Urban Heat Island Mitigation by Introducing Green Roof System

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Abstract. Urban Heat Island is a cumulative effect of negative environmental impacts caused by urbanization. This phenomenon is demonstrated in many cities and produced effects such as higher atmospheric temperatures, intensive precipitation, excessive solar radiation and role in increasing air pollution. The green roof system is capable of reducing the ambient temperature of the surrounding area of the building below thus to be one of the effective method to mitigate urban heat island effect one of the environmental issue face many urban cities. The study is focused on determining the effectiveness of the green roof in cooling down the ambient temperature of the air above it by comparing with exposed common rooftop. This study also aims to evaluate the air pollutant reduction of the green roof in to prove that green roof is able to improve air quality in urban cities. In this study, the temperature and air quality of two type of roof surfaces are recorded in 3 different sampling locations on a rooftop garden which is an extensive green roof system. The extensive green roof shows result in better air quality despite the carbon dioxide reading is not available. Temperature above the green roof appeared to be much lower than common rooftop without vegetation. The maximum temperature reduction by green roof during the hottest hour in a day which is 1230 hr recorded is 4.3°C when compare to open roof without vegetation. The highest temperature recorded on green roof is 36.9°C, and the highest temperature recorded on open roof without vegetation is 41.2°C. Effectiveness in reducing ambient temperature of the rooftop can be proven by implementing a green roof system.

Introduction

Around half of the world's human population lives in urban areas. It is expected that the global rate of urbanization is will increase in the near future. The negative impacts of the urbanization to the environment is mainly because of pollution production, the alteration of the physical and chemical properties of the atmosphere and the covering of the soil surface. When all these impacts are cumulated, a phenomenon is occurred considered as the Urban Heat Island (UHI). UHIs have been indirectly related to climate change due to their contribution to the greenhouse effect, and therefore, to global warming. The UHI phenomenon is considered to be as a major problem for human population in the 21th century, as a result of urbanization and industrialization [16].

Rapid and uncoordinated urbanization has a profound impact on the quality of thermal environment has been confirmed with temperate countries, but studies are relatively lacking in the low tropics, particularly with quantitative evaluation. According to the recent study, the intensity of UHI of the city of Kuala Lumpur the temperature difference between urban and rural areas varies from 3.9 to 5.5°C and concluded that the increase in the intensity of the UHI of the city of Kuala Lumpur is more than one degree Celsius (1.5°C), which is a recognized value whenever the human health and comfort are the concern [6]. An observation indicates that commercial centers such as Klang and Kuala Lumpur are usually several degrees warmer than the surrounding countryside. The mean annual temperature difference between the city and the airport during an average was approximately 1 to 2°C, however, the temperature differential could go up to 6 to 7°C under a calm and relatively clear sky nights [6].

Cause and Effect of UHI

The term UHI effects are the impacts of urbanization on the thermal environment. It is the surface temperature anomalies that resulted by those effects mostly originate near the ground surface. Heat islands are caused by urbanization, when buildings, roads and paved surfaces store the heat during the day and then release it slowly during the evening keeping urban lands hotter than surrounding areas [13]. Despite heat islands may form on any rural or urban area, and at any spatial scale, cities are favored, since the building's surfaces in the city are prone to release large quantities of heat. Many features of the physical structure of the city can give impact on the urban climate and negatively results in amplifying urban heat island intensity [17]. The anomalous urban ground surface temperature anomalies will unavoidably flow both upward into the atmosphere downward toward the subsurface. As the temperature of the urban area rose, the need of air-conditioning system installs in the building to provide a comfy for the commercial or residential building is increased too. Meaning that the energy consumption is increased as well [12].

The intensification of an urban heat island has regional-scale effects on air quality, energy demand and public health [8]. According to [10], UHI phenomenon intensifies the demand for energy, speeding up the production of toxic smog and producing human thermal discomfort and health troubles by increasing heat waves over cities. Other than that, UHIs promote high air temperatures that contribute to formation of ozone precursors, which combined photo chemically produce ground level ozone. UHI during summer season significantly reduces the outdoor air quality and intensifies the energy demand of a city and causes extensive power blackout may happens caused by the increase of the air condition usage. When concerning about health issue cause by UHI, a direct relationship has been discovered between UHI intensity peaks and heat-related illness and fatalities. Reports show that thousands of people annually die as a result of heat related diseases [5]. Urban heat islands increase overall electricity demand, as well as peak demand, which generally occurs on hot summer weekday afternoons, when offices and homes are running cooling systems, lights, and appliances. According to the research by [12], he confirms that on a basis of hour-to-hour temperature data, the large increase in cooling energy and peak demand which due to the heat island effect, which are shown to increase by as much as 100%. As energy consumption elevated significantly due to the urban heat island, tremendous stress has been put onto power generation sector in order to generate enough energy to sustain the demand of the city. Consequently, when large scale power plants generate power by burning fossil fuel, which in turn leads to an increase in air pollutant and greenhouse gases emissions. Atmospheric chemistry cycle can be accelerated by the increase in temperature in urban areas which lead to an increase of ground-level ozone. Warmer air can also cause emissions of the biogenic hydrocarbons to increase and the rate of evaporation for synthetic volatile organic compounds (VOCs) will be higher too, both result the production of troposphere ozone [5].

Green Roof and Benefits

Green roof, or garden roofing is a new emerging technology that mitigate urban heat island. According to [14], green roof is a green space created by adding layers of growing medium and plants on top of a traditional roofing system. Plants are one of the essential elements for a healthy city. Greenery system provides enormous benefits to an urban area which includes less energy demand, pollutant reduction, run-off water management and better ecosystem [7]. A green roof is typically a garden grown on a rooftop. The system can be simply planting a turf on the rooftop, generally termed an 'extensive' rooftop garden system, or as complex as a fully accessible park complete with trees and vegetation, termed an 'intensive' system. No matter what type of system is chosen, the components of a green roof remain essentially the same [14].

There are generally two main types of green roof systems; extensive and intensive which different in term of cost, depth growing medium, and the selected plants [2]. An intensive green roof is like a conventional garden, or park, with almost no limit on the type of available plants, including large trees and shrubs. It is often accessible and can be applied for recreational and leisure purposes. Intensive green roofs are generally heavier with deeper layer of growing medium and have greater needs for irrigation and maintenance. They generally require more structural support to accommodate the weight of the additional growing medium and public use. Extensive green roof system is a simpler, lighter weight design. It is often not accessible and are characterized by low weight, low capital cost, and low plant diversify, generally as a turf like surface. The concept is to design a rugged green roof that needs little maintenance or human intervention once it is established. Due to its light weight design, extensive systems will require the least amount of added structural support and may not require permanent irrigation system. Thus, extensive green roofs are well suited to roofs with little load bearing capacity and sites which are not meant to be used as roof gardens.

There are three main categories of benefit that green roofs are able to provide, namely economic benefits, amenity and aesthetic benefits, and environmental benefits. Economic benefits include energy conservation, extends roof lifespan [18]. Amenity and aesthetic benefits are including visual aesthetic value, health and horticultural therapy and recreation and leisure place. Whereas for environmental benefits come to the better storm water management, urban heat island effects reduction, improve air quality, sound insulation and bio diversify habitat. The vegetation planted on rooftops has a cooling effect by dissipating some of the city heat through the process of evapo-transpiration. Different to conventional construction materials such as concrete and asphalt as example that absorb large amount of solar energy lead to ambient temperature rising, green roof reduces the amount of radiated heat by absorbing and/or deflecting the solar radiation [18]. While compare to other type of conventional roof, roof with reflective coating, green roofs shown to be a promising option in term of cooling. On a sunny, 26°C day, a dark roof can reach a temperature of up to 80°C, a white roof, 45°C, and a green roof, 29°C [11]. When less solar energy and heat are radiated back to the city atmosphere due to the presence of the plant, green roofs reduce the ambient temperature in the city. If green roof system is aggressively implemented in urbanized region, large amount of radiated solar energy will be absorbed and cool down through the process of evapo-transpiration. Through UHI mitigation, cooler communities require less energy consumption thus produce less production from power plants. Additional trees and vegetation remove more pollutants from the air. Nevertheless, cooler air temperature slow down the formation of smog. Green roof is able to alleviate a variety of airborne contaminants. According to a German study, green roof reduced diesel engine air pollution has been demonstrated with a significant result [9]. Vegetation improve surrounding air quality by removing air pollutants and greenhouse gas emissions through dry deposition and carbon sequestration storage. [15] found 21% and 37% reduction of nitrous acid and sulphur dioxide respectively directly above a newly installed green roof. Not to mention an estimate of 0.2kg of particulates remove per year per square meter of grass roof [14]. Other than that, as mentioned above ground-level ozone formation accelerate readily with the rise in air temperature. Hence, green roofs aid to slow down this formation when they reduce the surrounding ambient temperature [7].

The research aims to determine the effectiveness of green roof system in reducing the temperature in the surrounding of the chosen building by identify the temperature difference between conventional rooftop and green rooftop. The research also includes the need to determine the ability of green roof to improve the air quality above it whether it is directly or indirectly. The area of this study is to determine the effectiveness of green roof system in mitigating UHIs effect in urban area by comparing the temperature of the roof of with installed green roof system and temperature of a conventional roof. The parameters in the comparison are fall into two categories, which are thermal aspect - temperature and relative humidity, and air quality - carbon dioxide (CO_2), ammonia (NH_3), oxide nitrogen (NOx), and oxide sulphur (SOx).

Methodology

This section demonstrates the method use to carry out testing to obtain the required data for analysis purposes to evaluate the effectiveness of green roof system to reduce ambient temperature in the roof.

Information Collection

This study begins with collecting relevant data and information about urban heat island effects and its mitigation measures, along with information about green roof system and its performance from previous study. Information is gathered from books, journals, previous research, online journal, and internet.

Parameters and Sampling

The studied area was conducted in a high-rise building in Putrajaya which its roof is comprised of open roof surface and an extension green roof surface. Parameters that involved in this study are divide into two which are thermal performance and air quality parameters. Thermal performance basically consists of temperature (ºC) and relative humidity (RH). While air quality comprises of ozone (O_3), oxide nitrogen (NO_x) and oxide sulphur (SO_x). The sampling station for both parameters will be determined by observation. An early visited to the study area was conducted to identify the right sampling location. The condition of the location, material of the surface, exposure to sun have been determined, and type of vegetation is living grass with average height of 60 mm. Three sampling locations have been selected, which are (i) green roof with living grass, (ii) open roof without plant and (iii) open space on ground. The purpose of this sampling is to identify any differences that occur between each types of condition in term of its thermal appearance.

Figure 1: The probe is set up 300 mm above the ground to obtain data

For the purpose of this study, equipment that will be using are Graywolf Direct Sense TOX PPC Kit to collect air quality and temperature data, However, for the humidity data, Testo 175 H1 will be used. The data collected has been analyzed based on their parameters with plotting graph and chart to shows their pattern and characteristic. Ambient temperature versus time graph are plotted and compared with all different sampling location to find out the differences. Other data such as relative humidity, ozone, nitrogen oxide, sulphur oxide, and ammonia have been plotted on graph for better presentation.

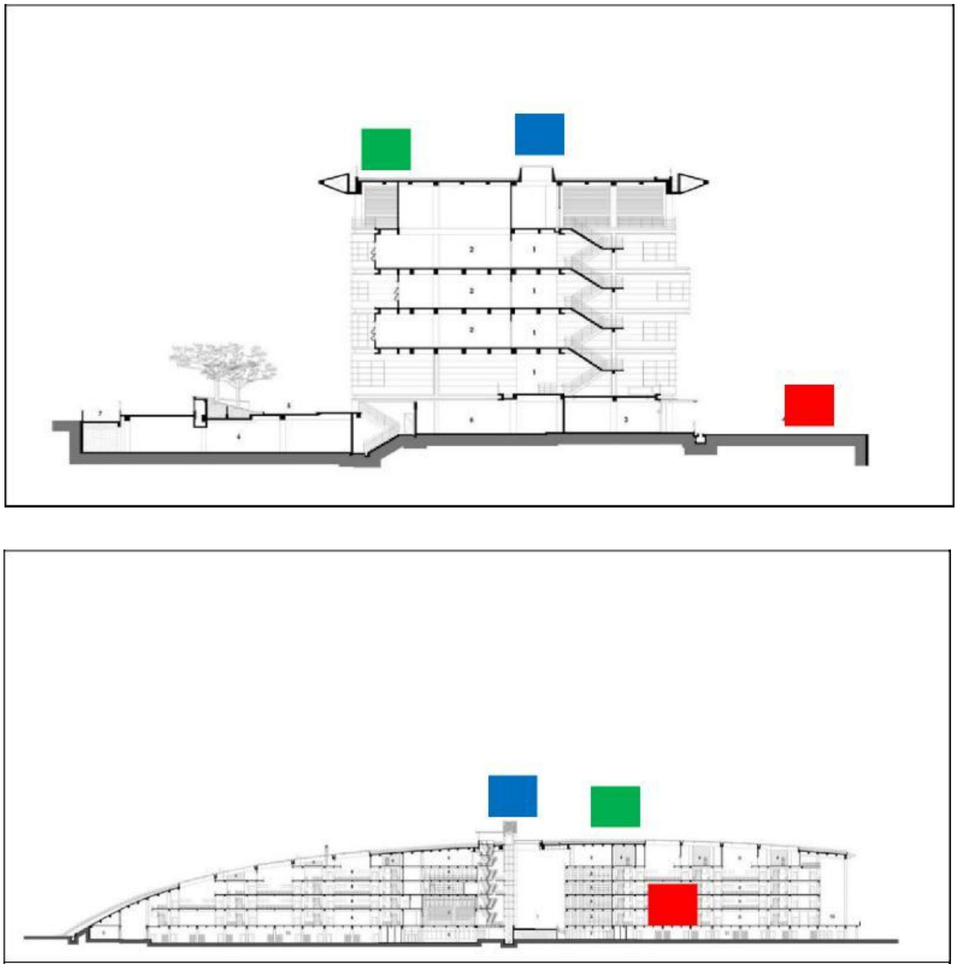

Figure 2: Locations which the sampling being took place

(i) Green roof

(ii) Open roof with vegetation

(iii) Open Space on Ground

Result and Discussions

The result was split into two categories which are thermal performance and air quality. The data were compared between sampling locations in order to acquire the patterns of the data that each type of surfaces behaved.

Temperature

The different of temperature between the green roof with living grass and the open roof without vegetation has been recorded and computed. From the figure below, we can see there are significant differences between two roofs temperatures, as the maximum difference in temperature can be observed during 1230 hr the temperature differs a margin of 10.4% or 4.3°C. However, the temperature at 0800 hr shows only minimal difference in temperature between the green roof and open roof without vegetation as the sun is not yet rise, which only differs for 7.8% or 2.3°C. The plant area indicates a lower temperature during the hottest hour in a day, and the open roof area without vegetation that is directly expose to the sun indicates a higher temperature in the same particular hour.

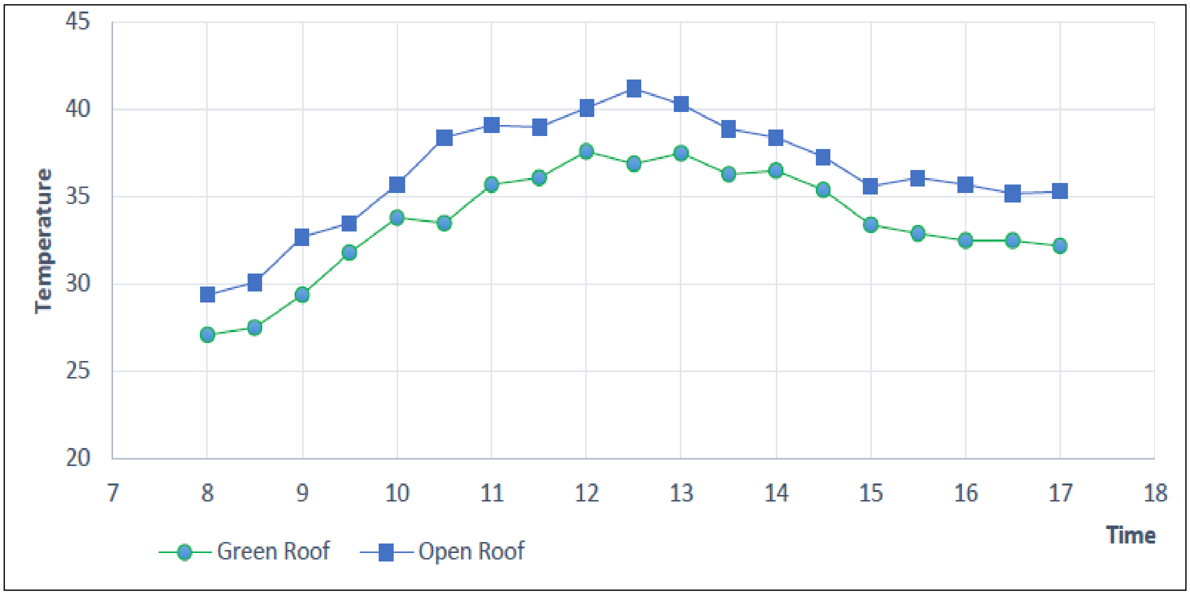

Figure 3: The graph shows significant different between the temperature of the green roof with living grass and open roof without vegetation from 0800 to 1700 hr.

From the graph in above, it illustrates that green roof is capable of reducing the temperature by absorbing the thermal heat radiated by the sun even during the hottest hour in a day. It proves that even in the harshest thermal environment, green roof is able to improve the condition of an exposed roof. According to [15], 6 to 10°C in temperature reduction can be achieved when a common roof is covered with green vegetation, and after the installation of the green roofs, the reduced in the diurnal difference in the temperature are very substantial. Although the margin of temperature differences is not very obvious, but a numbers of building within a single urban area will exert an obvious effect to the area's temperature.

The temperature difference between open roof with vegetation and open space on ground level was compared too. It is essential also to compare the temperature difference between open roof without vegetation and open space on ground to determine the thermal absorption characteristics between open roof and open ground. The open roof without vegetation is a surface made up of concrete block, and the open space on ground is made up of concrete finishing. Based on Figure 4 below, minimal difference in temperature can be observed during 0800 hr with only 0.1°C different, however, during 1230 hr we can see there are big different in temperature between the open roof and open space on ground, as open roof without plant is 1.4°C higher than the open space on ground.

The slight variation of temperature between open roof and open space on ground level can be explained by the thermal mass of their material. Both surfaces are made from concrete material which mean they have similar thermal absorption properties. In the research did by [6], the primary material used for urbanization are concrete, asphalt and roofing tile have a much greater heat capacity than the natural surface such as forest that have been increasingly displace within metropolitan regions.

Therefore, urban fabric tends to absorb large amount of heat from sun radiation during day light, then slowly emitted into the air when night fall. There are two main parameters that influence the solar radiation reaching the roof deck, leaf foliage and soil media. The more extensive the foliage density of a particular plant, the more the heat flux through the roof decreases [20] and the greater the decrease in surface temperatures [21].

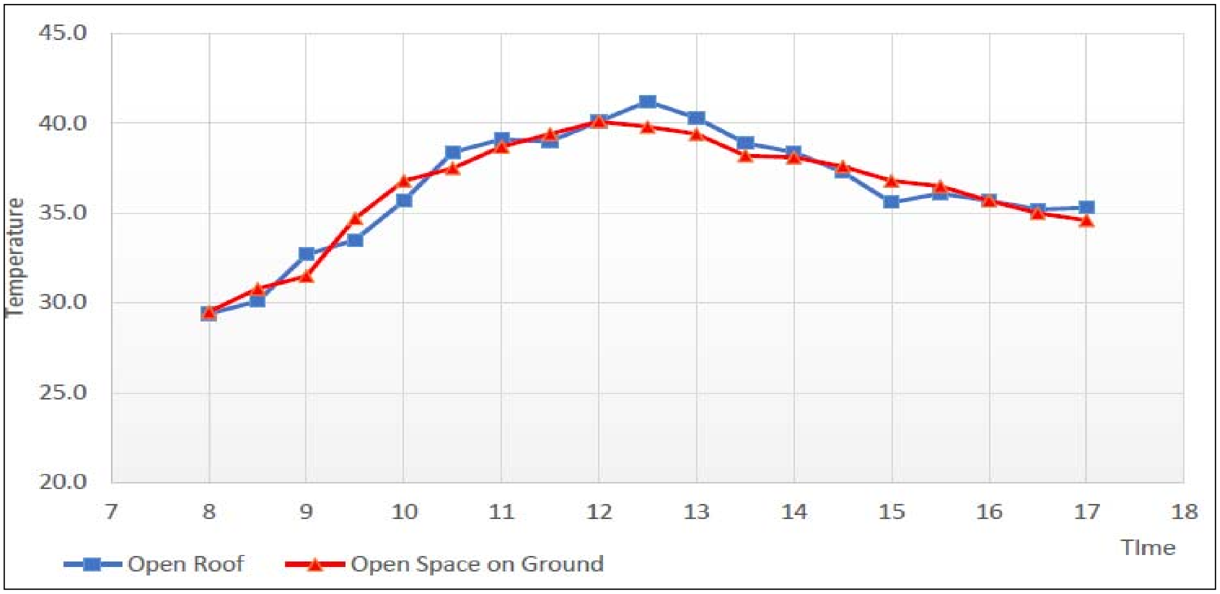

Figure 4: There are significant different in temperature between the open roof and open space on ground level can be observed during 1230 hr. The difference in temperature for the rest of the hours show minimal variation between the two surfaces

Relative Humidity

The evapotranspiration of the plant and the soil layer enable the roof to retain a certain amount of water, it is the main aspect for the reduction of the temperature of the buildings. Vegetation intercepts radiation and provide shade area that can help to reduce the temperature. Evapotranspiration process carry out by the grass releases water vapor into the air on the rooftop will help to maintain the relative humidity even during the hottest hour in a day. The percentage difference in humidity between green roof and open roof is first compared. As Figure 5 shows that the humidity percentage of the green roof during 1300 hr is significantly higher by 8.8% when compared it to the open roof without vegetation.

The humidity reading of open roof without vegetation drops significantly during the afternoon which is 54.1% with a temperature of 41°C.Whereas the humidity of the green roof decreased to 61.5% with a temperature of 36.9°C in the same particular hour. The relative humidity of the green roof is higher than the open roof even in the morning which are 85.1% and 74.2% or evening which are 76.9% and 67.7%. We can conclude that the humidity for both roofs drop accordingly along with the temperature above the roofs as shown in Figure 5, as the humidity drop when temperature rise and increase when the temperature started to drop. The water holding capacity of the air will increase dramatically if the temperature increases as well. However, the amount of water remains the same, but not the ability of the air to hold water. The relative humidity of a warmer air which can hold more water is less than the same air at a lower temperature.

On the other hand, relative humidity of cooler air increases because cooler air can hold less water. Vegetation plays an important role in surface cooling in the presence of high moisture levels by evaporating and removed latent heat from soils and transpiration from plant [19]. Most of the urban fabric lacks of water retention ability when comparing to natural surfaces such as forest and plants. In urban areas, where the fraction of the surface covered by vegetation is particularly low and surfaces tend to be water-resistant, potential surface cooling due to the loss of latent heat from vegetation and soil is reduced.

Figure 5: The comparison between green roof humidity and open roof humidity shows green roof retained more moisture in the air than open roof

Sulphur Dioxide

According to study, green roofs contributes in improving air quality in cities by reducing the air pollutant particles and compounds with its plants and growing medium as well. Green roof is expected to improve the air quality on the roof which include sulphur dioxide (SO_2). Sulphur dioxide is a pungent and irritating smell toxic gas at standard atmosphere. The difference of sulphur oxide amount between green roof and open roof is compared. Figure 6 illustrated the amount of oxide sulphur in the air above green roof and open roof.

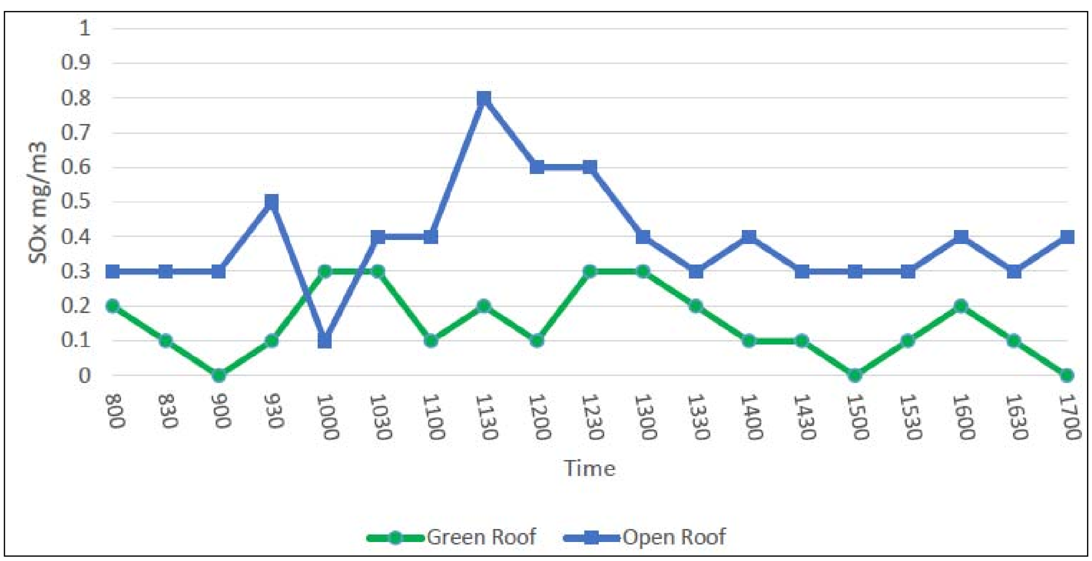

Figure 6: The graph illustrates the amount of oxide sulphur in the air on green roof and open roof. Higher oxide sulphur content could be observed during hotter temperature, 1130 hr to 1300 hr.

Based on Figure 6, the amount of oxide sulphur comparison between these 3 locations is fluctuated throughout the day. But the oxide sulphur concentration on the green roof is significantly lower when compared to the SO_2 concentration on open roof, where the highest reading of SO_2 on green roof is 0.3

mg/m^3 (0.106 ppm), and the lowest reading recorded is 0 mg/m^3. Whereas, the peak reading of sulphur oxide recorded on open Roof is 0.8 mg/m^3. The chart also shows that higher SO_2 content can be observed from 1130 hr to 1300 hr where the temperature is higher in the day, with highest SO_2 concentration recorded is 0.8 mg/m^3 (0.284 ppm) for both open roof and open space on ground. The result shows that green roof has reduced the concentration of SO_2 in the air above it. In one of [15] field study, they have measured the concentration of air pollutants and particulate matters on a roof with 4000 m^2 area in Singapore, they found that the level of SO_2 in air above the roof after the installation of green roof was reduced by 37%. There are minimal different of concentration of the sulphur oxide between open roof and open ground.

On the other hand, Figure 7 shows the amount of sulphur oxide which been compared between the open roof area and open ground. Both surfaces have similar highest reading of SO_2 amount which is 0.8 mg/m^3. However, the surrounding air contaminants at the studied areas might be affected by a nearby cooling plant which emit gas such as SO_2. But after the analyzed the data, we can assume that the effects from the plant emission has no obvious impacts to our study's results.

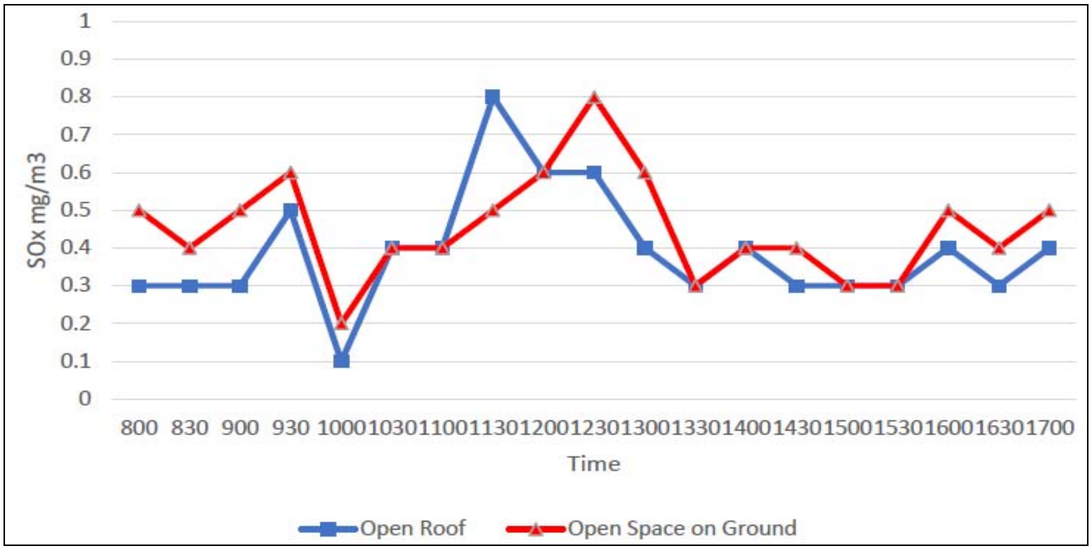

Figure 7: The amount of sulphur oxide is compared between open roof and open ground

Nitrogen Dioxide

The difference of oxide nitrogen (NO_x) concentration between the green roof and open roof has been pointed out in Figure 8. The result indicates a huge marginal different of NO_x between the green roof and open roof. The graph shows the highest amount of NO_x on green roof is 0.83 mg/m^3 (0.401 ppm) at 1230 hr, and the highest reading from open roof without vegetation is 1.47 mg/m^3 (0.726 ppm) at 1130 hr. The highest different in percentage when comparing two highest recorded reading for the two surfaces is 53.1%. open roof is 0.77 mg/m^3 higher than the green roof during 1100 hr in the morning.

From the data above, we can assume that green roof might actually be effective in improving air quality which it shows containing less NO_2 in its air. But be aware that there is a cooling plant located not more than 200 m far away from the studied area which has NO_2 emission. There will slightly effect the true concentration of the NO_2 in the studied area. Vegetation plays a role in lowering surface temperatures through latent heat removal from soils via evaporation and transpiration in the presence of high moisture levels [19]. According to [18], NO_x production through air conditioning can be reduced by lowering the temperature inside buildings. NOx can be reduced when the ambient city temperature is reduced by up to 3°C. Therefore, NOx and VOCs reactions will be slow when the needs for air conditioning are reduced because the ambient temperature surrounding the buildings is lowered by green roofs.

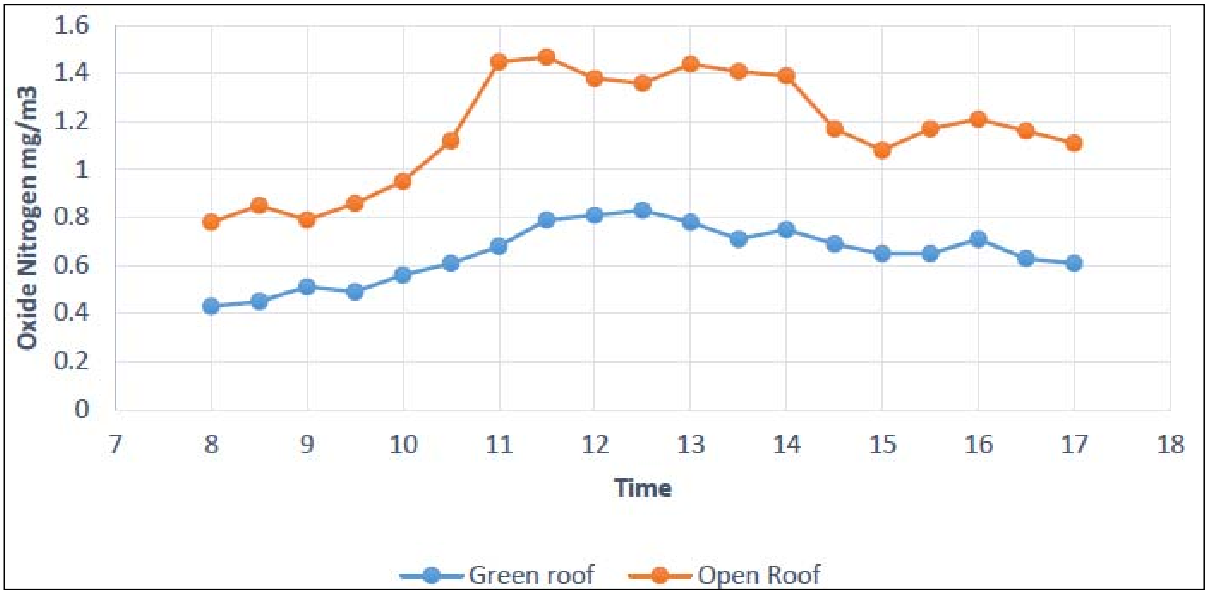

Figure 8: Significant difference in NO_2 concentration from 0800 hr to 1700 hr between two surfaces. Green roof contained less NO_2 in its air compared to open roof without planting area.

Ozone

A comparison of ground-level ozone has been computed in Figure 9 which shows the different of ozone amount above the air of green roof with plants, open roof without plant, and open space on ground. The pattern of the chart indicates a fluctuation pattern of ozone amount throughout the day from morning until evening.

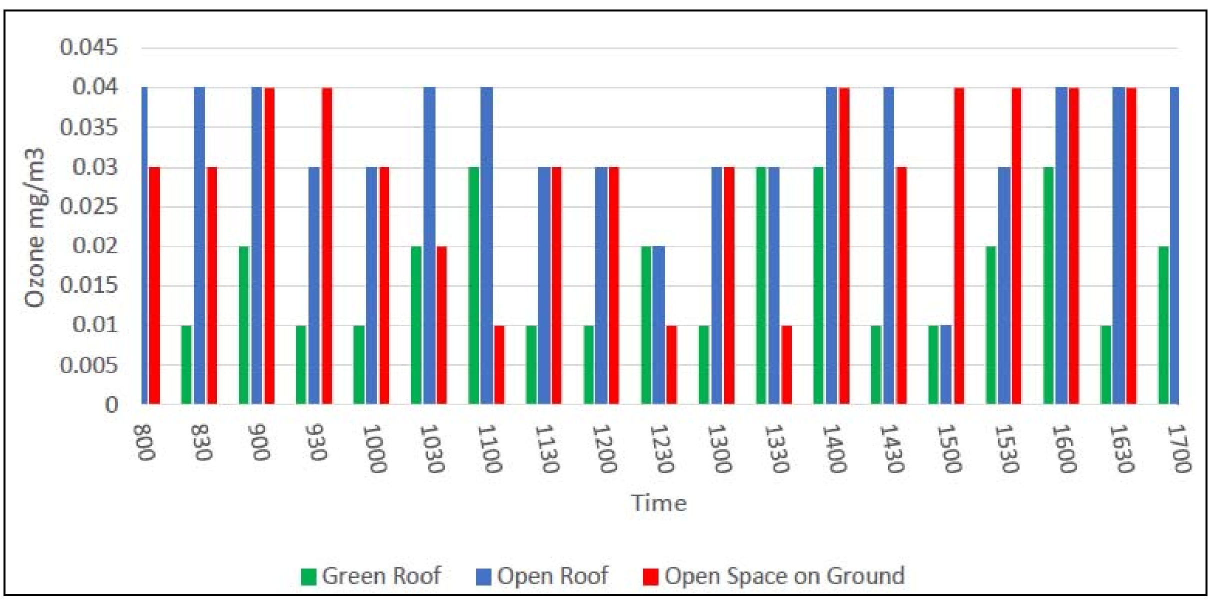

Figure 9: Comparison of ozone (O_3) above the air of three surfaces, green roof with plant, open roof without plant, and open space on ground.

The highest amount of ozone been recorded in this studied area is found on open roof without plant and open space on ground which is 0.04 mg/m^3 (0.019 ppm). Based on the chart below, we can see that the amount of ozone above the green roof is generally lower than the other two surfaces. The highest amount of ozone recorded is 0.03 mg/m^3 (0.014 ppm). Although the difference is very little but it will certainly give a large impact to the air quality in cities when the numbers of roof is increase. However, the difference of O_3 amount between open roof and open space on ground level is not very significant as we can observe in Figure 9. However, averagely, we can assume that the O_3 concentration in the green roof's air is lower than open roof and open space. When the albedos of urban surfaces are replaced by vegetation, evapo-transpiration cooling of the plant will lowers the ambient temperature in the surrounding. Then, the lowered ambient temperature slows down the photochemical reactions therefore leads to less of pollutants such as ozone [1].

Conclusion

The study of UHI's Mitigation by introducing green roof has achieved its objective. Despite facing many difficulties when conducting the testing, including difficulty in acquiring permission to enter study area, instruments shortage in laboratory and economy constraints, this study has been successfully carried out. The study area selected is located at the rooftop garden of Heriot Watt University, Putrajaya. It is a 230 m long and 30 m wide with a 30° curvature rooftop structure, where it held a 6900 m^2 green roof with living grass.

The field studies and research that have been carried out have shown the main purpose of implementing green roof which is to lower the ambient temperature on the rooftop in order to reduce the formation of urban heat island in urban area. The maximum temperature reduction by green roof during the hottest hour in a day which is 1230 hr recorded is 4.3°C when compare to open roof without vegetation. The highest temperature recorded on green roof is 36.9°C, and the highest temperature recorded on open roof without vegetation is 41.2°C. Thus, we can conclude that green roof provide lower ambient temperature than conventional rooftop and is a method to be used to mitigate urban heat island effect.

The relative humidity was recorded in the field study, the data collected shows that lower humidity is recorded on the open rooftop without vegetation when compare to green roof where has higher humidity in the same hour. The lowest humidity recorded for green roof is 60.2%, whereas the lowest humidity recorded on open roof without plant is 54.1%. the grass on green roof carry out evapo-transpiration process which will release in to the air above the green roof and the moisture trapping soil underneath the grass help the green roof to retain its humidity even in the hottest hour of the day.

Other than that, the research also computed the air quality and presented in chart. From the results we can see that the air above the green roof with living grass contain less air pollutant such as oxide nitrogen, oxide sulphur, ozone, ammonia and carbon monoxide. Thus, this has proven our hypothesis that green roof is able to improve air quality in the air.

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