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SUMMER PASSIVE COOLING POTENTIAL OF AN EXTENSIVE GREEN ROOF IN INDIAN COMPOSITE CLIMATE: A SIMULATION STUDY

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ABSTRACT

Green roofs are a very important passive cooling technique which helps in reducing thermal heat gain and further reduction in temperature inside any habitable space. It relies on the thermal insulation of soil, shading by plant foliage and transpiration cooling, to reduce the indoor temperature. Green roof reduces the problem of solar roof heat gain with the help of plants.

Simulations are essential tools for preliminary evaluations. It helps in foreseeing the effects of a certain technology, without physically constructing a model, which can be costly, and time taking. Green roof simulations help in predicting the outcomes of such installations without being built. The purpose of this study was to model, simulate, and compare the temperature reductions and relative humidity for a habitable room with extensive green roof, and a room without green roof, in a composite Indian climate. DesignBuilder software was used in this study. Two cases were considered for the modules, one with extensive green roof and the other with bare roof. Internal temperature and humidity data was gathered for both the cases. Simulations were performed for a period of one month i.e. from 12th May to 12th June (generally the hottest 30 days of the year), and hourly results were collected. The simulation results clearly highlight the amount of temperature reductions inside a habitable space, which is bringing the indoor environment close to the comfort range with respect to Indian context. This study hence shows that extensive green roofs are beneficial in providing better internal comfort during the summer months.

KEYWORDS: Extensive Green roofs, Simulations, DesignBuilder, Thermal Comfort

I. INTRODUCTION

India is developing at a steady pace. This development often has side effects like pollution, greater energy demand, warmer cities, and climate change. Cities are in need to implement techniques that can solve these problems. The techniques must be energy efficient, easily implementable and should tackle multiple problems. One such technique is green roofing.

A green roof is one that has a vegetation, soil and drainage layer after the structure of roof. Green roof reduces the problem of solar roof heat gain with the help of plants. It relies on the thermal insulation of soil, shading by plant foliage and transpiration cooling, to reduce the indoor temperature. It is an energy efficient technology for cooling interiors of the building and reducing urban heat island [1]. According to O.H. Koenigsberger and E. Martin, as the surfaces of the buildings that receive solar radiation, walls only receive about two-thirds of the maximum solar radiation that falls on the roof, and considerably less than this on the wall, which faces away from the equator [2], [3]. As a designer, it is important to focus on the temperature reduction from the roof surface. Green roofs help in limiting the insolation on roofs. There exist two classifications of green roofs – extensive and intensive. Extensive green roofs have shallower substrates (less than 200 mm) and does not add excessive weights over the roof structure [4]. Intensive green roofs have substrates more than 200 mm in thickness and generate additional loads on the roofs. Extensive green roofs can be installed over an existing roof as it doesn't impose greater loading conditions on the existing structure. Intensive green roofs require additional supports as the loading conditions is greater [5].

Green roof is passive cooling technique. Passive cooling techniques involves natural processes for cooling [6], [7].

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Jim, (2017) has identified the origins of green roofs clustered into five different periods, across the world and has found that new innovations have enhanced the scope of green roofs. He highlights that vernacular green roof began as a matter of chance in a positive way and the core principle and practice of green roof have unchanged till date.

Ran & Tang, (2017) have identified that green roofs with nighttime ventilation can reduce the average indoor temperature up to 2.3°C compared to wall insulation and nighttime ventilation.

As per the studies for comparison between green roof and conventional RCC roof test cells done by Pandey, Hindoliya, & Mod, (2012) in city of Ujjain, India, the results indicate that the green roof test cell always perform better in summer season. The green roof test cell also reduced high temperatures and diurnal temperature fluctuations. They had also used Artificial Neural Network (ANN) for gauging reduction in heat gain from roof which provided higher prediction rate of 93.8-98.5%. The study also highlighted the energy saving potential of green roof.

Of the five roofs investigated in the study by Yang, Wang, Cui, Zhu, & Zhao, (2015) in Guangzhou (China), green roofs showed the best thermal performance. The study highlighted the comparison of exposed roof to that of green roofs, whereby green roofs provided a cooler indoor air temperature 0.9–1.0◦C as compared to that of exposed roof in summers.

Goussous, Siam, & Alzoubi, (2015) in their study in Jordan, compared regular roof and green roof highlighting the reduction in temperature inside room eventually leading to reduction of energy consumption. The study also highlighted calculations and computer simulation to demonstrate the thermal benefits of a green roof.

In this paper, extensive green roof has been discussed and focused upon, as it is easier to retrofit the existing roofs with an extensive green roof along with cost benefits of installation as compared to that of intensive ones. Researchers like R. Srivastava, and A. Gagliano have found out the benefits of Green roofs when compared to conventional roof, some of which are listed in Table 1 [1], [5], [11], [13]–[16]. Green roofs are considered as a substitute for natural soft paved areas that provide outdoor healthy space and increases the aesthetic value [17].

Table 1: Benefits of Green roofs over conventional roofs

Benefits	Green Roof	Conventional Roof
Storm water volume retention	10-35% during wet season, 65-100% during dry season	None
Urban Heat Island Mitigation	Prevents temperature increase	With Light colored roof
Temperature mitigation	Enhanced cooling and thermal insulation	Can be achieved with insulation
Air Quality	Filters air and Increases evapotranspiration	None
Energy saving potential	92% energy savings compared to conventional roofs	-

Various studies on green roofs around the world have drawn conclusion that it aids in lowering of temperature inside the room when compared to bare roofs. Table 2 compiles some of the relevant experimental and simulation studies. Simulations are essential tools for preliminary evaluations. It helps in foreseeing the effects of a certain technology, without physically constructing a model, which can be costly, and time taking. In architecture, simulations aids in assessing the future built environment by predicting temperature reductions, visual comfort, life cycle costs, energy saving potential in buildings and many other relevant attributes. With the help of simulation studies, one can also assess how parameters can affect thermal comfort. Thermal comfort is affected by many factors like, air temperature, air velocity, relative humidity, radiant environment, clothing and activity level, out of which air temperature is the most common measure of comfort and is most widely understood [18].

ISSN: 2277-9655
Impact Factor: 5.164
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Table 2: Various research on Green roofs

Research	Area/Location	Climate	Conclusions
Experimental results			
Huang, Chen, & Liu, 2018	Taichung, Taiwan	Humid Subtropical	Plants reduced 3.98 °C (maximum) when compared with the bare soil roof
Jiang & Tang, 2017	Chongqing, China	Warm and Humid Climate	Peak indoor air temperature reduction of 3.3 °C on average with fan, 3.0 °C on average when using natural ventilation
Bevilacqua, Mazzeo, Bruno, & Arcuri, 2016	Calabria, Italy	Mediterranean Climate	Reduction of internal environment temperature of 2.3 °C (average) in summers
He, Yu, Dong, & Ye, 2016	Shanghai, China	Subtropical Monsoon	Free float - Indoor air temperature 2 °C lower than common roof at noon
Simulated results			
Ran & Tang, 2017	Shanghai, China	Humid Subtropical	Green roof combined with ventilation kept the indoor temperature below 29 °C
Jaffal et al., 2012	La Rochelle, France	Temperate Oceanic	With a green roof, the summer indoor air temperature was decreased by 2 °C

The purpose of this study is to model, simulate, and compare the temperature reductions and relative humidity for a room with extensive green roof, and a room without green roof, in a composite Indian climate. A climatic zone that does not have any season for more than six months may be called as composite zone [23]. While many researchers have simulated the energy performances, and heating and cooling loads of the rooms with green roofs [10], [16], [24], [25], seldom has been done for simple thermal comfort parameters, and for a free float condition in an Indian composite climate. This paper is focused on calculating the impact of extensive green roof on the indoor air temperature and humidity in a free-floating condition.

II. MATERIALS AND METHODOLOGY

Relevant parametric values were selected from the literature, followed by the selection of location. It was followed by the creation of geometries in DesignBuilder software [26]. DesignBuilder is a graphical tool for creating geometries and materials which runs on the EnergyPlus simulation engine. EnergyPlus is developed by the US Department of Energy to aid designers and architects to perform whole building simulations. It was chosen because of its ease of use, it's user interface convenient for architectural simulation research and the inclusion of Sailor's model of vegetative roof energy balance [27]. DesignBuilder has a module to specify green roof parameters, which aids in simulating one. After modeling, materials were assigned to the geometries. Values of thermal coefficients and other relevant data were added. The simulation was run and the result data were collected. The methodology can be seen in Figure 1.

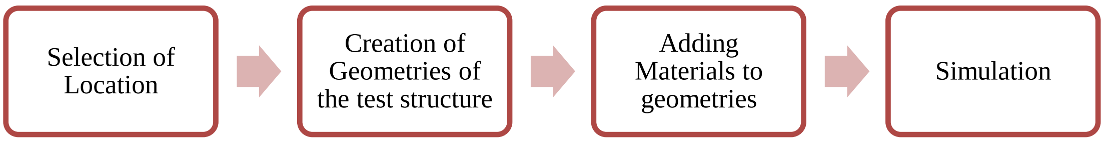


Figure 1 : Methodology for the given study

The individual steps of the methodology are explained in detail in the succeeding sub sections.

Selection of location

The city of Raipur, capital of the state Chhattisgarh (21.2514° N, 81.6296° E, 289.5 m above sea level), situated in the east central part of the state was selected for this study. The city has composite climate [23] with mean annual rainfall of 1489 mm out of which 90% is during the monsoon months of June to September [28]. The relative humidity of the city is maximum in the month of August (85%), followed by July (83%). Summer months of March, April and May have low RH of 46%, 40% and 37% [28] respectively.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

The usual temperature during peak summer goes up to 40 °C - 45 °C. This makes the cooling load inside the building to rise. A typical resident of Raipur city depends on artificial cooling technologies like evaporative water coolers, and air conditioners to achieve comfort during the summer months.

Geometries of test structure

Test structures were modeled in DesignBuilder with inside dimensions of 3m x 3m x 3m (l x b x h). The model has a parapet of 0.3 m, to aid in the placement of green roof. The model was created as per the usual construction techniques prevalent in Indian context. It was aligned across the north-south axis. The room had a door, no windows, and no provisions for natural/mechanical cooling and ventilation, for a free float condition. After the creation of geometries, materials were imparted to the geometries in the DesignBuilder.

Two cases were considered for the modules, one with extensive green roof and the other with bare roof. Internal temperature and humidity data was gathered for both the cases. Data for ambient temperature and humidity was also collected through simulation. Pictorial representation of the room can be seen in the Figure 2.

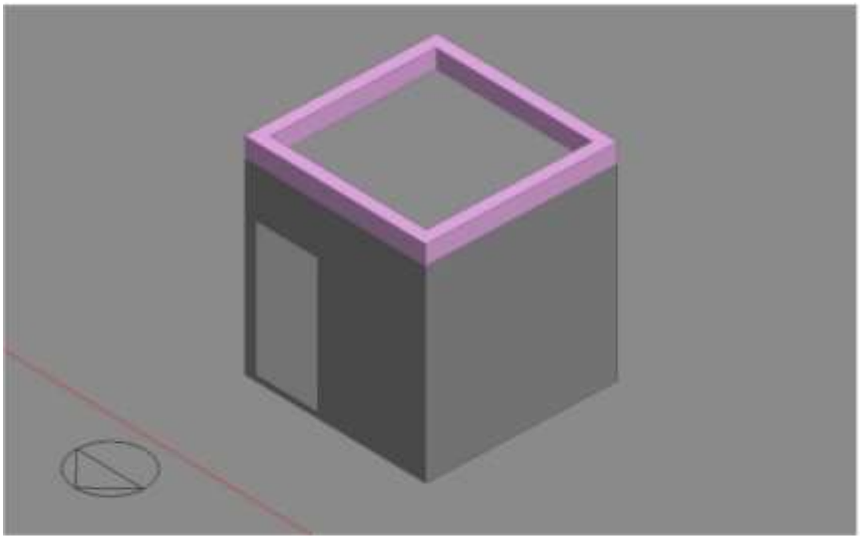


Figure 2: Representation of the green roof test structure in DesignBuilder

Materials

The walls and parapet are made up of 230 mm wide, of fly ash bricks. It also has a cement plaster of thickness 18 mm on the outside and 12 mm on the inside. Reinforced cement concrete 100 mm thick was used as the roofing material. Five subsequent layers above the concrete roof layer was added for extensive green roof. The bottom layers acts for waterproofing and drainage, over which soil layer and plant layer is stacked. Thermal conductivity, specific heat, and density values of few materials were obtained from the "Assembly U-factor calculator" tool available at CARBSE's website [29]. CARBSE is the Centre for Advanced Research in Building Science and Energy which is supported by Ministry of New and Renewable Energy, Government of India, and is accredited by various agencies. The values of the parameters assigned to the layers can be seen in Table 3.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

Table 3 : Thermal Properties used for the Test Structure

<table>
<tr><td colspan="3">Layer</td><td>Thermal conductivity (W/m-K)</td><td>Specific heat (J/kg-K)</td><td>Density (Kg/m3)</td></tr>
<tr><td rowspan="2">Wall</td><td colspan="2">230 mm fly ash brick</td><td>0.64</td><td>661</td><td>1240</td></tr>
<tr><td colspan="2">Cement plaster (18 mm outside and 12 mm inside)</td><td>1.21</td><td>662</td><td>1880</td></tr>
<tr><td>Floor</td><td colspan="2">100 mm reinforced concrete + 1 % steel</td><td>2.3</td><td>1000</td><td>2300</td></tr>
<tr><td rowspan="5">Roof</td><td colspan="2">100 mm concrete + 1 % steel</td><td>2.3</td><td>1000</td><td>2300</td></tr>
<tr><td>1.3 mm Acrylic based elastomeric waterproofing membrane</td><td rowspan="4">Combined layer</td><td rowspan="4">0.98</td><td rowspan="4">880</td><td rowspan="4">1460</td></tr>
<tr><td>20 mm Recycled Polypropylene drainage layer</td></tr>
<tr><td>0.9 mm Polystyrene filter and root barrier</td></tr>
<tr><td>100 mm Soil</td></tr>
</table>

Thermal conductivity is the property of a material to transfer heat. Higher the thermal conductivity, higher is the heat transferred through that material. Lower thermal conductivity means that the material exhibits insulation property. Specific heat is the amount of thermal energy required, per kg of a material, to increase the temperature of the material by one unit. It is usually expressed in Joules per Kilogram Kelvin.

Additional values were required by the model for the green roof layer, which includes the height of the plants, leaf area index, leaf reflectivity and leaf emissivity. According to D.J. Sailor [27], Leaf area index (LAI) is "the dimensionless ratio of the projected leaf area for a unit ground area". LAI has decisive impact on the shading effect [30]. For this study, a higher value of LAI (LAI = 5) was considered to assess the maximum temperature differences. The additional parameters entered in the DesignBuilder can be seen in Table 4.

Table 4 : Properties of Green roof layer

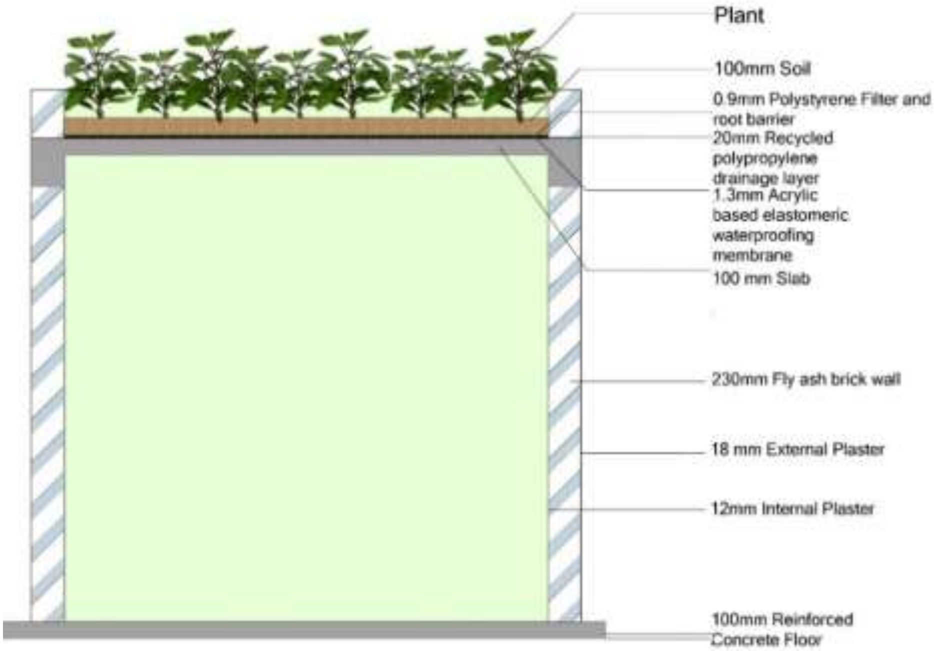
Layer	Values
Height of plant	0.10 m
LAI	5
Leaf Reflectivity	0.22
Leaf Emissivity	0.95
Max volumetric moisture content at saturation	0.50
Min residual volumetric moisture content	0.01

Simulation

The scenario considered is free floating which means that there were no heating or cooling systems installed in the room. Additionally, there were no windows in the rooms for natural ventilation. ISHRAE's (Indian Society of Heating, Refrigerating and Air Conditioning Engineers) EnergyPlus weather data file of year 2002 (latest available is taken in DesignBuilder) for the city of Raipur was used in the simulation. The interior of the test structure was considered as a thermal zone. Simulations were performed for a period of one month i.e. from 12th May to 12th June (generally the hottest 30 days of the year every year). Two cases, one with extensive green roof and the other with bare conventional RCC roof, were simulated and hourly results were collected. This aids in comparing the daytime and nighttime readings which are discussed in the next section.

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

(a)



(b)

Figure 3 : (a) 3D representation of green roof (b) Section of green roof

III. RESULTS

The simulation shows that the extensive green roof was more capable of decreasing the internal air temperature than the bare roof during the simulated summer month. The results are compiled in Table 5. Average temperature difference inside the green roofed room compared to conventional room was 3.01 °C. The maximum internal temperature difference between green roofed test structure versus bare roof test structure was 6.31 °C on 9th June at 17:00 hours. The minimum internal temperature difference between green roofed test structure versus bare roof test structure was 0.85 °C on 31st May 10:00 hours. Figure 4 shows the graph plotting the external temperature, internal temperature of the bare roof test structure, and the internal temperature of the green roof test structure. The graph shows that the temperature inside the green roof test structure is lower than the conventional bare roof test structure throughout the day, and at night. A slight time lag can be seen between the peaks of the external temperature and the inside temperature of the green roofed test structure. This shows that the green roof is able to decrease the peak cooling load during the summer month. The maximum outdoor temperature 44.9°C was recorded at 15:00 on 11th June, and the maximum internal temperature inside the bare roof was 40°C on 11th June at 17:00, while the maximum internal temperature inside the green roof was 36.3°C on 11th June at 17:00. This shows that the difference between outdoor temperature and indoor temperature inside green roof was close to 8.6°C and the time lag between maximum temperatures were 2 hours. The minimum outdoor temperature was usually recorded around 4:00 hours, while the minimum internal temperature for green roof was usually recorded around 5:00 – 6:00 hours.

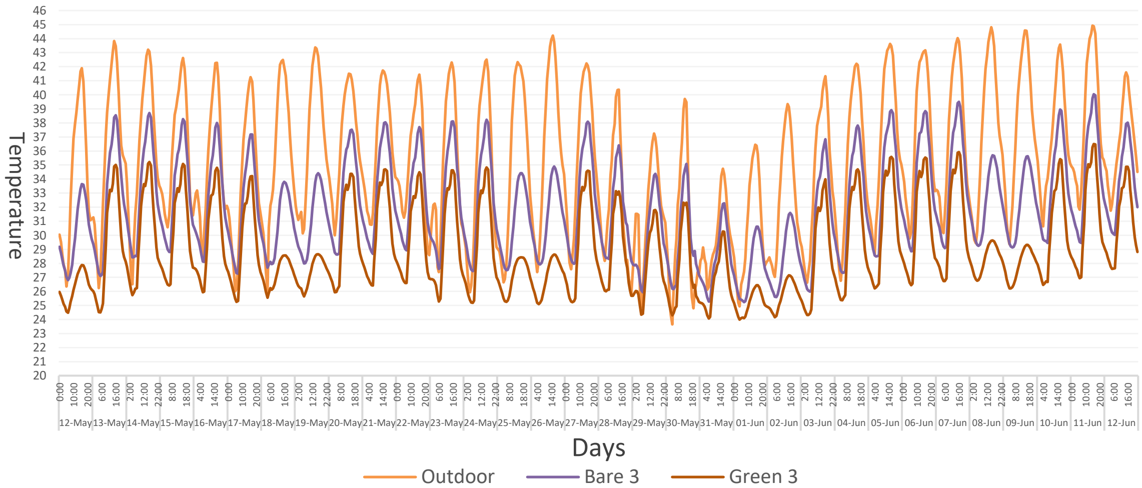


Figure 4 : Air temperature results for 24 hours

Figure 5 shows the graph plotting the external humidity, and the internal humidity of the green roofed and bare roofed test structures. While green roofs were able to decrease the internal temperature, it increased the internal humidity when compared to the conventional bare roof. Humidity inside the green roof was usually more than the conventional bare roof.

The average increase in the internal humidity of the green roofed test structure compared to the conventional bare roof test structure was 7.34 %. The maximum increase in humidity inside the green roofed structure was 18.16 % (1st June 19:00 hours) compared to the conventional bare roof structure, while the minimum was 2.49 % (5th June 12:00 hours). Figure 5 shows that the humidity level from 28th May to 3rd June were higher than the rest of the days which indicates possibility of precipitation. The humidity inside the green roof structure was 100 % for a few hours during this period.

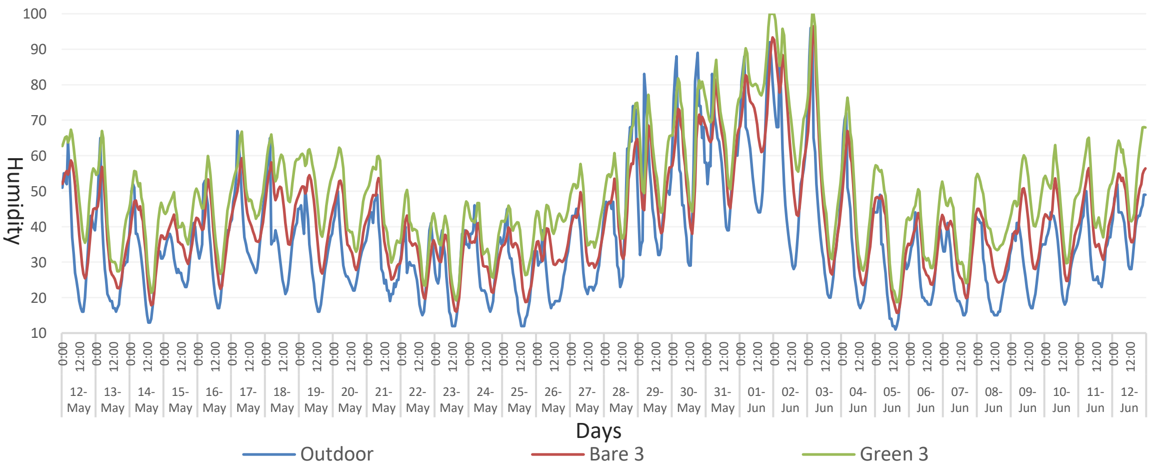


Figure 5 : Humidity results for 24 hours

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

The average difference in the internal temperature of green roof test structure and the conventional bare roof test structure, during daytime (6:00 hours to 18:00 hours) for the period of 12 May to 12 June, was 2.90 °C, while it was 3.13 °C during nighttime (18:00 hours to 6:00 hours). Figure 6 plots the daytime temperatures. It is relevant from the graph that the temperature inside the green roof stays lower than the outdoor temperature, as well as the internal temperature of the bare roof, throughout the day.

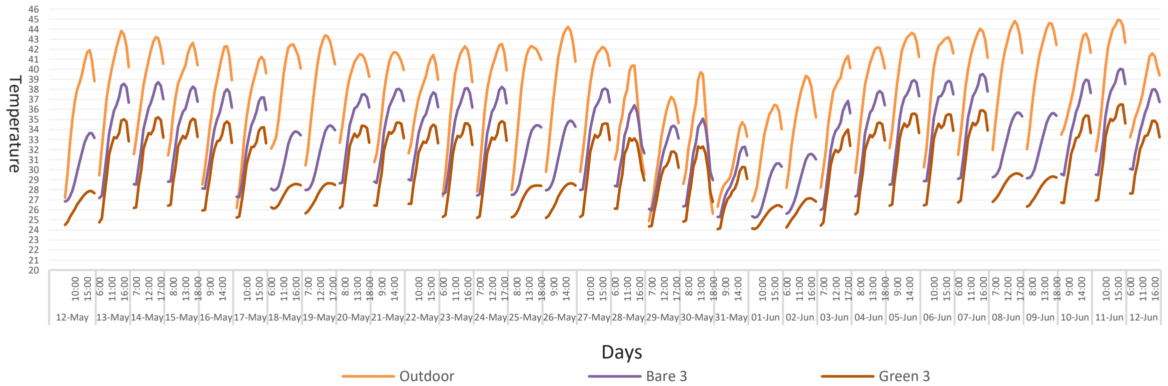


Figure 6 : Temperature results for daytime

Figure 7 plots the nighttime temperatures of the two test structures with outdoor temperature. It can be seen from the graph that during the precipitation days (28th May to 3rd June), the nighttime temperature inside the green roofs were sometimes equal or higher than the outdoor temperature, but it is still lower than the internal temperature of bare roof test structure. During the usual summer days, the nighttime temperature inside the green roof is lower than both outdoor temperature as well as the internal temperature of the bare roof structure.

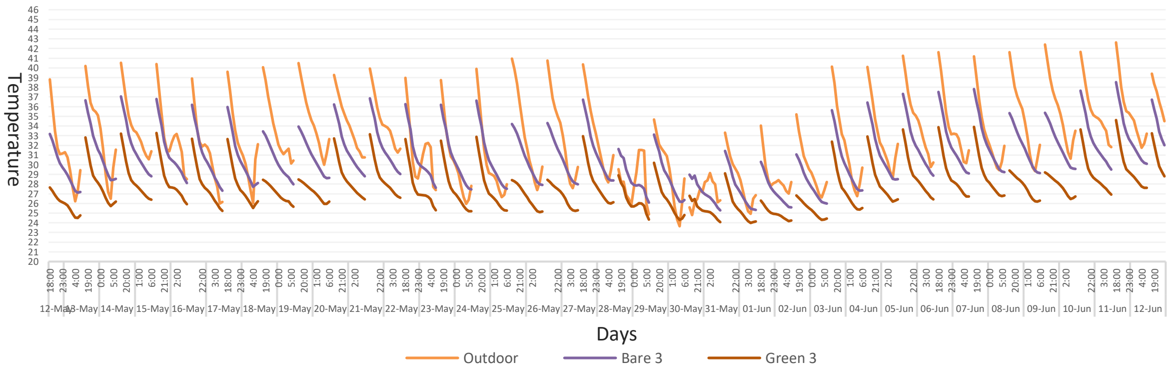


Figure 7 : Temperature results for nighttime

The average difference in the humidity of green roof test structure and the conventional bare roof test structure, during daytime (6:00 hours to 18:00 hours) for the period of 12 May to 12 June, was 6.44 %, and 8.27 % during nighttime (18:00 hours to 6:00 hours). Figure 8 plots the daytime humidity. It is relevant from the graph that the humidity values inside the green roof test structure was higher than the bare roof test structure as well as the outdoor humidity, throughout the daytime.

ISSN: 2277-9655
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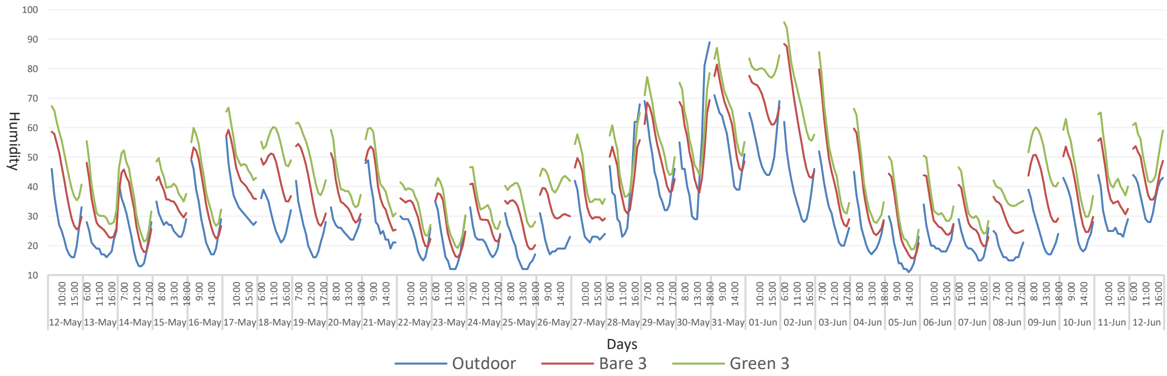

Figure 8 : Humidity results for daytime

Figure 9 plots the nighttime humidity. It can be seen from the graph that during nighttime the humidity inside the green roof structures varies, it is usually higher than the humidity inside the bare roof structure, but sometimes it is lower than the outdoor humidity (generally during the precipitation periods of 28th May to 3rd June).

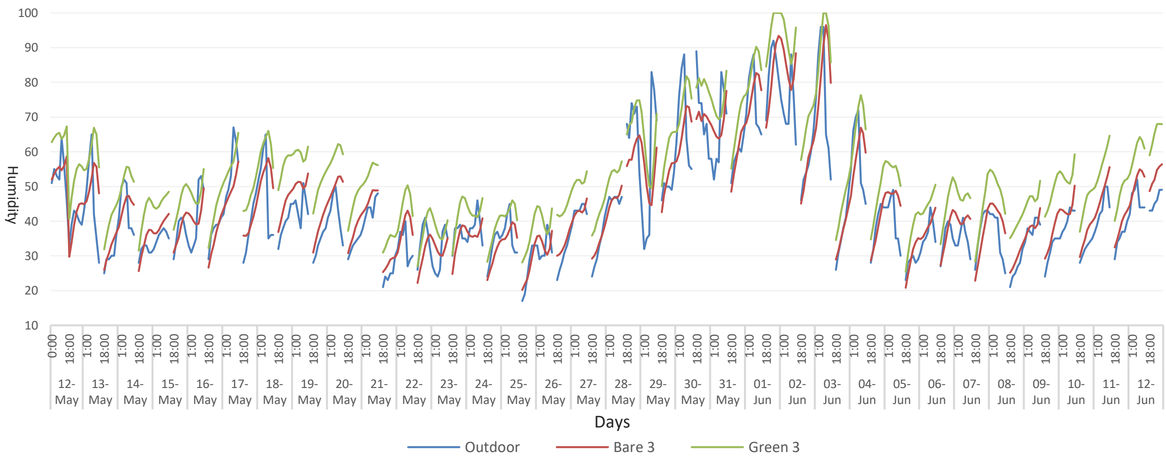

Figure 9 : Humidity results for nighttime

Table 5 shows the average, maximum and minimum values of the two parameters (temperature and humidity) for both the test structures and the hourly differences between the values of the two test structures. Hourly differences values consider the data of conventional and extensive green for the same hour and subtracts it.

Table 5: Table of simulation results

Duration	Parameter (inside room)		Conventional RCC Roof	Extensive Green Roof	Hourly Differences between Conventional RCC and Green Roof
Diurnal	Temperature	**Average**	31.86 °C	28.86 °C	3.01 °C
		Maximum	40.04 °C	36.50 °C	6.31 °C
		Minimum	25.24 °C	23.99 °C	0.85 °C
	Humidity	**Average**	42.20 %.	49.54 %.	7.34 %.
		Maximum	96.5 %	100.0 %	18.16 %
		Minimum	15.72 %	18.69 %	2.49 %
Daytime (6:00 to 18:00)	Temperature	**Average**	33.03 °C	30.14 °C	2.90 °C
		Maximum	40.04 °C	36.50 °C	6.31 °C
		Minimum	25.24 °C	24.07 °C	0.85 °C
	Humidity	**Average**	39.22 %	45.66 %	6.44 %
		Maximum	88.40 %	95.77 %	17.59 %
		Minimum	15.72 %	18.69 %	2.49 %
Nighttime (18:00 to 6:00)	Temperature	**Average**	30.68 °C	27.55 °C	3.13 °C
		Maximum	38.52 °C	34.61 °C	6.14 °C
		Minimum	25.29 °C	23.99 °C	1.21 °C
	Humidity	**Average**	45.26 %	53.52 %	8.27 %
		Maximum	96.48 %	100.00 %	18.16 %
		Minimum	20.18 %	25.40 %	3.52 %

IV. CONCLUSION

The simulation results clearly highlight the amount of temperature reductions inside a habitable space, which is bringing the indoor environment close to the comfort range with respect to Indian context. The results also show positive output in terms of diurnal temperature reductions. This amount of temperature reductions clearly directs that there will be a huge savings in terms of energy and costs. The results also show time lag in the heat transfer to the indoor area; which further adds to the peak load reduction in energy and costs. The maximum temperature difference between the bare roof and green roof was 6.31 degree Celsius. The maximum temperature recorded inside the bare roof structure was 40.04 degrees whereas the maximum temperature recorded inside the green roof structure was 36.50 degrees.

The study and simulation provide a clear picture of the importance of extensive green roofs in Indian composite climate during summer months, highlighting it as a very important passive cooling technology. Simulation studies along with literature review opens up new venues for a wide range of research possible in the area of extensive green roofs.

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