. 2008, Jayasooriya *et al*. 2017). Literature shows for O_3, vertical gardens achieve a decrease between 2 and 40% (Sicard *et al*. 2018). Green walls may cause a decrease of up to 40% for NO_2 and 60% for PM_{10} (Baik *et al*. 2012, Pugh *et al*. 2012). In comparison, measures such as vehicular restrictions may decrease NO_2 and PM_{10} up to 9.4% and 30.5%, respectively (Santos *et al*. 2019).

2 METHODOLOGY

2.1 Atmospheric Pollutants Absorption from the Ambient Air

Air quality measurements were carried out for gases and particles (between July and September of 2018) in the areas surrounding four vertical gardens and in areas outside their zone of influence in the city of Quito, Ecuador. Figure 1 shows the four case studies (CS) analyzed.

Figure 1. Location of case studies and measurement locations in Quito.

The first case (CS1) was divided into two stages: CS1A, located in the School of Architecture, Design, and Arts of the Pontifical Catholic University of Ecuador (FADA-PUCE), comprised of an active outdoor vertical garden of 4.30 m^2 designed in the PUCE (Davis *et al*. 2016). The measurements were made between September 07 and 12, 2018. One measurement was carried out on the air exit point in contact with the garden (indoors), and another measurement was carried out in a central courtyard (outdoors). The CS1B was located within a FADA office used as a control point (indoors). The measurements were made between September 20 and 21, 2018. The second assessed passive vertical garden (CS2) was located within a private office (ENNE Architects) with an area size of 16.8 m^2. One set of measurements was carried out in the office (indoors), with another set of measurements in the terrace (outdoors). The measurements were made between July 09 and 16, 2018. The third assessed garden (CS3) is located within the Government Financial Platform, which has vertical gardens making up a total area of 497 m^2. One round of measurements was carried out in the garden hall (indoors) and another in the 5th floor balcony of the building (outdoors). The measurements were made between July 16 and 25, 2018. The fourth garden (CS4) located within the Pablo Palacio library was a passive indoor vertical garden of 46 m^2. The set of measurements were carried out inside the library (indoors), and the other in the surrounding street (outdoors). The measurements were made between July 25 and 30, 2018.

The ambient air quality was measured using AEROQUAL's AQM60 Environmental Monitor V5.0, where NO_2, O_3, and carbon dioxide (CO_2) were the analyzed parameters. The particle material was monitored using Metone's AEROCET 831 equipment, where $PM_{2.5}$ and PM_{10} particle material were measured. Gas concentrations (NO_2, O_3, and CO_2) were measured in parts per million (ppm), and particle concentrations ($PM_{2.5}$ and PM_{10}) were measured in $\mu g/m^3$ under local conditions. Data capture from gas monitoring was carried out every two minutes during at least 72 hours. CO_2 was measured with a non-dispersive infrared sensor, while NO_2 and O_3 were measured with gas-sensitive semiconductor (GSS) sensors. Data capture from particle monitoring was carried out every minute during at least 48 hours for $PM_{2.5}$ and PM_{10} with a particle counter. Hour averages were set from the analyzed parameters, and the variation percentages ($\%V$) were assessed between the measurements carried out in areas surrounding vertical gardens and in areas without their influence using Eq. (1).

$$\% V = \frac{V_j - V_e}{V_e} * 100 \tag{1}$$

where *Ve* is the value of the parameter analyzed in the environment without vertical garden influence, and *Vj* is the value of the parameter analyzed in areas surrounding vertical garden.

2.2 The Behavior of the CS1A Garden Against Gas Emissions from An External Source

The active CS1A vertical garden was exposed to gas emissions from a chainsaw (a gas-fueled internal combustion engine) in February 2019. Measurements were carried out using a Testo 350XL emissions analyzer. Temperature (Temp in °C), carbon monoxide (CO), nitrogen oxides (NO_x), SO_2 were parameters analyzed in ppm, and CO_2 was analyzed in percentage. Particle material was monitored using Metone's AEROCET 831 equipment. Particle material with a diameter of less than 1, 2.5, 4 and 10 micrometers (PM_1, $PM_{2.5}$, PM_4, PM_{10}) and total suspended particles (TSP), all of them measured in $\mu g/m^3$ under local conditions, were found. Measurements were carried out in a chainsaw exhaust vent (M_1), on the entrance of a vertical garden (M_2) and on the air exit of the active garden described in CS1A (M_3). Data capture was carried out every two minutes (for 10 minutes) using electrochemical sensors for SO_2, nitrogen monoxide (NO), NO_2, and CO, and using a non-dispersive infrared sensor for CO_2 and a thermocouple for the temperature. Data capture was carried out every minute (for 10 minutes) using a particle counter for PM_1, $PM_{2.5}$, PM_4, PM_{10}, and TSP. The gas emission retention percentage ($\%R$) of the vertical garden was determined by applying Eq. (2).

$$\% R = \frac{V_e - V_s}{V_e} * 100 \tag{2}$$

where *Ve* is the value of the parameter analyzed in the entrance of the CS1A vertical garden and *Vs* is the value of the parameter analyzed in the exit of the CS1A vertical garden. Entry and exit values were assessed through Welch's test, assessing significant differences between values on the garden's entry and exit.

3 RESULTS

3.1 Contribution of Vertical Gardens to Surrounding Air Quality

The results showed in Figure 2 were estimated by applying Eq. (1). Negative values show that there was a decrease in pollutants in areas surrounding the vertical gardens, meaning the air quality was improved due to the influence of each garden. Prior studies report a similar analysis on the San Blas vertical garden, located in the Historic Center of Quito, which achieved an 87% decrease in O_3 and of 39% in NO_2 when compared to measurements carried out on streets of the same area (Ramírez *et al*. 2019).

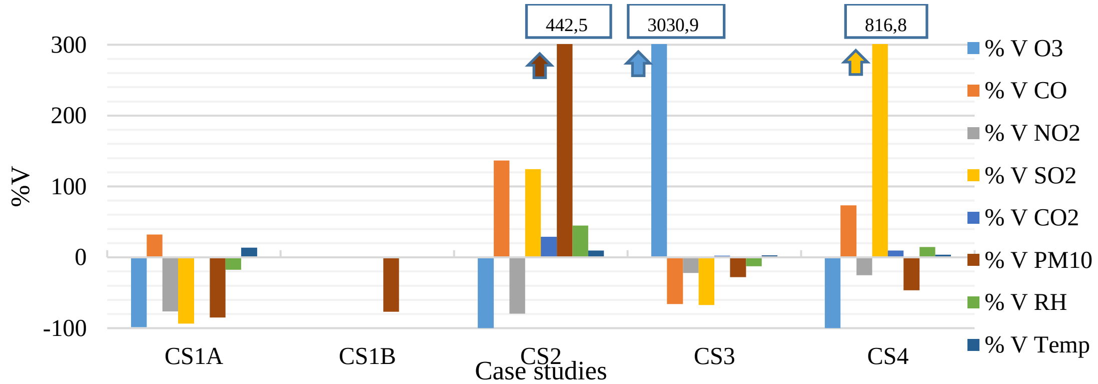

Figure 2. Variation percentage of parameters monitored in vertical garden. Values that exceed the scale show the percentages of variation in numbers.

3.2 Contribution of Vertical Gardens to Surrounding Air Quality

The hypothesis of statistically significant differences between pollutant concentration values existing on the CS1A entry and exit was assessed through Welch's test, which assesses the Student t using an associated p-value of 0.05. As a result, the alternative hypothesis was accepted for PM_1, $PM_{2.5}$, PM_4, PM_{10}, TSP, Temp, SO_2 and CO_2. However, the hypothesis was null for carbon monoxide (p-value of 0.0620) and nitrogen oxides (p-value of 0.0874), proving that in these pollutants there is no statistically representative difference of concentration variation. Table 1 summarizes the results of active CS1A against gas emissions from an external source. Figure 3 shows the results of gas emission, particle retention percentages and temperature variations.

Table 1. Assessment of the behavior of CS1A against gas emissions and particles.

Sample	PM_1 (μg/m^3)	$PM_{2.5}$ (μg/m^3)	PM_4 (μg/m^3)	PM_{10} (μg/m^3)	TSP (μg/m^3)	Temp (°C)	CO (ppm)	NO_x (ppm)	SO_2 (ppm)	CO_2 (%)
Chainsaw (M_1)	NA	NA	NA	NA	NA	50.2	3737	38	127	1.52
Entry (M_2)	92.0	1907.5	7778.4	8354.3	8366.3	26.9	655	9	44	1.09
Exit (M_3)	107.7	2070.9	5681.1	5818.4	5826.6	23.5	504	10	30	1.14

NA: corresponds to measurements that were not carried out.

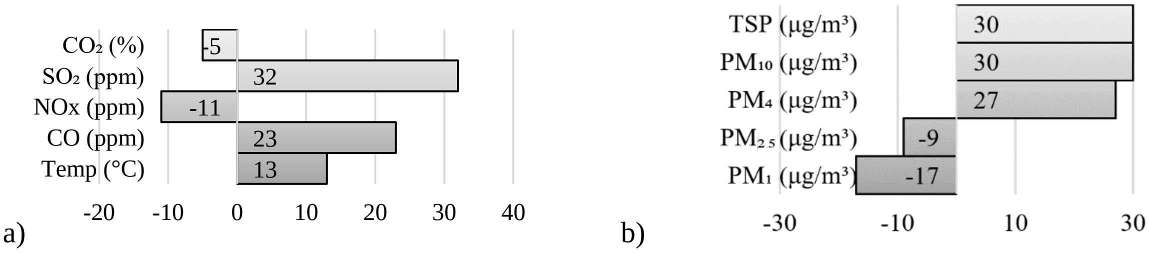

Figure 3. a) Gas emissions and b) particle retention percentage in the CS1A garden.

4 DISCUSSION

Green infrastructures absorb atmospheric pollutants through the leaf's stomata and the adhesion of particles, depending on the plant features and on their absorption mechanisms. The removal of pollutants is selective and may have positive and negative effects on the air quality, as a result of the sedimentation speed of each pollutant and of their concentration (Abhijith *et al*. 2017, Allen 1990). The literature review highlighted that the most efficiently absorbed pollutants are O_3 (36-43%), PM_{10} (33-48%) and NO_2 (11-21%) (Jayasooriya *et al*. 2017). In situ measurements carried out in indoor vertical gardens (CS2, CS4) show a consistent decrease in O_3 and NO_2 and an increase in CO and CO_2 concentrations. On the other hand, decreases in CO, SO_2, NO_2, $PM_{2.5}$, and PM_{10} can be seen in outdoor gardens (CS3). The decrease in PM_{10} and TSP match the estimations carried out by models in other regions (Jayasooriya *et al*. 2017). Additionally, a strong increase in O_3 levels is observed caused by the exposition of the vertical garden to solar radiation and the presence of plant species that emit volatile organic compounds, which favors the formation of O_3. Likewise, the proximity to the Metropolitan Park of Guangüiltagua, with a strong presence of Eucalyptus species, favors this increase (Sicard *et al.* 2018).

In the active CS1A garden, two types of measurements were carried out. The first was to determine the garden’s contribution to air quality. The results proved that the active CS1A garden decreased the $PM_{2.5}$ and PM_{10} levels in 79 and 85% in regards to outdoor levels. Furthermore, indoor air quality was improved by 4% and 8% for $PM_{2.5}$ and PM_{10} respectively, when compared to an indoor environment without an active garden (CS1B). Second, the gas emission absorption potential with direct incidence on an active garden was set through measurements carried out in a controlled environment using an internal combustion engine. The particle retention capacity of the CS1A garden is positive for particles with a size larger than 4µm. The larger the size of the particles, the higher the retention efficacy. The increase of particles of smaller size may be due to the turbulence created by the air which runs through the CS1A garden. The statistical analysis proved that all variables, except CO y NO_x, present significant changes between the air entry and exit in CS1A. The gas which shows the highest retention rate is SO_2 (32%). The decrease in SO_2 may be linked to its higher water solubility when compared to other assessed pollutants (CO y NO_x) (Sander 2015), which means that CS1A would absorb it alongside the humidity retained by the active garden. There is also a significant Temp decrease (13%) as corroborated by previous studies (Davis *et al*. 2016). Furthermore, there is a significant CO_2 increase due to cellular breathing processes during measurements.

In summary, the active CS1A garden shows a decrease in all pollutants, with the exception of CO, during the assessment of pollutant absorption from vertical gardens from the ambient environment. However, gas emission experiments suggest that there is a significant decrease only in SO_2. We may say that gases which affect the air quality surrounding a vertical garden are removed through a progressive process which is not immediately achieved, with the exception of SO_2, due to its higher affinity to humidity. In the case of particles, CS1A is efficient when decreasing high concentration levels (up to 10 times the levels found in ambient air). However, the higher the concentration of entry particles, the less efficiency shown.

5 CONCLUSIONS

Experimental studies on the behavior of several vertical gardens in the city of Quito were carried out in order to verify their contribution to the air quality of the surrounding environment and, likewise, the behavior of an active vertical garden when retaining pollutants from gas emissions was assessed. It can be observed that indoor vertical gardens show an air quality improvement regarding particles, O_3, and NO_2 in all cases. However, the presence of outdoor vertical gardens may cause an O_3 increase if the adequate species are not chosen, or if there is an influence of species such as Eucalyptus, which emits great quantities of volatile organic compounds that cause the formation of photochemical oxidants. The removal of particles in an active vertical garden depends on the concentration and the size distribution of the particles at the garden's entry. Decrease rates of up to 30% can be achieved in the case of gas emissions incidence, with entry concentrations of up to 10 times of those registered in the ambient air. Gases that affect the quality of a vertical garden's surrounding air quality are removed through a progressive process which is not immediately brought into action (except SO_2, due to its higher affinity to humidity).

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