Eco Cities 2025, 6(1), 2988.
https://doi.org/10.54517/ec2988

Article

Improving indoor temperatures through a homemade green roof modular system

Renato Castiglia Feitosa[1,*], **Sara Wilkinson**[2]

[1] Department of Sanitation and Environmental Health, National School of Public Health, Oswaldo Cruz Foundation, Rio de Janeiro 21041-210, Brazil
[2] University of Technology Sydney, Sydney 2007, Australia
*** Corresponding author:** Renato Castiglia Feitosa, renato.feitosa@fiocruz.br

CITATION

Castiglia Feitosa R, Wilkinson S. Improving indoor temperatures through a homemade green roof modular system. Eco Cities. 2025; 6(1): 2988. https://doi.org/10.54517/ec2988

ARTICLE INFO

Received: 31 October 2024
Accepted: 26 December 2024
Available online: 3 January 2025

Abstract: Increased urbanisation has led to a worsening in the quality of life for people in large cities due to the increase in indoor temperatures. Retrofitted green roofs may attenuate housing temperatures, due to the isolation and passive cooling properties of these vegetated systems. For this purpose, this research reports on an experiment using a green roof modular system to compare indoor and outdoor temperatures before, and after, a green roof set up in an existing depot in Rio de Janeiro, Brazil characterized by high temperatures for most parts of the year. The modular system comprised previously used pallets covered with geotextile and planted with succulent species with low watering needs and reduced maintenance processes. Compared to the outdoor environment, mostly warmer indoor conditions were converted to cooler temperatures and due to its thermal properties, which provide insulation, evapotranspiration, and shading the green roof system presented a potential to attenuate the heat exchange and improve indoor conditions. A homemade lightweight modular system can widespread green roofs on a city scale.

Keywords: green roof retrofit; indoor temperatures; health environment; thermal comfort; green cities

1. Introduction

Urban environments have experienced rapid expansion, which contributed to creating urban canyons, where heat is trapped between buildings, leading to negative effects on human health [1–6]. The changes in the original land conditions and the decline, or absence, of green areas result in significant heat gain since solar radiation is mostly absorbed by hard dark surfaces found on dwellings, increasing indoor temperatures. To offset these effects, green roofs are suggested to mitigate these drawbacks of the urbanization processes.

Due to its insulation and the cooling effects of evapotranspiration, green roofs comprise an interesting alternative for energy savings in attenuating cooling demands [7–9]. In addition, the environmental benefits of green roofs lead to potential reductions in operational carbon emissions, reductions in the urban heat island, increases in biodiversity, housing temperature attenuation and reductions in stormwater run-off [7,10–12].

Thermically green roofs promote attenuation of heat influx and outflux through insulation [7,8,13–29]. In tropical countries, heat gain in indoor environments occurs through the roof due to the lack of insulation. There is a consensus that in poorly insulated dwellings, green roofs can enhance the insulation properties, reducing the heat gain and improving indoor thermal comfort without the need for artificial cooling that requires energy demand. Green roofs can provide an annual energy-saving potential for cooling in buildings with no insulation between 22% and 45% [20]. A study from Singapore showed that an extensive green roof covered with turf provided an energy saving of about 11% compared to a non-insulated bare roof [30].

Green roofs can be classified as extensive or intensive. Extensive roofs comprise vegetation composed of short plants, introduced in shallow soils, with depths less than 15 cm [31] and are characterized by requiring low maintenance and intermittent watering [32]. Intensive green roofs are characterized by soil substrates up to 1m depth and can support bigger plants that require higher levels of maintenance and irrigation [32].

Considering the lack of areas available for vegetation establishment in urban centres, rooftops offer good areas, potentially available for planting. However, it is important to highlight that the vegetation setup on rooftops must meet structural requirements, considering that most of the existing buildings were not designed to support heavy additional loads. To comply with structural criteria, green roofs supplied in lightweight modular systems are imperative. Similarly, several studies used of green roofs considering a lightweight approach [33–37]. Rather than direct contact with the roof and avoiding green roof setup restrictions to commercial brands or suppliers, an inexpensive modular homemade solution is tested and proposed. This modular system aims to enable off-site planting, cultivation, and maintenance. Besides, the lightweight characteristic enables the application of these systems at scale due to the low additional structural load allowing these green roofs to be fitted to existing rooftops with no requirement of structural reinforcement.

This paper reports on an experiment to evaluate the green roof influence between outdoor and indoor temperatures using a modular lightweight system planted with succulents. The experimental setup was performed in the Oswaldo Cruz Foundation (Rio de Janeiro—Brazil). A depot (as shown in **Figure 1** below) was used to compare outdoor and indoor temperatures simultaneously, 105 days before and, 105 days after the green roof setup. Data was collected using thermal data loggers over the summer and autumn 2018 seasons. The paper discusses the findings and the potential for retrofitting residential stock using a homemade solution with lightweight plastic pallets planted with succulents.

2. Materials and methods

The methodology comprised the development of simple technologies to mitigate the problems created by increasing urban densification and uncomfortable indoor air temperatures in housing. In the present work, lightweight and low-cost techniques that minimize costs related to the installation of the green roof and allow off-site planting and maintenance were adopted. Lightweight removable modules, comprising rectangular pallets covered with geotextile, soil, and vegetation, were used to cover a concrete slab (15 cm thick) of an existing depot at Oswaldo Cruz Foundation (Fiocruz), Rio de Janeiro, Brazil.

The assemblage of the vegetated modules comprises the following steps. Plastic pallets (1m × 1m) are selected as a frame for the green roof system, due to its resistance to weathering. These pallets are covered with a geotextile fabric that retains the soil particles and allows the water flow. Cavities are created in the geotextile between the free spaces of the pallets, providing soil beds for the plants. The geotextile is fixed with plastic straps, on the four sides of the pallets, and the plants are placed in the soil. The vegetated modules are placed on the rooftop once the plants are fully developed. The cost for this vegetated system varied between US 13 $\$/m^2$ and 15 $\$/m^2$. However, different plastic containers can be used for the purpose.

The lightweight characteristic of the vegetated modules lies in the adoption of a shallow soil substrate. However, it is important to consider that the shallow soil substrate limits the size of plants, which in turn can limit the thermal performance of green roofs when compared to green roofs that support larger vegetation. The weight of planted pallets varied from 60 kg to 80 kg, considering dry and saturated conditions, respectively, allowing its application without structural reinforcement. In addition, one of the innovative aspects of this choice is that the modules can be assembled at home without being subjected to any patent or brand since the materials are commercially available, adaptable and affordable. These characteristics provide potential to widespread the use of green roofs in a substantial coverage of roof areas in the urban environment. The benefit of this choice is that all the activities for the green roof assemblage are performed away from the rooftop, minimizing the risk of accidents and unclean sites. In addition, the harsh climate conditions of the rooftop, such as wind and solar radiation, may be harmful to the initial development of the vegetation. **Figure 1** shows the sequence of the green roof assemblage.

Figure 1. Stages of the green roof assemblage **(a)** initial planting of succulents on the pallets after the geotextile coverage; **(b)** development of the vegetation; **(c)** pallets positioning before the assemblage on the rooftop; **(d)** green roof modules after the placement on the rooftop; **(e, f)** external view of the green roof.

Rather than succulents, a different study has suggested the use of *Stachys* for green roofs [38]. However, due to their survival capability in shallow substrates [38] and lower levels of maintenance, succulent plants mostly composed of *Callisia repens* and *Kalanchoe delagoensis* were adopted, since they represent a group of drought-tolerant plants with low watering needs. Succulent species have a Crassulacean acid metabolic (CAM) that protects their photosynthesis from CO_2 and H_2O stresses, using a mechanism of switching photosynthesis pathways [39]. In the site study, there is no irrigation system, and due to their drought resistance, the plants survive only depending on the local precipitation.

To evaluate the performance of green roofs in temperature attenuation, two temperature data loggers were placed, at the same wall, inside and outside of the depot about 1.8 m above the floor. As shown in **Figure 2**, the dimensions of the depot are: 4 m length; 2m width; 2.5 height, and its walls are 15 cm thick, constructed with bricks covered with cement mortar and painted white. There are no windows, and access is provided by a 1.5 m × 2. m (width × height) door that remains closed most of the time.

The dimensions of the rooftop are 4.2 × 2.1 m, and eight pallets were used to cover it. The temperature records were taken every 30 minutes for approximately 210 days, using a commercial USB data logger Extech TH10, which has a temperature (T) range from −40 to 70 °C (−40 to 158 °F), and an accuracy of 0.6 °C (1 °F).

The original survey was conducted over a period of 420 days. The initial 210 days performed from 26 March to 22 October 2018 were going to be repeated in the same period in 2023. However, due to the COVID-19 contingency plan, the experimental site had to be inactivated at the beginning of 2023. Thus, only 2018 data could be presented in this study.

Considering that the local climate is predominantly warm for the entire year, we decided to select a period where the temperature oscillates from warm (26 March: end of summer), to cool (11 July: winter) and back to warm conditions (22 October). Thus, indoor and outdoor temperatures were compared simultaneously 105 days before (26 March 2018–11 July 2018), and 105 after (11 July 2018–25 October 2018) the green roof was set up (11 July).

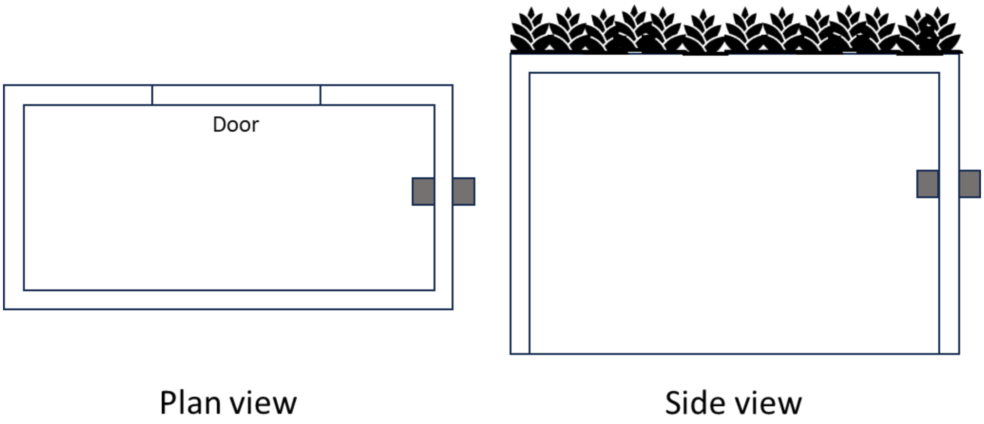

Figure 2. Depot view and position of the data loggers (grey squares).

3. Results

Figure 2 shows the indoor (blue) and outdoor (orange) temperatures, as well as the simultaneous temperature differences (the yellow line) between these two environments before, and after, the green roof setup (grey line—11 July 2018). In general, compared to external outdoor temperatures, indoor temperatures shifted downwards after the green roof was set up. However, it is important to highlight that apart from green roof intervention, lower temperatures were mostly observed during the day, and higher temperatures, were observed from the end of the afternoon to the beginning of the morning. The lower part of **Figure 3** shows this trend.

Regarding the differences between indoor and outdoor temperatures (the yellow line), positive values represent warmer indoor conditions, whereas negative values represent the opposite. In terms of daily average temperatures (dotted line), even though the indoor temperatures were slightly higher than the outdoor temperatures, the results indicated an improvement in thermal indoor conditions after the green roof set up. The initially higher indoor temperatures decreased after the installation of the vegetation, approaching the outdoor conditions, indicating the insulating properties of the green roofs.

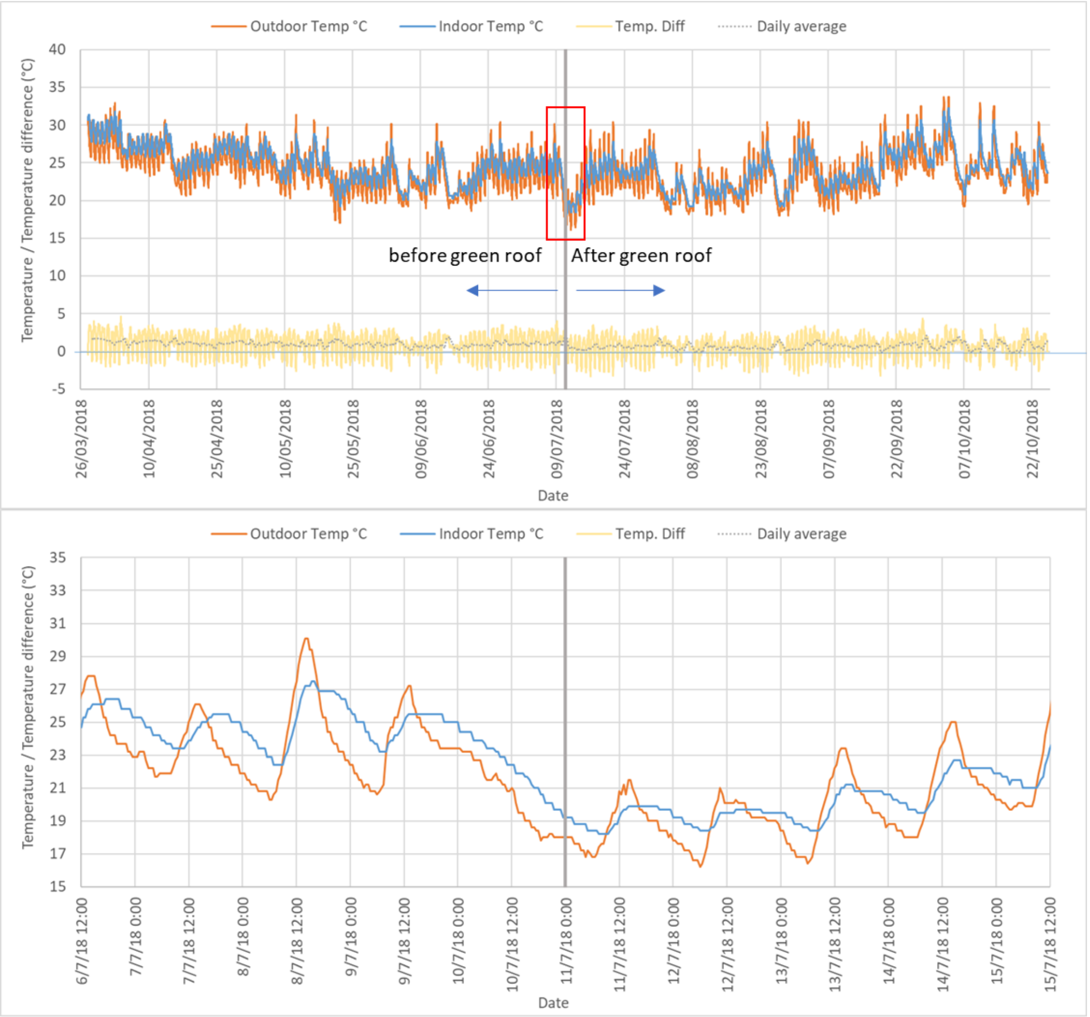

Figure 3. Indoor and outdoor temperatures before and after the green roof setup on the depot. The lower illustration details (red square on the upper picture) the differences between the temperatures.

The following histogram (**Figure 4**) presents a comparison between indoor and outdoor temperatures, before and after, the green roof was set. This figure classifies the temperature according to the frequencies of occurrence over each period of 105 days. For instance, 105 days before the green roof the indoor temperatures varied between 28 and 30 °C 8.2% of the time, and after the green roof set the temperatures in this range diminished to 4.2% of the time.

As shown in **Figure 4**, compared to outdoor temperatures, after the green roof set up the indoor temperatures shifted to the left towards lower temperature levels. While the higher number of occurrences remained on the same outdoor temperature (t) range (22 °C $< t \leq$ 24 °C), after the green roof setup the indoor temperatures decreased, shifting higher frequencies of temperature ranging from 24 °C $< t \leq$ 26 °C to 22 °C $< t \leq$ 24 °C. However, it is worth noting that for indoor and outdoor temperatures, it is evident that after the green roof was set up lower frequencies for higher temperature ranges are noticeable, since 83% of wintertime occurred after the green roof set up in this experiment.

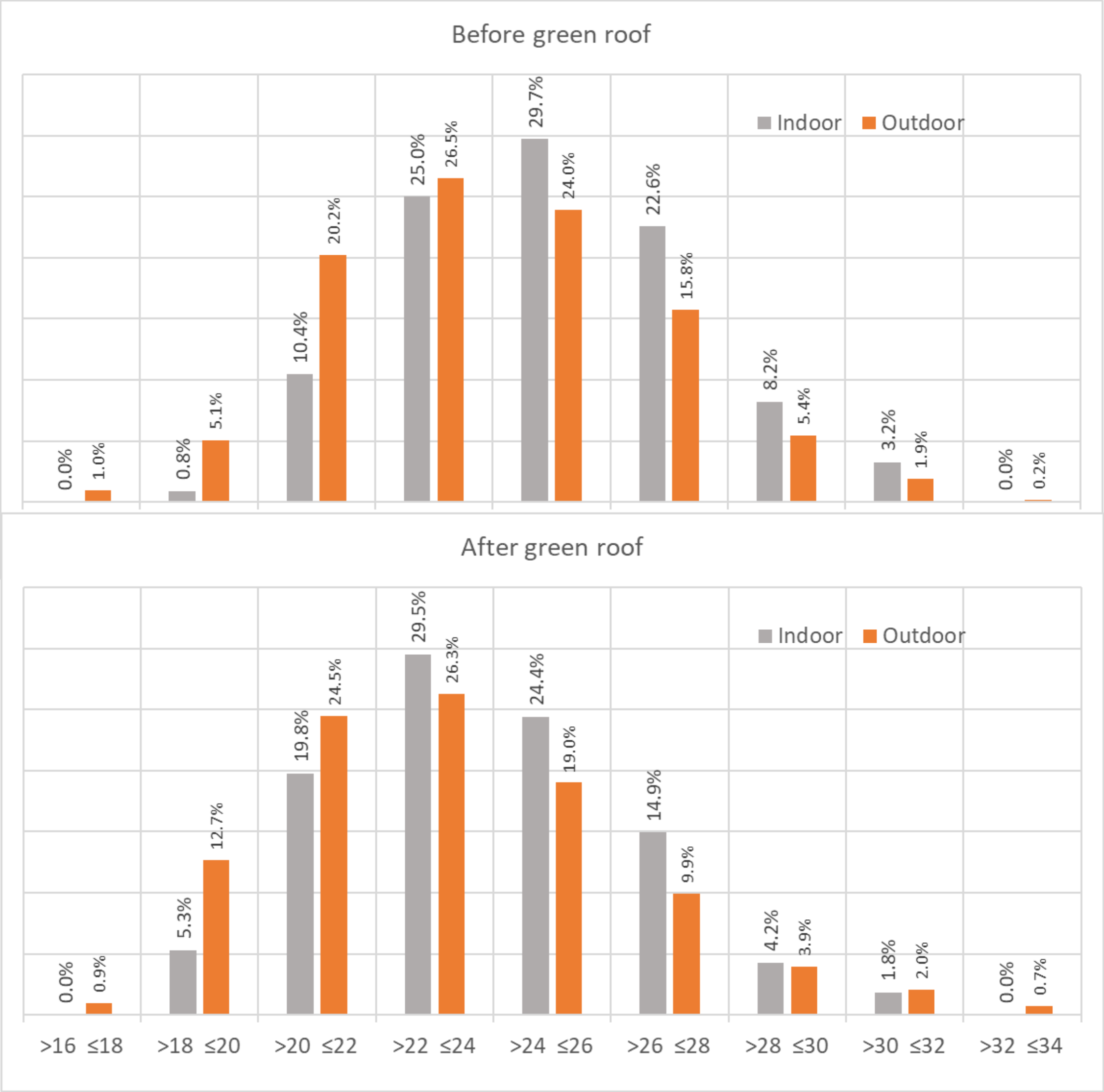

Figure 4. Histogram of indoor and outdoor temperature ranges (in degrees Celsius) before and after the green roof setup.

Regarding the differences observed between indoor and outdoor temperatures, it is evident that the green roof set-up promoted cooler conditions in the indoor environment. **Figure 5** presents a histogram of these temperature differences, before and after the green roof setup, where positive differences comprise warmer indoor conditions, and negative differences comprise the opposite. In general, the temperature differences were substantially reduced. Extremes of warmer indoor conditions (3 ℃ to 4 ℃) were reduced from 3% to zero, whereas extremes of cooler conditions (−3 ℃ to −4 ℃) were created. Positive differences from 1 ℃ to 3 ℃ were reduced from 54% to 12% and negative differences of the same magnitude increased from 14% to 48%.

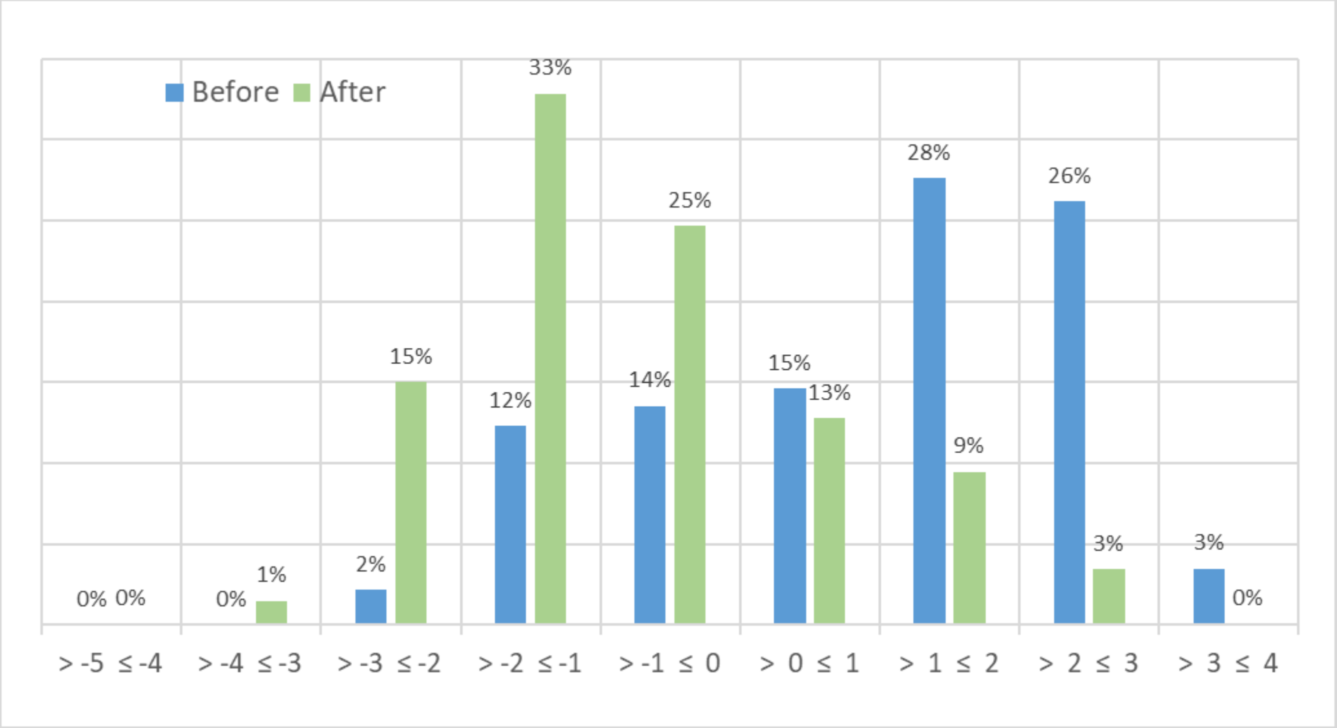

Figure 5. Histogram of temperature differences between indoor and outdoor environments, before and after the green roof setup.

In general, the green roof turned a warmer environment into a cooler environment. As shown in **Figure 6** before the green roof setup, the indoor temperatures were warmer 72% of the time, whereas after the setup the warmer indoor conditions reduced substantially to 25.8%. Neutral conditions, where temperature differences are negligible, increased from 2.9% to 4%, and cooler indoor temperatures increased from 25.2% to 70.1%.

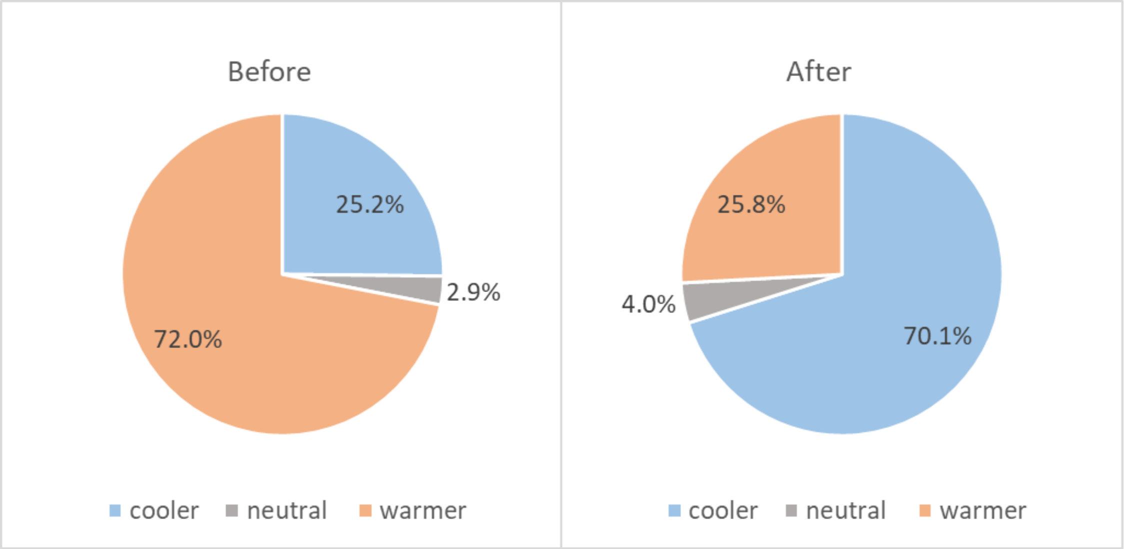

Figure 6. Summary of indoor conditions before and after the green roof setup.

4. Discussion

The results showed that the indoor conditions improved thermally after the green roof set up. Similar findings were observed by Parizotto and Lamberts [40] comparing green, ceramic, and metallic roofs. Several studies have established that green roofs can reduce indoor temperatures providing a significant improvement in thermal comfort [11,23,24,32,41–48].

As shown in **Figures 3** and **4**, the results concur with previous studies [10,12,49], indicating the insulation properties of green roofs, and their role in attenuating extreme temperatures. Green roofs improve thermal performance in buildings, increasing roof insulation. The positive and the negative differences, between indoor and outdoor temperatures before and after the green roof setup, indicate respectively the potential for gaining and avoiding heating loss. These results concur with experiments performed by dos Santos et al. [46]. Similarly, the positive differences commonly occur during the afternoon and the negative differences between the end of the day and the beginning of the next morning.

The results present a delay between indoor and outdoor temperatures, showing that green roofs provide inertia during rising and lowering temperatures, concurring with previous studies [7,29,46]. Besides insulation, green roofs promote thermal mass, absorbing and storing thermal energy, leading to a temperature delay [7,29]. The delay between indoor and outdoor temperatures leads to warmer indoor temperatures between the end of the afternoon and the early morning. As pointed out by dos Santos et al. [46], the heat is absorbed and stored in the soil during the day and released over the night, leading to a delay in the heat transfer process.

As shown in **Figure 5**, after the green roof installation, the indoor temperatures were reduced compared to outdoor temperatures. Comparing green to a conventional roof [20] observed a decrease of up to 3 °C in indoor temperatures. This reduction in indoor temperature occurs due to the solar attenuation by vegetation and by the thermal insulation properties of the green roofs [50]. The reduction in heat exchange in green roofs occurs not only due to the vegetation, that provides shading but also by the soil substrate. Even though soil moisture was not measured in the present study, the relation between air and water content in the soil plays an important role in the cooling properties of green roofs [7,8,12,13,17,18,49,51,52]. The thermal performance of green roofs is inversely proportional to the soil moisture content since water conducts heat better than air [13]. Similarly, higher heat transfer was observed for soils with higher water content [7,13,20,30]. Although air is a better insulator than water, is important to highlight that water promotes passive cooling through an evapotranspiration process. According to [51] under dry conditions, green roofs attenuated the heat flux into a building by 60%. However, in wetter conditions, the evapotranspiration processes are responsible for heat removal from the buildings. The soil water content plays an important role in heat loss when evapotranspiration is significant [7]. Despite the different behaviour from other plant species, evapotranspiration rates in succulents are significant in humid soil conditions. During drier conditions, the transpiration ceases, and the evapotranspiration equals evaporation [24,53].

As shown in **Figure 6**, the indoor conditions changed substantially compared to outdoor conditions, after the green roof set up, reverting mostly warmer conditions to cooler conditions, due to the combination of insulation and evaporative cooling processes. A similar trend was observed simulating the coverage of an existing rooftop in a building in Melbourne [8] and Sydney [48]—Australia, with vegetation. These results showed significant thermal improvements regarding the cooling effects of the green roofs. Other studies also revealed the cooling effects of green roofs. A reduction in the rooftop surface temperature up to 20 °C was observed after the green roof was set up in an existing building [19], resulting in an attenuation in heat influx and a decrease in the surrounding air temperature. Compared to a concrete rooftop, under high warm climate conditions, green roofs reduced internal roof surface temperatures up to 12.4 °C. Opposite, under cold conditions, the internal roof surface temperatures were warmer by up to 5.8 °C, indicating the efficiency in thermal regulation of the green roofs for damping influx and outflux of heat [16,29]. A similar observation is also evident in other Brazilian regions with similar climates to Rio de Janeiro, after the green roof installation in a garage building in Recife, Brazil [54].

In summary, green roofs have a significant impact on temperature attenuation improving indoor temperatures. Even though in the present study, the rooftop surface temperature has not been monitored, it is expected that the attenuation in indoor temperatures occurs exclusively by the substantial reduction in the temperature of the rooftop surface by shading, thermal insulation, and evapotranspiration. The higher the insulation, the lower the heat transfer and, the thermal conductivity. The heat transfer to the indoor environment was substantially reduced compared to a conventional roof. However, the heat transfer increased slightly for drier soil conditions, indicating the role of evapotranspiration in heat removal [14]. A damping in thermal conductivity led to warm indoor temperatures in cold episodes during the winter and cooler indoor temperatures during the summertime [15]. A compilation of several studies, listing the most common properties of the green roofs in different climates indicated significant surface temperature reduction highlighting the effects of insulation, evapotranspiration, and heat flux [12,47,52,55]. Thus, the results concur with several studies presented in the literature [29,33,35,56], showing the green roof's potential to attenuate indoor temperatures. Similar measures of green roof retrofit considering removable modules with lightweight characteristics can be adopted in existing buildings, improving indoor temperatures.

5. Conclusion

Green roofs are not simply just an aesthetic design option. More than that, they contribute to improving health conditions in the urban environment, isolating thermally hot human-made surfaces and providing evapotranspiration to places with a lack of green areas.

This study intended to evaluate the improvement of indoor conditions after the establishment of vegetation on the roof of an existing depot using a modular and inexpensive homemade solution as garden beds. Compared to outdoor temperatures, the attenuation in indoor temperatures after the green roof setup was significant. Even though the indoor temperatures were higher from the end of the afternoon to the early morning, the indoor temperatures shifted downwards after the establishment of the vegetation on the rooftop of an existing depot, lowering the differences between indoor and outdoor temperatures. Statistically, after the green roof setup, the mode of the indoor temperatures decreased by approximately 2 ℃, whereas the outdoor temperatures remained in the same range. The differences between indoor and outdoor temperatures changed substantially. Higher frequencies of warmer indoor conditions from 1 ℃ to 2 ℃, turned into higher frequencies of cooler indoor conditions of the same magnitude. In general, mostly warmer indoor conditions were converted to cooler temperatures when compared to the outdoor environment, thereby showing the green roof's potential to attenuate the heat exchange and improve indoor conditions, due to its thermal properties that provide insulation, evapotranspiration, and shading.

The application of green roofs can contribute to mitigating the energy demand for cooling during warmer months and warming during cooler months. Due to insulation, evapotranspiration and shading, green roofs can also contribute to improving the conditions of outdoor environments, reducing air temperature and attenuating urban heat islands.

Modular systems provide facilities to apply green roofs on a city scale since it comprises a low-cost alternative and easy maintenance. The use of succulent plants, characterized by drought resistance, minimizes working labour for conservation activities and water supply for watering. The methodology presented in this study gathers a homemade lightweight, affordable and inexpensive solution for modular green roofs offering a path to widespread the use of green roofs in urban areas. The adoption of green roofs on a large scale can positively influence human conditions, contributing to turning city centres into healthier and sustainable environments.

Author contributions: Conceptualization, RCF and SW; methodology, RCF; validation, RCF; formal analysis, RCF; investigation, RCF and SW; data curation, RCF; writing—original draft preparation, RCF; writing—review and editing, RCF

and SW; visualization, RCF; supervision, RCF; project administration, RCF. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Heaviside C, Macintyre H, Vardoulakis S. The Urban Heat Island: Implications for Health in a Changing Environment. Current Environmental Health Reports. 2017; 4(3): 296–305. doi: 10.1007/s40572-017-0150-3
2. Gronlund CJ, Zanobetti A, Schwartz JD, et al. Heat, Heat Waves, and Hospital Admissions among the Elderly in the United States, 1992–2006. Environmental Health Perspectives. 2014; 122(11): 1187–1192. doi: 10.1289/ehp.1206132
3. Hondula DM, Barnett AG. Heat-Related Morbidity in Brisbane, Australia: Spatial Variation and Area-Level Predictors. Environmental Health Perspectives. 2014; 122(8): 831–836. doi: 10.1289/ehp.1307496
4. Ye X, Wolff R, Yu W, et al. Ambient Temperature and Morbidity: A Review of Epidemiological Evidence. Environmental Health Perspectives. 2012; 120(1): 19–28. doi: 10.1289/ehp.1003198
5. Susca T, Gaffin SR, Dell'Osso GR. Positive effects of vegetation: Urban heat island and green roofs. Environmental Pollution. 2011; 159(8–9): 2119–2126. doi: 10.1016/j.envpol.2011.03.007
6. Herrera-Gomez SS, Quevedo-Nolasco A, Pérez-Urrestarazu L. The role of green roofs in climate change mitigation. A case study in Seville (Spain). Building and Environment. 2017; 123: 575–584. doi: 10.1016/j.buildenv.2017.07.036
7. Castleton HF, Stovin V, Beck SBM, et al. Green roofs; building energy savings and the potential for retrofit. Energy and Buildings. 2010; 42(10): 1582–1591. doi: 10.1016/j.enbuild.2010.05.004
8. Jamei E, Thirunavukkarasu G, Chau HW, et al. Investigating the cooling effect of a green roof in Melbourne. Building and Environment. 2023; 246: 110965. doi: 10.1016/j.buildenv.2023.110965
9. Adilkhanova I, Santamouris M, Yun GY. Green roofs save energy in cities and fight regional climate change. Nature Cities. 2024; 1(3): 238–249. doi: 10.1038/s44284-024-00035-7
10. Solcerova A, van de Ven F, Wang M, et al. Do green roofs cool the air? Building and Environment. 2017; 111: 249–255. doi: 10.1016/j.buildenv.2016.10.021
11. Pastore L, Corrao R, Heiselberg PK. The effects of vegetation on indoor thermal comfort: The application of a multi-scale simulation methodology on a residential neighborhood renovation case study. Energy and Buildings. 2017; 146: 1–11. doi: 10.1016/j.enbuild.2017.04.022
12. Ouldboukhitine SE, Belarbi R, Djedjig R. Characterization of green roof components: Measurements of thermal and hydrological properties. Building and Environment. 2012; 56: 78–85. doi: 10.1016/j.buildenv.2012.02.024
13. Alcazar S, Bass B. Energy performance of green roofs in a multi storey residential building in Madrid. Greening Rooftops for Sustainable Communities. Washington DC; 2005.
14. Zheng X, Yang Z, Yang J, et al. An experimental study on the thermal and energy performance of self-sustaining green roofs under severe drought conditions in summer. Energy and Buildings. 2022; 261: 111953. doi: 10.1016/j.enbuild.2022.111953
15. Wei T, Jim CY, Chen Y, et al. Complementary influence of green-roof and roof-slab thermal conductivity on winter indoor warming assessed by finite element analysis. Energy Reports. 2022; 8: 14852–14864. doi: 10.1016/j.egyr.2022.11.019
16. López-Silva DV, Méndez-Alonzo R, Sauceda-Carvajal D, et al. Experimental comparison of two extensive green roof designs in Northwest Mexico. Building and Environment. 2022; 226: 109722. doi: 10.1016/j.buildenv.2022.109722
17. Saifi N, Belatrache D, Dadamoussa A, et al. Effects of green roofs and vertical greenery systems on building thermal comfort in dry climates: an experimental study. Journal of Building Pathology and Rehabilitation. 2023; 8(1). doi: 10.1007/s41024-023-00282-6
18. Borràs JG, Lerma C, Mas Á, et al. Energy Efficiency Evaluation of Green Roofs as an Intervention Strategy in Residential Buildings in the Field of Spanish Climate. Buildings. 2022; 12(7): 959. doi: 10.3390/buildings12070959
19. Fleck R, Gill RL, Saadeh S, et al. Urban green roofs to manage rooftop microclimates: A case study from Sydney, Australia. Building and Environment. 2022; 209: 108673. doi: 10.1016/j.buildenv.2021.108673
20. Niachou A, Papakonstantinou K, Santamouris M, et al. Analysis of the green roof thermal properties and investigation of its energy performance. Energy Build. 2001; 33: 719–29.
21. Aboelata A, Sodoudi S. Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo. Building and Environment. 2019; 166: 106407. doi: 10.1016/j.buildenv.2019.106407

22. Bevilacqua P, Mazzeo D, Arcuri N. Thermal inertia assessment of an experimental extensive green roof in summer conditions. Building and Environment. 2018; 131: 264–276. doi: 10.1016/j.buildenv.2017.11.033
23. Chowdhury S, Hamada Y, Shabbir Ahmed K. Indoor heat stress and cooling energy comparison between green roof (GR) and non-green roof (n-GR) by simulations for labor intensive factories in the tropics. International Journal of Sustainable Built Environment. 2017; 6(2): 449–462. doi: 10.1016/j.ijsbe.2017.09.001
24. Lin YJ, Lin HT. Thermal performance of different planting substrates and irrigation frequencies in extensive tropical rooftop greeneries. Building and Environment. 2011; 46(2): 345–355. doi: 10.1016/j.buildenv.2010.07.027
25. Fang CF. Evaluating the thermal reduction effect of plant layers on rooftops. Energy and Buildings. 2008; 40(6): 1048–1052. doi: 10.1016/j.enbuild.2007.06.007
26. Collins S, Kuoppamäki K, Kotze DJ, et al. Thermal behavior of green roofs under Nordic winter conditions. Building and Environment. 2017; 122: 206–214. doi: 10.1016/j.buildenv.2017.06.020
27. Morakinyo TE, Dahanayake KWDKalaniC, Ng E, et al. Temperature and cooling demand reduction by green-roof types in different climates and urban densities: A co-simulation parametric study. Energy and Buildings. 2017; 145: 226–237. doi: 10.1016/j.enbuild.2017.03.066
28. Squier M, Davidson CI. Heat flux and seasonal thermal performance of an extensive green roof. Building and Environment. 2016; 107: 235–244. doi: 10.1016/j.buildenv.2016.07.025
29. Ouldboukhitine SE, Belarbi R, Jaffal I, et al. Assessment of green roof thermal behavior: A coupled heat and mass transfer model. Building and Environment. 2011; 46(12): 2624–2631. doi: 10.1016/j.buildenv.2011.06.021
30. Wong NH, Cheong DKW, Yan H, et al. The effects of rooftop garden on energy consumption of a commercial building in Singapore. Energy Build. 2003; 35(4): 353–64.
31. Czemiel Berndtsson J. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering. 2010; 36(4): 351–360. doi: 10.1016/j.ecoleng.2009.12.014
32. Mihalakakou G, Souliotis M, Papadaki M, et al. Green roofs as a nature-based solution for improving urban sustainability: Progress and perspectives. Renewable and Sustainable Energy Reviews. 2023; 180: 113306. doi: 10.1016/j.rser.2023.113306
33. Galbrun L, Scerri L. Sound insulation of lightweight extensive green roofs. Building and Environment. 2017; 116: 130–139. doi: 10.1016/j.buildenv.2017.02.008
34. Kader SA, Spalevic V, Dudic B. Feasibility study for estimating optimal substrate parameters for sustainable green roof in Sri Lanka. Environment, Development and Sustainability. 2022; 26(1): 2507–2533. doi: 10.1007/s10668-022-02837-y
35. Arkar C, Domjan S, Medved S. Heat transfer in a lightweight extensive green roof under water-freezing conditions. Energy and Buildings. 2018; 167: 187–199. doi: 10.1016/j.enbuild.2018.02.056
36. Kostadinović D, Jovanović M, Bakić V, et al. Mitigation of urban particulate pollution using lightweight green roof system. Energy and Buildings. 2023; 293: 113203. doi: 10.1016/j.enbuild.2023.113203
37. Salvalai G, Marrone G, Maria Sesana M, et al. Lightweight extensive green roof for building renovation: Summer performance analysis and application in a living laboratory. Energy and Buildings. 2023; 298: 113589. doi: 10.1016/j.enbuild.2023.113589
38. Blanusa T, Vaz Monteiro MM, Fantozzi F, et al. Alternatives to Sedum on green roofs: Can broad leaf perennial plants offer better ‘cooling service’? Building and Environment. 2013; 59: 99–106. doi: 10.1016/j.buildenv.2012.08.011
39. Black CC, Barry C, Vickery H, et al. Crassulacean acid metabolism photosynthesis: “working the night shift”. Photosynthesis Research. 2003; 76.
40. Parizotto S, Lamberts R. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianópolis city, Southern Brazil. Energy and Buildings. 2011; 43(7): 1712–1722. doi: 10.1016/j.enbuild.2011.03.014
41. Yang W, Wang Z, Cui J, et al. Comparative study of the thermal performance of the novel green (planting) roofs against other existing roofs. Sustainable Cities and Society. 2015; 16: 1–12. doi: 10.1016/j.scs.2015.01.002
42. Wilkinson S, Feitosa RC, Kaga IT, et al. Evaluating the Thermal Performance of Retrofitted Lightweight Green Roofs and Walls in Sydney and Rio de Janeiro. Procedia Engineering. 2017; 180: 231–240. doi: 10.1016/j.proeng.2017.04.182
43. Cascone S, Catania F, Gagliano A, et al. A comprehensive study on green roof performance for retrofitting existing buildings. Building and Environment. 2018; 136: 227–239. doi: 10.1016/j.buildenv.2018.03.052
44. Castiglia Feitosa R, Wilkinson SJ. Small-scale experiments of seasonal heat stress attenuation through a combination of green roof and green walls. Journal of Cleaner Production. 2020; 250: 119443. doi: 10.1016/j.jclepro.2019.119443

45. Sangkakool T, Techato K, Zaman R, et al. Prospects of green roofs in urban Thailand—A multi-criteria decision analysis. Journal of Cleaner Production. 2018; 196: 400–410. doi: 10.1016/j.jclepro.2018.06.060
46. dos Santos SM, Silva JFF, dos Santos GC, et al. Integrating conventional and green roofs for mitigating thermal discomfort and water scarcity in urban areas. Journal of Cleaner Production. 2019; 219: 639–648. doi: 10.1016/j.jclepro.2019.01.068
47. Jamei E, Chau HW, Seyedmahmoudian M, et al. Review on the cooling potential of green roofs in different climates. Science of The Total Environment. 2021; 791: 148407. doi: 10.1016/j.scitotenv.2021.148407
48. Spagnolo J, de Dear R. A field study of thermal comfort in outdoor and semi-outdoor environments in subtropical Sydney Australia. Build Environ. 2003; 38(5): 721–738.
49. Hien Wong N, Chen Y, Leng Ong C, Sia A. Investigation of thermal beneÿts of rooftop garden in the tropical environment (Internet). Building and Environment. 2003; 38.
50. Fioretti R, Palla A, Lanza LG, et al. Green roof energy and water related performance in the Mediterranean climate. Building and Environment. 2010; 45(8): 1890–1904. doi: 10.1016/j.buildenv.2010.03.001
51. Lazzarin RM, Castellotti F, Busato F. Experimental measurements and numerical modelling of a green roof. Energy and Buildings. 2005; 37(12): 1260–1267. doi: 10.1016/j.enbuild.2005.02.001
52. Sun T, Bou-Zeid E, Ni GH. To irrigate or not to irrigate: Analysis of green roof performance via a vertically-resolved hygrothermal model. Building and Environment. 2014; 73: 127–137. doi: 10.1016/j.buildenv.2013.12.004
53. Zhao M, Tabares-Velasco PC, Srebric J, et al. Effects of plant and substrate selection on thermal performance of green roofs during the summer. Building and Environment. 2014; 78: 199–211. doi: 10.1016/j.buildenv.2014.02.011
54. Santana TC, Guiselini C, Montenegro AA de A, et al. Green roofs are effective in cooling and mitigating urban heat islands to improve human thermal comfort. Modeling Earth Systems and Environment. 2023; 9(4): 3985–3998. doi: 10.1007/s40808-023-01743-0
55. Li YY, Chung PR, Chen CY, et al. The Study on the Evaluation of Thermal Insulation Efficiency with Typical Plant Species of Roof Greenery in Kaohsiung. Procedia Engineering. 2017; 180: 252–260. doi: 10.1016/j.proeng.2017.04.184
56. Ayata T, Tabares-Velasco PC, Srebric J. An investigation of sensible heat fluxes at a green roof in a laboratory setup. Building and Environment. 2011; 46(9): 1851–1861. doi: 10.1016/j.buildenv.2011.03.006