Abstract: At present, the world is facing many hurdles due to the adverse effects of climate change and rapid urbanization. A lot of rural lands and villages are merged into cities by citizens, resulting in high carbon emission, especially in the built environment. Besides, the buildings and the construction sector are responsible for high levels of raw material consumption and around 40% of energy- and process-related emissions. Consequently, the interest in defining the carbon footprint of buildings and their components is on the rise. This study assesses the carbon footprint of a green roof in comparison to a conventional roof in a tropical climate with the aim of examining the potential carbon emission reduction by a green roof during its life cycle. A comparative case study analysis was carried out between an intensive green roof and a concrete flat roof located on two recently constructed commercial buildings in the Colombo district of Sri Lanka. Data were collected from interviews, project documents and past literature in addition to on-site data measurements and a comparison of life cycle carbon emissions of the two roof types was carried out. The results revealed that the operational phase has the highest contribution to the carbon footprint of both roof types. In the operational phase, the green roof was found to significantly reduce heat transfer by nearly 90% compared to the concrete flat roof and thereby contributed to an annual operational energy saving of 135.51 kWh/m². The results further revealed that the life cycle carbon emissions of the intensive green roof are 84.71% lower compared to the conventional concrete flat roof. Hence, this study concludes that the use of green roofs is a suitable alternative for tropical cities for improving the green environment with substantial potential for carbon emission reduction throughout the life cycle of a building.

Keywords: carbon emission; carbon footprint; energy consumption; green roofs; heat transfer; urbanization

1. Introduction

Rapid urbanization processes have resulted in many rural lands and villages being transformed into cities, particularly in developing countries around the world. This inadvertently has led to the damaging of green spaces and numerous other problems due to the non-sustainable and inefficient use of urban systems, including carbon emissions [1].

The world population living in urban areas is expected to increase from 55% (at present) to 68% by the year 2050 [2]. Furthermore, urbanization combined with the growth of the world population would add another 2.5 billion people to urban areas by 2050 [2]. Nearly 90% of this increase is happening in Asia and Africa [2]. With these increments, Sri Lanka, as an Asian country, will have to face several environmental devastations and issues including the high emission of carbon in the building sector. The buildings and construction sector consumes around 40% of global raw materials and contributes to 40–50% of greenhouse gas emissions [3]. Thus, decarbonizing and reducing emissions in the buildings and construction sector is critical to achieving the Paris Agreement commitments and the United Nations (UN) Sustainable Developments Goals (SDGs).

The green roof is one of the design solutions currently utilized to mitigate environmental extremes within the built environment [4]. A green roof involves a layer of vegetation or
greenery planted over a waterproofing membrane on top of the roof of a building [5]. They fall into three main categories: extensive, intensive, and semi-intensive (refer Section 2.1). There are several social, environmental, and economic benefits to green roofing, such as providing an attractive aesthetic appearance to urban areas [5], reducing heat, improving natural air quality, and improving weather in urban areas [1]. Despite these benefits, various aspects of green roofing, including assessing the direct energy savings and mitigated environmental impacts, still remain largely undetermined [6].

Research carried out by [7] in Wuxi, China, where the climatic conditions vary between a hot summer and cold winter, has found that a per unit area of a green roof can have a saving of 11.53 kWh energy per year and an annual carbon emission reduction of 9.35 kg m\(^{-2}\). The authors further noted that the green roof had a significant energy-saving effect in summer than in winter [7]. This study, however, incorporated an extensive-type green roof, and hence the applicability of these results to other types of green roofs is questionable. Similarly, [8] have quantified the energy savings of different types of green roofs in the Mediterranean climate for both heating and cooling seasons using a numerical model. The study carried out in Lisbon, Portugal found that intensive and semi-intensive green roofs demand significantly less energy than extensive green roofs, with extensive green roofs requiring approximately three times more energy (per year and square meter) than the intensive roof and two times more energy than the semi-intensive roofs [8]. Subsequently, the energy performance of each type of green roof was compared to conventional roof solutions (i.e., black roofs and white roofs). When compared to a black roof, the intensive green roof was found to use 45–70% less energy while comparison to a white roof accounted for 25–60% energy saving [8].

A study in Tokyo, Japan evaluating carbon dioxide reductions of green roofing found that the carbon reduction effect is proportional to the greenery area [9]. The carbon reduction was recorded as 2.93 kg CO\(_2\)/day when the roof was 100% covered in greenery while the emission reduction fell to 1.47 kg CO\(_2\)/day when the roof was 50% covered in greenery [9]. However, the focus of the study is generic in terms of the specific greenery types considered and its coverage area restricted its applicability and comparability to other contexts.

Contrary to the findings of the aforementioned studies, [10] found that the carbon emission of green roofs was higher than that of conventional roofs, based on a case study conducted in southern Brazil. The study calculated the carbon emissions per m\(^2\) for only the material production and transportation phases of two extensive-type green roofs located approximately 200 km away from each other. When comparing these results with two types of conventional roofing (i.e., ceramic-tiled roof and asbestos cement roof), the asbestos cement roof was found to have the best performance in terms of carbon emissions. According to the author, the transportation phase mainly contributed to this result and asserted that green roofs will take around 50–61 years to cover the carbon emissions made during the production and transportation phases through carbon sequestration [10].

The contrary nature of the findings of the aforementioned studies, along with their limitations, warrants the current study. As evidenced, most of the previous studies appear to have focused on the extensive type of green roofs whereas intensive green roofs are found to be more effective, particularly in terms of environmental performance [8,11]. Further, the environmental performance of green roofs is influenced by varying climatic conditions, as well as the construction methods and components used.

Relatively less attention has been given by researchers to exploring the suitability, applicability, and/or performance of green roofing in the Sri Lankan context. Being an island nation located within the tropics between 5\(^{°}\)55′ to 9\(^{°}\)51′ North latitude and between 79\(^{°}\)42′ to 81\(^{°}\)53′ East longitude, the climate of Sri Lanka could be characterized as tropical. The mean annual temperature of the country varies from 27 °C in the coastal lowlands to 16 °C in the central highlands (1900 m above mean sea level). The temperatures remain largely homogenous throughout the year with slight monthly variations caused by the seasonal movements of the sun and influences of rainfall. The mean annual rainfall varies
from under 900 mm in the driest parts (south-eastern and north-western) to over 5000 mm in the wettest parts (western slopes of the central highlands) of the country [12].

Research by [13] focused on the impacts of replacing existing flat slabs in Colombo city, Sri Lanka with green roofs. According to the authors, green roofs can play a major role in enhancing air quality and reducing the heat island effect, leading to higher levels of health and comfort for people living in cities.

Further, [14] examined the applicability of green roofs to Sri Lankan high-rise buildings. However, this study, which is limited to an opinion survey, did not take into consideration the different types of green roofs or focus on the assessment of benefits. On the other hand, studies such as [15–17] attempted to assess the benefits of green roofing by focusing on aspects such as life cycle costing, mitigation of the urban heat island effect, and thermal performance of green roofs in the local context. However, they still fall short in assessing the potential energy and carbon footprint reduction by green roofs in Sri Lanka. To fill this gap, the current study aims to assess the carbon footprint of an intensive green roof in comparison to a conventional roof.

This paper is organized into five main sections. Section 1 introduces green roofing and provides a clear background to the study. Section 2 provides a more in-depth review of the literature covering the concept of green roofing, its benefits, and carbon footprint. Section 3 explains the methodology adopted for the study including the specific data collection and analysis techniques used. The analysis and results of the study are presented in Section 4. Finally, a discussion of the study findings followed by the conclusions and practical implications of the study are presented.

2. Literature Review

2.1. Components and Types of Green Roofing

A green roof, also known as a living roof, can be simply identified as a rooftop that covers its surface with plants [4]. According to [18], a green roof can be considered as an engineered roof with vegetation planted on a substrate over a waterproofing layer. Even though a green roof incorporates certain components of conventional roofing such as roof decking, waterproofing, and an insulation layer, it is distinguished from traditional roofing due to its additional components [4]. These additional components include layers that protect the roofs from leakages, allow excess water drain, retain sufficient water to support the plants and vegetation, and prevent roots from penetrating the roof membrane [19]. Thus, a typical green roof consists of several layers, namely: plant/vegetation layer, growing medium/substrate, filter layer, drainage layer, protection layer, and waterproofing layer. Due to these additional components, green roofs can be constructed as an addition to conventional roofing, making it possible for existing roofs to be effectively reconstructed with green roofs [20].

Categorization of green roofs can be conducted based on several factors, such as growing medium thickness, application, vegetation type, layers, irrigation requirements, etc. [20,21]. Several researchers have identified that green roofs can be divided into two main categories, i.e., intensive and extensive green roofs [18,22]. Extensive green roofs have comparatively less thickness in their substrate and the additional weight to the structural load lies within the general loadbearing capacity of the structure. On the other hand, intensive green roofs are considered to be similar to roof gardens that people can access and enjoy [18]. Further, a semi-intensive type of green roof, which combines the features of both intensive and extensive systems, has also been identified [22].

2.2. Benefits and Limitations of Green Roofing

Typically, aesthetics, environment, and economic benefits are the main types of benefits highlighted by public and private parties in marketing green roofs among communities or target groups [18]. Some of the key benefits highlighted include:
- Pollution reduction: the growing medium and vegetation in green roofs can act as a natural cleaning filter, removing certain airborne particles and pollutants from the atmosphere [1,23].

- Energy saving and accrued cost-saving: green roofs can act as a heat-transfer-reduction method, resulting in lower energy requirements in buildings [21] in any climate, in either summer or winter [21]. According to [23], green roofs show a considerable reduction of air conditioning in summer and enough supplementation of insulation in winter. Further, the thermal protection of plants also contribute to thermal reduction (depending on their leaf area index), and in turn, energy savings [19].

- Psychological benefits: green roofs can enhance the aesthetic appearance of urban designs resulting in psychological benefits for communities [24]. The appearance of greenery or natural habitats can lead to stress reduction, positive thinking, decreased muscle tension, and lower blood pressure of individuals [18].

- Biodiversity and natural habitats: many natural habitats of species within and surrounding urban areas have been damaged or destroyed [1]. A well-designed green roof can mitigate these impacts and enhance existing habitats or even provide new habitats for both fauna and flora, resulting in increased biodiversity [21,25].

Likewise, green roofs are often regarded as an attractive solution for numerous issues in urban areas. However, there are certain constraints for green roofing implementation as well that need to be overcome [5]. Many of these constraints persist especially in developing countries where the government and policymakers do not understand or encourage the positive aspects of green roofs [26]. Moreover, high capital costs of construction, high maintenance costs, use of polymer materials, roof leakage problems, structural damages, and limited local research can be identified as other main limitations in the use of green roofs [5,26]. Indeed, according to [27], high initial cost and lack of awareness and knowledge are amongst the most significant barriers that discourage the application of green roofs.

Table 1 provides a summary of reviewed literature related to the benefits of green roofs. From the contents of Table 1, it appears that investigating the environmental performance and cost aspects of green roofs in different climatic conditions has received a high level of attention from researchers.

Table 1. Summary of previous studies on the benefits of green roofs.

| Type of Green Roof | Climate | Evaluated Benefits | Highlights/Remarks | Source |
|--------------------|---------|--------------------|--------------------|--------|
| Extensive          | Humid subtropical climate (Cfa) | Energy-saving and ecological benefits | 11.53 kWh saving per annum per unit area 9.35 kg m\(^{-2}\) annual CO\(_2\) reduction | [7] |
| Extensive, semi-intensive, intensive | Mediterranean hot summer climates (Csa) | Heating and cooling energy demands | Extensive green roofs required 3 times more energy than intensive ones and 2 times more energy than semi-intensive ones | [8] |
| Extensive          | Hot summer continental climates (Dwa) | Energy-saving | More than 44% energy savings and consumption reduction as cited in [7] | |
|                    | Tropical rainforest climate (Af) | Annual energy consumption, cost savings, roof thermal transfer | Energy consumption saving was converted into monetary units (1–15% savings) A significant reduction in peak heat transfer (81%) occurred in the rooftop garden with shrubs | [28] |
| Extensive          | Humid subtropical climate (Cfa) | Carbon dioxide emissions | CO\(_2\) emission of green roofs is larger than that of conventional roofs Only production and transportation phases were considered | [10] |
| Continuous extensive, modular extensive, continuous intensive | Tropical rainforest climate (Af) | Life cycle assessment for energy, greenhouse gas, and cost | Environmental performances of green roof systems depend on the typology and components used | [29] |
| Extensive, semi-intensive, intensive | Mediterranean hot summer climates (Csa) | Benefits associated with the installation of green roofs (majorly energy-saving and cost-saving) | Provides a review of the quantitative results obtained across the existing studies Less data availability on semi-intensive and intensive types | [11] |
2.3. Carbon Dioxide (CO$_2$) Emissions

Carbon footprint (CFP) is a measure of total greenhouse gases directly or indirectly emitted due to activity over the lifespan of a product, person, organization, city, or even a country [30]. It can include either all greenhouse gases expressed in tons of CO$_2$ equivalent or CO$_2$ only expressed in tons of CO$_2$ [30].

There are two main methods to calculate the CFP of a building, namely: (1) process-based method (bottom-up) and (2) economic input–output analysis method (top-down), which indirectly represent the micro and macro levels, respectively [31]. Under the process-based method, all the materials and energy used in the whole process are identified and emissions are measured, whereas the economic input–output analysis considers all the direct and indirect impacts involved in the supply chain [31]. The current study adopted the process-based method in order to obtain a more reliable result using high-level data, despite it requiring more time and resources. Further, the application of the input–output analysis method was restricted in this study due to the unavailability of required resource inputs and environmental output databases in the Sri Lankan context.

3. Materials and Methods

This study was conducted under three main phases: (1) A comprehensive literature synthesis on the concept of green roofing; (2) Preliminary interviews and site visits to gain a better understanding of the application of green roofs in Sri Lanka, where it is still a relatively new concept: (3) A comparative case study analysis between traditional and green roofing systems using life cycle carbon assessment. The cases were selected giving due considerations to aspects such as building location, service life, function, roof type, and roof area. Subsequently, an intensive-type green roof with an area of 426.56 m$^2$ located on top of a commercial building and a concrete flat roof with an area of 993.97 m$^2$ located on a building of similar functional type were selected as the two cases.

3.1. Profile of Selected Cases

An intensive green roof and a concrete flat roof located on two recently constructed commercial buildings were considered for the study. Both the sites were located in Ratmalana (6.8195° N, 79.8801° E) in the Colombo district. The area has a tropical climate. The average air temperatures vary from 25 °C to 32 °C (27.35 °C mean temperature) while the average total year rainfall varies between 2500 and 3000 mm. Most of the total rainfall is distributed from April to May and October to November. The average speed of wind in Ratmalana was 3.9 km/h in 2018 [12]. The two buildings were located approximately 250 m away from each other. Hence, the level of urbanization, climatic conditions, the intensity of sunshine, and exposure to the sun of the two types of roofs were similar in the two cases. Although there were minor differences in terms of other parameters such as the number of floors of the building and the service life of the roof types, the selected roofs can be generally considered comparable. The roof area of the selected conventional roof is more than double the size of the green roof. However, per unit area was considered in all the calculations and temperature measurements. The unit area for temperature measurements on both roofs was carefully positioned considering exposure to direct sunlight and avoiding disruptions due to surrounding boundary walls and trees, etc. Table 2 provides a basic profile of the selected cases.

The intensive green roof, which has been in operation since 2010, comprises several layers as illustrated in Figure 1. It is constructed on top of a reinforced concrete slab and consists of a waterproofing layer, a crushed rock layer, filter cloth, a sand layer, and a soil layer as the substrate of the vegetation layer. It acts as a habitat for nearly 30 different species of plants, trees, bushes, and grass of different sizes. The concrete flat roof includes only the typical layers of flat structural concrete slab and the waterproofing (Bituminous waterproofing sheet) layer on top of it.
Table 2. Profile of selected cases.

| Parameter                  | Intensive Green Roof | Concrete Flat Roof |
|----------------------------|----------------------|--------------------|
| Number of floors in the building | 4                    | 3                  |
| Service life (years)        | 9                    | 5                  |
| Roof area (m$^2$)           | 426.56               | 993.97             |
| Structure of the roof       | Reinforced concrete  | Reinforced concrete|
| Roof Layers (meters)        |                      |                    |
| Soil                       | 0.3683               | -                  |
| Sand                       | 0.0127               | -                  |
| Crushed rock               | 0.0762               | -                  |
| Reinforced Concrete         | 0.15                 | 0.2                |

Figure 1. Layers of the green roof.

3.2. Data Collection and Analysis

On-site temperature data measurements, drawings and specifications, and unstructured interviews with building owners and construction professionals were used to collect the required data for the life cycle carbon emission assessment. The details of materials such as soil, filter cloth, waterproofing, and transportation method of these materials and details of the fauna and flora in the vegetation layer were obtained from the owners of the buildings. Quantification of the carbon emission for the production, transportation, and construction stages was completed mainly based on the data collected from drawings, records, construction professionals, and previous related studies. Onsite temperature measurements were taken to assess the level of heat transfer through the roof in each building and to derive energy consumption during the operational phase. The temperatures in Sri Lanka remain largely homogenous throughout the year even though small variations can be caused by the seasonal movements of the sun and influences of rainfall during the periods April–May and October–November in the Colombo area. Accordingly, surface temperature measurements of the roofs were taken for 14 days intermittently during the months of July–August 2019, avoiding the rainy periods. As measuring equipment, an infrared thermometer and mini thermometer were used. Further, carbon emission factors related to the building phases were primarily extracted from the database of Inventory of Carbon and Energy [32] and the report published by the Sri Lanka Sustainable Energy Authority [33]. Other required carbon emission factors were obtained from secondary sources [34,35] as indicated under the respective tables. Table 3 summarizes the sources and the precise methods of data collection used in each stage.
Table 3. Main parameters and sources of data.

| Stage                  | Main Parameters                      | Source                          |
|------------------------|--------------------------------------|---------------------------------|
| Material production    | Materials and quantities             | Drawings, material recordings   |
|                       | Distance, vehicle type,              | Personal communication,         |
|                       | capacity of vehicle                  | technical Specification         |
| Material transportation| Construction activity, used machinery type | Personal communication,        |
|                       |                                     | Common industry practice        |
| On-site construction   | Electricity consumption              | On-site data measurement        |

Green roofs, especially the intensive types, are a recent development in Sri Lanka. Hence, their life spans are yet to be established in the local conditions. According to [11], the current green roof systems are expected to have an average service life of 40 years, although this may vary with the materials used and the application of techniques involved. However, the professionals (i.e., the structural engineer and the maintenance officer) involved in the construction and maintenance of the selected green roof were of the expectation that the green roof should undergo a major replacement or repair of its elements within 30–40 years. Having considered this, the analysis was carried out for 30 years of life span as the results are expected to be definite for the said period. The study used Equation (1) for the assessment of life cycle carbon emission of both roofs. Finally, a comparative analysis of life cycle carbon assessment was performed between the concrete flat roof and the green roof to determine the potential CFP reduction by an intensive green roof.

\[ C_{LC} = C_M + C_T + C_C + C_{O&M} + C_d \]  

\( C_{LC} \)—Total life cycle carbon emission  
\( C_M \)—Carbon emissions at material production  
\( C_T \)—Carbon emissions at material transportation  
\( C_C \)—Carbon emissions of on-site construction  
\( C_{O&M} \)—Carbon emissions at building operations and maintenance  
\( C_d \)—Carbon emissions at deconstruction

The scope of this study is limited to the carbon emission accruing from production, transportation, construction, and operational phases. Most importantly, the carbon sequestration during the photosynthesis process within the entire life of the green roof was excluded in this analysis due to time constraints. The effect of the latter on reducing the carbon emission level during the project life cycle is significant.

4. Results and Discussion
4.1. Calculation of Carbon Emissions in Production, Transportation, and Construction Phases of the Green Roof

This section presents the carbon emission of green roofs associated with the material production, transportation, and construction phases. The production phase involves carbon emissions in the production of all the materials used in each layer of green roofing, while the transportation phase includes the carbon emissions in transporting all those materials from the suppliers to the construction site. The construction phase includes all typical activities involved in the construction of the roof and the respective carbon emissions. The carbon emission factors respective to these three phases were extracted by referring to carbon emission databases. In addition, technical specifications and data from previous studies carried out in South Asian countries were considered in the absence of data for the local context.

4.1.1. Material Production Phase

This phase elaborates the carbon emissions due to the production of the materials. Therefore, it mainly focused on embodied carbon of the materials which were consumed in the roof construction. The green roof consists of certain organic materials which did not
go through any production process. Such materials were neglected during the analysis. However, the quantity of such organic materials was calculated along with the other materials by referring to drawings and material records. Table 4 presents the amount of each material consumed, the respective density values, and carbon emission factors. Using these data, the CFP of the production phase was calculated as given in Table 4.

Table 4. Carbon emission per m$^2$ of green roof area during the production phase.

| Material          | Area/Volume (m$^3$) | Density (kg/unit) | Mass (Kg) | * Carbon Emission Factor (kgCO$_2$/kg) | CO$_2$ Emission (kgCO$_2$) | CO$_2$ Emission per m$^2$ |
|-------------------|---------------------|-------------------|-----------|----------------------------------------|-----------------------------|---------------------------|
| Ready mix Concrete| 63.9                | 2400              | 153,563.0 | 0.2600                                 | 40,477.49                   | 94.89                     |
| Steel (R/F)       | -                   | -                 | 14,537.7  | 1.3100                                 | 19,044.43                   | 44.65                     |
| WP paint          | 426.6               | 2                 | 853.1     | 2.1200                                 | 1808.63                     | 4.24                      |
| Crushed rock      | 32.5                | 2240              | 72,809.3  | 0.0048                                 | 349.48                      | 0.81                      |
| Filter cloth      | 426.6               | 4.88              | 2081.6    | 6.26/m$^2$                             | 2670.29                     | 6.26                      |
| Sand              | 5.4                 | 2240              | 12,134.8  | 0.0048                                 | 58.25                       | 0.14                      |
| Soil              | 157.1               | 1460              | 229,370.0 | -                                      | -                           | -                         |

Carbon emission per m$^2$ of green roof (kgCO$_2$): 150.99

Sources—^ [36], * [32], # [37].

The comparison of percentage weight and embodied carbon for the major construction materials used in green roofs is illustrated in Figure 2.

![Figure 2. Percentage weights and carbon emissions per m$^2$ of green roof area.](image)

As shown in Figure 2, concrete, which is the main structural material, has the highest contribution of 62.8% (94.89 kgCO$_2$ per m$^2$ out of 150.99) to the total carbon emission of the green roof. Other materials significantly contributing to CFP during the production phase are reinforcement (29.57%), filter cloth (4.14%), and waterproofing paint (2.8%). In contrast, crushed rock (0.5%) and sand (0.09%) have the least contribution to carbon emission during the production phase, even though the quantity of crushed rock used (28.44%) (72.81 kg out of 256) is comparatively high. Hence, the selection of low-embodied carbon materials could further decrease CFP in the production phase.

4.1.2. Material Transportation Phase

The vehicle types used and their capacities were determined considering the current material transportation practices in Sri Lanka. In instances where exact distances traveled were unavailable, the average distances from the particular location of the factory/supplier to the site were taken as the distance of a one-way trip. A summary of the carbon emissions thus calculated during the material transportation stage is given in Table 5.
Table 5. Carbon emission per m² of green roof area during the transportation phase.

| Material          | Vehicle Type       | Trip(No) | One-Way Distance (km) | * Carbon Emission Factor (kgCO₂/km) | CO₂ Emission (kgCO₂) | CO₂ Emission per m² (kgCO₂) |
|-------------------|--------------------|----------|------------------------|-------------------------------------|---------------------|----------------------------|
| Ready mix Concrete| Transit mixture (5 m³) | 13       | 12.6                   | 1.099                               | 360.03              | 0.840                      |
| Steel (R/F)       | 20-ton trailer     | 1        | 17.4                   | 0.858                               | 29.86               | 0.070                      |
| WP Paint          | 8-ton truck        | 1        | 1.0                    | 0.241                               | 0.48                | 0.001                      |
| Sand              | 8-ton truck        | 2        | 5.1                    | 0.241                               | 4.92                | 0.012                      |
| Soil              | 20-ton truck       | 12       | 13.9                   | 0.777                               | 259.21              | 0.610                      |
| Filter Cloth      | 8-ton truck        | 1        | 15.0                   | 0.241                               | 7.23                | 0.016                      |
| Crushed rock      | 20-ton truck       | 4        | 16.9                   | 0.777                               | 105.05              | 0.246                      |

Carbon emission per m² of green roof (kgCO₂) 1.790

* Source—[34]. Note—number of trips = quantity of the material/capacity of the vehicle.

4.1.3. Construction Phase

In calculating carbon emissions during the construction phase, the typical construction activities of a roof were considered. The lifting, pouring, and compaction of concrete, rebar, and reinforcing, and soil lifting were considered as the construction activities which resulted in carbon emissions. Generally, the construction of a green roof involves activities such as soil laying and compaction. However, these activities were performed manually in the current study, resulting in no carbon emissions. Hence, these activities were not considered in calculating the CFP of the construction phase. Along with material quantity requirements already calculated under the production phase, the energy use rate and coefficient factors were used for the calculation of carbon emission for each activity. Technical specifications and secondary data were considered to extract the energy use rate. Further, the coefficient factor of fuel usage and electricity consumption were considered as 2.68 kg CO₂/L and 0.5845 kgCO₂/kwh, respectively [33,34]. Accordingly, Table 6 presents the calculation of carbon emissions during the construction stage.

Table 6. Carbon emission per m² of green roof area during the construction phase.

| Construction Activity | Material Quantity | * Energy Use Rate | Coefficient Factor | CO₂ Emission (kgCO₂) | CO₂ Emission per m² (kgCO₂) |
|-----------------------|-------------------|-------------------|--------------------|----------------------|----------------------------|
| Lifting and pouring   | 63.98 m³          | 0.770 L/m³        | 2.68 kgCO₂/L       | 132.04               | 0.310                      |
| concrete (pump car)   |                   |                   |                    |                      |                            |
| Compaction (vibrator) | 63.98 m³          | 0.210 L/m³        | 2.68 kgCO₂/L       | 36.01                | 0.080                      |
| Rebar and reinforcing | 14,537.73kg       | 0.002 kwh/kg      | 0.5845 kgCO₂/kwh   | 16.99                | 0.040                      |
| Lifting materials: soil | 229,370.83kg   | 0.003 kwh/kg      | 0.5845 kgCO₂/kwh   | 402.20               | 0.940                      |

Carbon emission per m² of green roof (kgCO₂) 1.376

* Sources—[34,35].

4.2. Calculation of Carbon Emissions in the Production, Transportation, and Construction Phases of the Concrete Flat Roof

As presented in Tables 4–6, a similar kind of approach and calculations were carried out to calculate the carbon emissions of the concrete flat roof. Accordingly, the carbon emission values obtained for production, transportation, and construction phases were 137.77 kgCO₂/m², 1.19 kgCO₂/m², and 0.56 kgCO₂/m², respectively. Thus, it was noted that carbon emissions from the production to construction phases were comparatively higher in the green roof than the concrete flat roof due to the additional materials (such as sand, soil, filter cloth, crushed rocks) used and the construction activities (such as soil lifting) associated with the green roof.
4.3. Calculation of the Carbon Emissions during the Operational Phase of the Green Roof and Concrete Flat Roof

On-site temperature measurements were obtained to determine the heat transfer and subsequent energy consumption savings of the building with the green roof. As primary data, surface temperature measurements of slab top and slab soffit of both the buildings were taken for 14 days, scattered over the period June–August 2019 using an Infrared (IR) Thermometer. These temperature measurements were taken thrice (03) a week, five (05) times a day from 0800 h to 1730 h for both the buildings. Since both the selected cases were commercial buildings, certain restrictions were placed by the management due to security concerns. Hence, it was not possible to take temperature measurements before 0800 h and after 1730 h and the duration and number of measurements that could be taken per day were also constrained. Non-air-conditioned areas were selected when measuring the temperatures of internal roof surfaces to avoid the cooling effects due to air conditioning. The mean temperatures were derived for slab top and slab soffit of both the buildings and they were found to be 33.62 °C and 30.27 °C, respectively, for the green roof and 41.93 °C and 32.7 °C, respectively, for the concrete flat roof. Figure 3 presents the average surface temperature differences of each roof over the 14-day period. The results revealed that the temperature difference is considerably low in green roofs almost every day irrespective of the weather conditions (weather conditions of the fifth, ninth, twelfth, and thirteenth days were cloudy and rainy) (See Figure 3).

![Figure 3. Average surface temperature differences.](image)

Afterward, the heat transfer through each roof was quantified by applying Equation (2) on heat loss. Heat loss indicates the heat transfer of an object to its ambient environment through conduction [38].

\[
Q = \frac{A(T2 - T1)}{\sum L/K}
\]

Source—[39].

- **Q** = Heat transfer (Watt)
- **K1, K2, K3** = Thermal conductivity of materials
- **A** = Considered Area
- **L1, L2, L3** = Thickness of material layers
- **T2** = Temperature of the outer face of the outside material layer
- **T1** = Temperature of the inner surface of the inside material layer
Table 7 summarizes the results of the heat transfer calculation. As the thermal conductivity of materials is an important property for this calculation, it was extracted from the material profiles of the Inventory of Carbon and Energy database. From the results, it appears that the green roof transfers less heat through its layers, thereby leading to several environmental, social, and economic benefits. The comparison of heat transfer levels in green roofs and concrete flat roofs shows that the green roof reduces heat transfer by 89.95%.

Table 7. Calculation of heat transfers per m² of roof area.

| Title 1                                      | Green Roof | Concrete Flat Roof |
|----------------------------------------------|------------|-------------------|
| Average slab top temperature (T2) (°C)       | 33.62      | 41.93             |
| Average slab soffit temperature (T1) (°C)    | 30.27      | 32.7              |
| Average difference (T2 – T1) (°C)            | 3.36       | 9.23              |
| * Thermal conductivity of materials (K) (Wm⁻¹ °C⁻¹) |            |                   |
| Concrete                                     | 1.7        | 1.7               |
| Soil (earth)                                 | 1.28       | -                 |
| Sand                                         | 1.74       | -                 |
| Crushed rock (aggregate)                     | 1.8        | -                 |
| Thickness of the layers (L) (m)              |            |                   |
| Concrete                                     | 0.15       | 0.2               |
| Soil (earth)                                 | 0.3683     | -                 |
| Sand                                         | 0.0127     | -                 |
| Crushed rock (aggregate)                     | 0.0762     | -                 |
| Σ L/K value (m² °C/W)                         | 0.43       | 0.12              |
| Heat transfer (Q) (W/m²)                     | 7.89       | 78.47             |

* Source—[32]: extracted from the material profiles.

It was assumed that the energy consumption of the roof in the operational phase is identical to the heat transfer through the roof. Therefore, the required energy for cooling the building (due to heat transfer through the roof) is equal to the heat transfer obtained in Table 7. Accordingly, the energy consumption per annum of both roofs was assessed to calculate the CFP of the roofs in the operational stage. Since both the buildings have similar functions, 5 working days per week with 8 h of electricity usage per day was assumed in the calculations given in Table 8.

Table 8. Carbon footprint per m² of roof area during the operational stage.

|                              | Green Roof | Concrete Flat Roof |
|------------------------------|------------|-------------------|
| Total energy consumption per day (Wh/m²) | 63.12      | 627.76            |
| Working days per month       | 20         | 20                |
| Energy consumption per month (kWh/m²) | 1.26       | 12.56             |
| Energy consumption per annum (kWh/m²) | 15.15      | 150.7             |
| Energy-saving by green roof per annum (kWh/m²) | 135.55 (150.7 – 15.15) |
| * Carbon emission factor from electricity generation in Sri Lanka (kgCO₂/kWh) | 0.5845     | 0.5845            |
| Carbon footprint (CFP) per annum (kgCO₂/m²) | 8.85       | 88.1              |
| CFP per m² for 30 years of operational life (kgCO₂) | 265.65     | 2641.8            |
| Carbon emission reduction per m² of roof area | 89.94%     |                   |

* Source—[33].

4.4. Calculation of the Life Cycle Carbon Emission

Life cycle carbon emission refers to the summation of the carbon emissions from each stage of the life cycle. Since the demolition and disposal stages were excluded from the scope of this life cycle assessment, the summation of each phase from material production to the end of the operational stage was considered in calculating the CFP.
The life cycle CFP was found to be 419.82 kgCO₂/m² for green roofs and 2781.32 kgCO₂/m² for concrete flat roofs as per the summary of carbon emissions presented in Table 9. Accordingly, total carbon emission from the green roof (roof area: 426.56 m²) for 30 years is calculated as 179.08 tCO₂, while the same for the concrete flat roof (roof area: 993.97 m²) is 2764.55 tCO₂. As per the results, the CFP per m² of the conventional roof is nearly six times higher than the CFP per m² of the green roof.

| Life Cycle Phase          | Carbon Emission per m² (kgCO₂) | Green Roof | Conventional Roof |
|---------------------------|---------------------------------|------------|-------------------|
| Material production       | 150.99                          | 137.77     |
| Material transportation   | 1.80                            | 1.19       |
| Construction              | 1.38                            | 0.56       |
| Operation                 | 265.65                          | 2642.81    |
| Total per m²              | 419.82                          | 2781.32    |

The critical stages of CFP have been identified separately in Figure 4 for each roof type. As shown in Figure 4, the operational and material production stages have accounted for 63% and 36%, respectively, of the carbon footprint of the green roof. However, in the case of the concrete flat roof, around 95% of the contribution to the CFP is made during the operational stage, whereas only 5% is made during the material production phase. The remaining stages have a very marginal impact on the CFP of the concrete flat roof. Therefore, as evidenced by Figure 4a,b, the operation stage has the highest impact on CFP in each roof type.

![Figure 4. (a) Carbon emissions from the building life cycle stages for the green roof; (b) Carbon emissions from the building life cycle stages for the concrete flat roof.](image)

4.5. Discussion

This study aimed to assess potential reductions in energy consumption and CFP by using green roofs in a local context. The lack of studies on the CFP of green roofs together with varying results obtained in previous studies based on different climatic conditions and roof types have encouraged the current study into a life cycle carbon assessment of an intensive-type green roof and a conventional concrete flat roof using a process-based carbon assessment method.

The current study revealed that low heat transfer through the green roof resulted in low energy consumption and thereby low carbon emissions during the operational phase when compared to the conventional roof. Consequently, the green roof was found to account for an energy saving of 135.5 kWh per m² of roof area per annum (i.e., a saving of 89.95% when compared to the concrete flat roof). This finding is different from some of the previous research findings [7,8]. For example, [8] found that an intensive green roof...
uses 45–70% and 25–60% less energy when compared to a black roof and a white roof, respectively, in the Mediterranean climate. This difference in findings could be attributed to the differences in climatic conditions as well as the types of conventional roofs used in the two studies. Further, [7] found that the average daily energy saving of a green roof in summer was 10.33% compared to a non-green roof. However, this was an experimental study where an extensive type of green roof and a non-green roof were constructed in the same location for the purpose of the research study. However, the current study findings can be considered to depict the actual practical usage of an intensive green roof in a commercial building in a tropical climatic context.

According to findings, the life cycle CFP of the green roof was found to be 14 kgCO$_2$ m$^{-2}$ per year whereas it was 92.7 kgCO$_2$ m$^{-2}$ per year for the concrete flat roof. Consequently, it was found that the annual CO$_2$ reduction by the green roof was 78.71 kgCO$_2$ m$^2$ per annum, which was a CFP reduction of 84.9%. This is in line with the findings of some previous studies [7,9]. Ref. [7] quantified that an extensive type of green roof can reduce CO$_2$ emissions by 9.35 kg m$^{-2}$ annually. However, this figure was derived based on average values for summer and winter in China, whereas no such seasonal climatic differences are applicable to Sri Lanka. Hence, the substantial CFP reduction in the current study could again be attributed to the differences in climatic conditions and the type of green roof studied.

On the other hand, [10] found that based on the assessment of carbon emissions during production and transportation phases, extensive green roofs make a significantly higher contribution to CFP than conventional roofs. The author further stated that green roofs may take 50–61 years to recover the carbon emissions made during the production and transportation phases through carbon sequestration. However, the author did not consider the operational phase, where the current study found substantial energy savings, leading to higher CFP reductions in the green roof when compared to a conventional roof. In fact, the current study reveals that only 36% and 1% of CFP are accounted for by the material production and transportation phases, respectively, in the case of the green roof, and that 63% of contribution to CFP happens during the operational phase.

In terms of the material production stage, [10] quantified the carbon emission of material production in two different extensive green roofs. The results revealed that the first roof had quantified emissions of 12.32 kgCO$_2$/m$^2$ (excluding concrete and reinforcement) whereas the second green roof had only 4.00 kgCO$_2$/m$^2$ of emissions. The current study results indicate 11.42 kgCO$_2$/m$^2$ (excluding concrete and reinforcement) of carbon emissions for an intensive green roof. The changes in the type and the quantities of materials used in the sub-layers of each green roof could lead to such differences in carbon emissions due to differences in the embodied energy levels of various materials. Hence, paying attention to using low embodied carbon materials during material selection will be helpful in reducing the CFP of the production phase.

5. Conclusions

This study focused on a comparative analysis of life cycle carbon emissions of an intensive green roof and a conventional concrete flat roof. It was found that the carbon emissions of a green roof during production, transportation, and construction phases are higher than those of the concrete flat roof. The increased CO$_2$ emissions of the green roof during these phases are attributed to the additional materials used in the green roof, which have undergone several production, transportation, and construction processes. However, findings revealed that during the operational phase, the CO$_2$ emissions of green roofs are nearly 90% less when compared to the conventional concrete flat roof. The green roof was found to have heat transfer reductions leading to energy consumption savings. It also resulted in reducing the discomfort of the occupants due to daytime heat, although this was not measured as part of this study. The study further concludes that the green roof was able to achieve nearly 85% of life cycle CFP reduction by saving 78.71 kg CO$_2$ m$^{-2}$ of CO$_2$ per annum. This CFP reduction could be further improved through the selection
of sustainable materials with low embodied carbon during the production stage, where the CFP of green roofs was found to be higher than the conventional roof. Therefore, this study provides a clear idea of the CFP of an intensive green roof during different life cycle stages. The study provides a comprehensive comparative assessment of the performance and potential benefits of an intensive green roof in terms of heat transfer, energy savings, and carbon emissions from a tropical climatic perspective. The authors thereby believe that the study will promote the effective and sustainable adoption of green roofs. It is further expected that these study findings will contribute to the wider knowledge base, leading to the enhanced use of green roofs in local as well as global contexts.

This study was limited to a single intensive type of green roof and fails to consider carbon sequestration during the photosynthesis process during the life of the green roof. Moreover, as discussed above, the level of CFP reduction and energy saving could also vary according to the type of green roof. Therefore, it is recommended that future studies be conducted to assess the CFP of other green roof types and to address the impact of carbon sequestration in green roofing to enhance the further adoption of green roofs.

Author Contributions: Conceptualization, M.N. and N.Z.; methodology, M.N., T.R. and N.Z.; formal analysis, M.N.; investigation, M.N. and T.R.; resources, N.Z.; data curation, M.N.; writing—original draft preparation, M.N.; writing—review and editing, N.Z., S.G. and T.R.; visualization, M.N.; supervision, N.Z., S.G. and T.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data available on request to the authors.

Acknowledgments: Authors greatly acknowledge the financial support given by the University of Moratuwa Senate Research Committee for the open access publishing.

Conflicts of Interest: The authors declare no conflict of interest.

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