# Influence of Leaf Area Index and Plant Height on Green Roof Carbon Footprint in Moroccan Residential Buildings in Hot Climates

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**Abstract.** Green roofs are a sustainable solution to reduce energy consumption and carbon footprints, especially in hot climates. This study investigates the influence of two key design parameters, Leaf Area Index (LAI) and plant height, on the thermal performance and carbon footprint of residential buildings in Morocco. Using advanced simulation techniques, the study evaluates the impact of these parameters on electricity consumption for heating and cooling. The results show that increasing LAI and plant height reduces cooling-related $CO_2$ emissions by up to 3.87%, with taller plants and denser vegetation improving shading and evapotranspiration. However, during heating days, these parameters increase $CO_2$ emissions by up to 13.12%, due to reduced solar heat gain. Annual $CO_2$ emissions are reduced by approximately 1.13% when green roofs with optimized vegetation are implemented. The findings highlight the need for season specific maintenance practices, such as watering green roofs during cooling seasons and trimming vegetation during heating seasons, to balance energy performance. This study provides practical recommendations for optimizing green roof designs to support Morocco's climate goals and sustainable urban development.

## 1 Introduction

Green roofs are increasingly recognized as a pivotal strategy for enhancing urban sustainability by mitigating the environmental challenges associated with urbanization, such as the urban heat island (UHI) effect, high energy consumption, and elevated greenhouse gas emissions [1]. In regions with hot climates, such as Morocco, these benefits are particularly significant due to the acute energy demands for cooling and the pressing need to reduce carbon footprints in residential buildings [2]. This study investigates the influence of key green roof design parameters, namely Leaf Area Index (LAI) and plant height, on the carbon footprint of residential buildings in Moroccan hot climates.

### 1.1 Rationale and goals

Morocco's ambitious climate goals, as outlined in its Nationally Determined Contributions (NDCs) under the Paris Agreement, include reducing greenhouse gas emissions and increasing energy efficiency in buildings [3]. Green roofs offer a promising solution to achieve these objectives by providing thermal insulation, enhancing energy efficiency, and acting as carbon sinks. However, the performance of green roofs depends significantly on their design parameters, such as the type of vegetation, substrate thickness, LAI, and plant height [4], [5].

The rationale for this study stems from the need to quantify the energy performance of green roofs in Moroccan residential buildings, explore the role of Leaf Area Index (LAI) and plant height in reducing energy demands and carbon emissions, and provide region-specific recommendations to optimize green roof designs for hot climates. This research seeks to address the existing knowledge gap regarding the interplay of these parameters under hot climate conditions and aims to inform and support sustainable building practices in Morocco and similar regions.

### 1.2 Literature review

The integration of green roofs into urban landscapes has been widely studied, with research highlighting their ability to reduce energy demands, mitigate UHI effects, and sequester carbon. According to Sailor (2008), green roofs can reduce the cooling load of buildings by 25-50%, depending on the vegetation and substrate properties [6]. Similarly, Berardi et al. (2014) emphasized that vegetation type and maintenance play a critical role in determining the overall energy savings and carbon offset potential [1].

Leaf Area Index (LAI), which represents the leaf surface area per unit ground area, is a crucial factor influencing the shading and evapotranspiration capacity of green roofs. Studies by Getter and Rowe (2006) demonstrated that green roofs with higher LAI exhibit

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better thermal performance due to enhanced shading and reduced heat flux [7].

Furthermore, plant height contributes to the microclimatic modification potential of green roofs by influencing airflow and the depth of shading. While most studies have focused on temperate climates, research specific to hot climates remains limited. For instance, Ascione et al. (2013) explored the performance of green roofs in Mediterranean climates but did not extensively analyze the individual effects of LAI and plant height [8]. Lambarki et al. (2024) reported that extensive green roofs in Nador, Morocco, lowered mean radiant temperatures by 3–8.76°C on 60% of rooftops, resulting in a 17.53–43.82% reduction in air conditioning energy consumption. This translated to savings of $1.63–$4.07 million, despite the high initial investment of $84.44 million [9]. In the Moroccan context, there is a lack of detailed studies examining how these parameters can be optimized for maximum energy savings and carbon footprint reduction.

This paper builds on the existing literature by focusing on the unique climatic conditions of Morocco and providing empirical insights into how LAI and plant height affect the carbon footprint of residential buildings in hot climates.

## 2 Methodology

### 2.1 Climatic conditions

The study focuses on Marrakesh, Morocco, a city characterized by a hot semi-arid climate. The climatic conditions, characterized by significant seasonal variations in temperature and solar radiation as illustrated in [Fig. 1,2], are crucial for assessing the performance of green roofs.

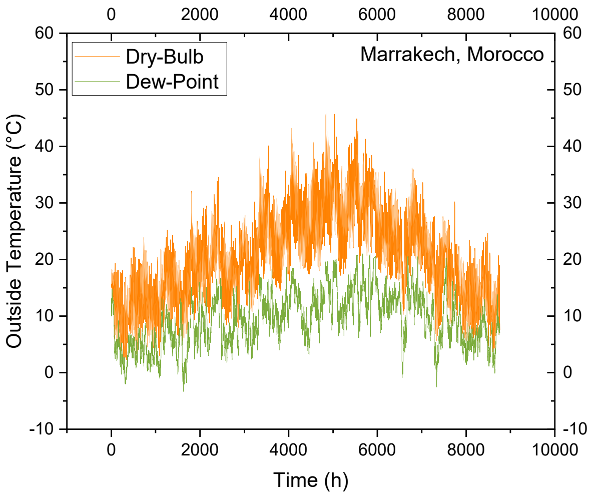


**Fig. 1.** Temperature throughout the year in Marrakesh.

This wide temperature range highlights the need for building solutions that can provide thermal regulation throughout the year. Peak solar radiation occurs during the summer months, contributing to increased cooling loads for buildings. The high levels of solar insolation make Marrakesh an ideal location to evaluate the potential of green roofs to mitigate thermal gains and reduce energy consumption.

This study utilizes meteorological data obtained from Meteonorm software, including hourly temperature profiles, solar radiation levels, humidity, and wind speed. This data provides a robust foundation for evaluating the performance of green roofs under local climatic conditions.

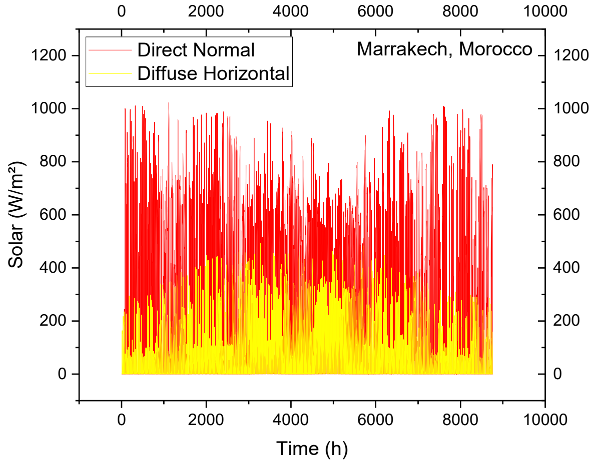


**Fig. 2.** Solar radiation throughout the year in Marrakesh.

### 2.2 Case study building

The typical residential building structure used in this study is consolidated in [Tab. 1], which outlines key construction elements, including the roof, walls, floors, ground, and glazing. The building envelope is designed to balance insulation and natural light, with a focus on thermal performance and energy efficiency as showing in [Fig. 3]. This overview serves as the basis for analyzing the thermal characteristics of the structure.

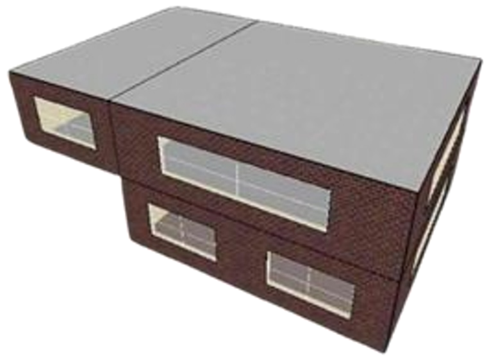

**Fig. 3.** Three-dimensional of typical residential building.

**Table 1.** Overview of typical residential building structure.

| Constructions | Area (m²) | U-value (W/m². K) |
|---|---|---|
| Roof | 140,2 | 0,621 |
| Wall | 182,3 | 0,732 |
| Floor | 46,1 + 94,1 | 0,685 |
| Ground | 92,2 | 0,685 |
| Glazing | 78,1 | 1,96 |

This detailed parameterization provides a comprehensive basis for evaluating the EcoRoof's impact on building energy efficiency and thermal behavior as detailed in [Tab. 2].

**Table 2.** EcoRoof properties and parameters.

| Soil surface | Plant surfaces |
|---|---|
| Force thickness: 0.3048 m | Height of plants: 0.0100 m < H < 1.0000 m |
| Conductivity: 1.0000 W/m. K | Leaf Area Index: 0.0010 < LAI < 5.0000 |
| Specific heat: 1000 J/kg. K | Leaf reflectivity: 0.220 |
| Density: 1900.00 kg/m³ | Leaf emissivity: 0.950 |
| Vapor factor: 150 | Minimum stomatal resistance: 180 s/m |

As outlined in [Tab. 3], the overall activity status of the residential building examines key factors such as occupancy, heating, cooling, and ventilation. The schedule illustrates the dynamic changes in these parameters throughout the day, reflecting typical residential patterns, including periods of high and low activity. This structured analysis provides valuable insights into the building's energy performance and usage patterns.

**Table 3.** The activity status of the residential building.

| HVAC | Activity | Schedule |
|---|---|---|
| Occupancy | Density: 0,0229 people/m² | Until: 07:00, 1,<br>Until: 08:00, 0.5,<br>Until: 09:00, 0.25,<br>Until: 22:00, 0,<br>Until: 23:00, 0.25,<br>Until: 24:00, 0.75, |
| Heating | Setpoint: 20°C<br>CoP: 2.000 | Until: 09:00, 1,<br>Until: 20:00, 0.5,<br>Until: 24:00, 1, |
| Cooling | Setpoint: 26°C<br>CoP: 2.500 | Until: 09:00, 1,<br>Until: 20:00, 0,<br>Until: 24:00, 1, |
| Ventilation | Outside air:<br>3.000 ac/h | Until: 07:00, 1,<br>Until: 08:00, 0.5,<br>Until: 09:00, 0.25,<br>Until: 22:00, 0,<br>Until: 23:00, 0.25,<br>Until: 24:00, 0.75, |

In this study, the building's thermal modeling and the evaluation of green roof performance were conducted using DesignBuilder and EnergyPlus, following the same simulation methodology detailed in [5] . The simulation parameters, material characteristics, and physical models (such as the Conduction Transfer Function method and adaptive convection algorithms) were consistently applied to ensure the comparability and reliability of the results [10].

## 3 Results and discussions

Plant height and Leaf Area Index (LAI) both significantly influence the carbon footprint associated with heating and cooling energy demands, as illustrated in [Figs. 4,5,6, and 7]. Conversely, for heating days, taller plants lead to an increase of approximately 13.12% in the carbon footprint, and denser vegetation with higher LAI results in a smaller increase of about 3.17%.

The yearly $CO_2$ emissions from electricity consumption for heating and cooling show a clear reduction with the implementation of green roofs. For a roof without plants, the emissions are 2849.07 kg $CO_2$. Introducing plants with 1LAI reduces the emissions to 2841.58 kg $CO_2$, representing a decrease of approximately 0.26% compared to no plants. Increasing the vegetation density to 3LAI further reduces emissions to 2829.74 kg $CO_2$, which is approximately 0.68% lower than emissions with no plants. Adding taller plants with a height of 0.4H achieves the most significant reduction, bringing the emissions down to 2817.02 kg $CO_2$, a decrease of approximately 1.13% compared to no plants.

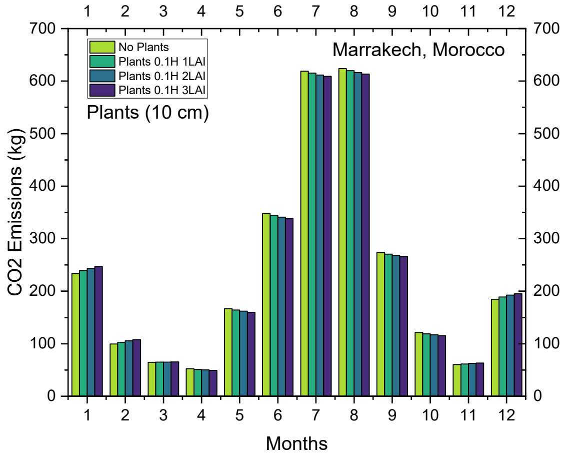


**Fig. 4.** $CO_2$ Emissions for 10 cm Plants with varying LAI.

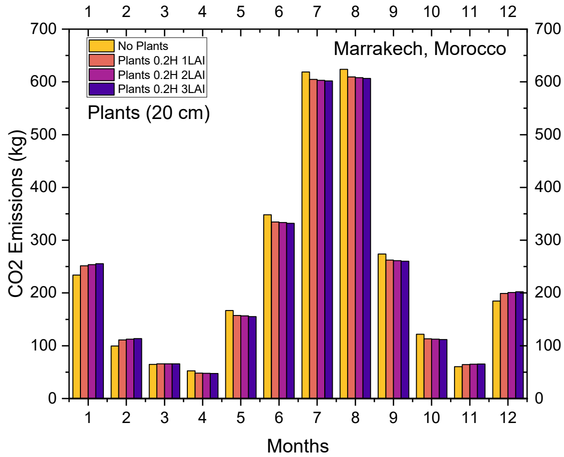


**Fig. 5.** $CO_2$ Emissions for 20 cm Plants with varying LAI.

The increase in heating-related $CO_2$ emissions with green roofs is due to reduced solar heat gain caused by shading, which increases reliance on heating systems. These reductions in cooling-related emissions are attributed to enhanced shading and evapotranspiration effects, which lower heat gain and cooling energy demand. This highlights the trade-offs in energy performance, emphasizing the need to optimize plant height and LAI to balance heating and cooling efficiency. Despite this trade-off, green roofs show significant potential to reduce the carbon footprint of buildings by lowering electricity consumption for heating and cooling, contributing to greater energy efficiency and sustainability.

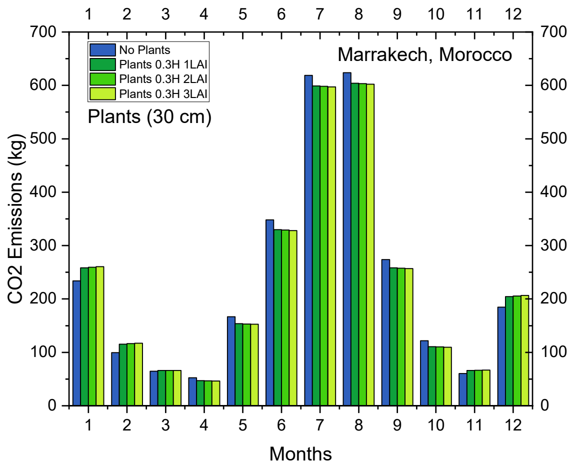


**Fig. 6.** $CO_2$ Emissions for 30 cm Plants with varying LAI.

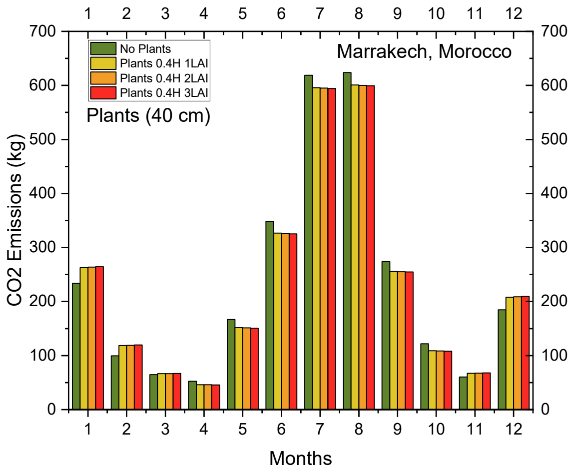


**Fig. 7.** $CO_2$ Emissions for 40 cm Plants with varying LAI.

Seasonal maintenance of green roofs is essential: watering during cooling periods enhances evapotranspiration, while trimming plants during heating periods increases solar heat gain. Additionally, integrating radiative sky cooling can passively reduce roof temperatures at night, further improving year-round energy performance [11].

## 4 Conclusion

This study highlights the significant potential of green roofs to improve energy efficiency and reduce the carbon footprint of residential buildings in hot climates like Morocco. The findings demonstrate that introducing plants with a 1 LAI reduces annual $CO_2$ emissions from electricity consumption for heating and cooling by approximately 0.26%, while increasing LAI to 3 achieves a reduction of 0.68%. Taller plants with a height of 0.4H lead to the most significant reduction, lowering emissions by 1.13% compared to a roof without plants.

For cooling days, plant height and LAI contribute to reductions in carbon footprint by 3.87% and 1.00%, respectively, through enhanced shading and evapotranspiration, which reduce cooling energy demand. Conversely, during heating days, taller plants increase the carbon footprint by 13.12%, and higher LAI results in a smaller increase of 3.17%, primarily due to reduced solar heat gain caused by shading.

These results underscore the importance of optimizing plant height and LAI and implementing seasonal maintenance practices, such as watering green roofs during cooling seasons and mowing vegetation during heating seasons, to balance energy performance. This study provides actionable recommendations to support Morocco's climate goals and sustainable building practices in hot climates, bridging a critical gap in green roof research.

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