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Investigating green roofs' CO_2 sequestration with cold- and drought-tolerant plants (A short- and long-term carbon footprint view)

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Abstract

In recent years, green roofs have become the subject of increasing interest because of their good aesthetic qualities, energy conservation, and ability to reduce thermal island effect and absorb greenhouse gases, especially carbon dioxide (CO_2). Given the typically significant carbon emission of construction activities, adding any extra component to a structure increases the amount of carbon to be released during the execution stage. This also applies to green roofs, which require more materials and more extensive construction activities than traditional roofs. However, plants of green roofs absorb substantial amounts of CO_2 during their lifetime, thus leaving both short- and long-term positive impacts on the building's carbon footprint. This study investigated the short- and long-term effects of green roofs on carbon footprint, as compared to conventional roofs. For this investigation, the CO_2 uptake of eight plant species with suitable drought- and cold-resistant properties was measured by Infrared Gas Analysis (IRGA) and the effect of green roof on the building's carbon footprint was analyzed using the software Design Builder. The results showed that building a green roof instead of a traditional roof increases the carbon emission of the construction process by 4.6 kilograms per square meter of roof area. Investigations showed that, under high light intensities (1500–2000 μmol/m^2.s), *Sedum acre L* has the best performance in compensating the extra carbon emission imposed on the construction process (in 264 days only). Under low light intensities (1000–1500 μmol/m^2.s), *Frankenia laevis* showed the best increase in the amount of carbon uptake (2.27 kg/m^2.year).

1. Introduction

With the continued use of fossil fuels in numerous industries and vehicles, there is a clear view of the impact of greenhouse gas emissions on the acceleration of climate change, as this phenomenon is having undeniable effects on the environment, society, and economy (González and Navarro 2006). Therefore, minimizing the emission of CO_2, as the most important greenhouse gas, is now a major subject of interest to many scholars of environmental studies, economics, and even politics (Fenner et al. 2018). Many construction activities, including the production and transportation of raw materials and the building operation itself, have a noticeably high carbon emission (Nadoushani and Akbarnezhad 2015). In addition, the building sector accounts for roughly 30% of the global CO_2 emission, and should, therefore, be given a high priority in the efforts to devise and develop sustainable solutions to reach an acceptable level of carbon emission (Jeong et al. 2012). One of these efforts is to promote the use of building materials with low environmental impacts. The roof, as one of the core components of all buildings, plays a key role on the transfer of energy between the interior and the exterior and therefore has a massive impact on the building's carbon footprint. The approach known as green roofs has many advantages over traditional roofs, including lower energy loss and higher energy retention in buildings, reduced thermal island effect, better stormwater management, longer lifespan, competitive return on investment, lower air and noise pollution, and the ability to create a more pleasant environment for residents (Takebayashi and Moriyama 2007; Carter and Jackson 2007; Sailor 2008). Research has shown that green roofs can reduce a building's cooling load in the summer by about 6% and lower its annual energy consumption by about 1% (Li and Yeung 2014). Given the ability of green roofs to reduce the energy consumption of buildings, the effective use of this structural element can be very helpful in decreasing the buildings' overall carbon footprint. In addition, the vegetation of these roofs can absorb CO_2 by photosynthesis, thereby reducing the amount of carbon released to the atmosphere.

Given the necessity of controlling carbon emissions, as the main cause of climate change, carbon footprint has been the subject of numerous studies. Li et al. (2010) studied the amount of CO_2 absorbed by green roofs using the Infrared Gas Analysis (IRGA) technique. In a study by Cole (1998) on the carbon footprint of building a concrete structure and related transportation activities, he reported that carbon footprint varies with the grade of concrete and the amount of reinforcement. In another study, Whittinghill et al. (2014) investigated the carbon sequestration rate of green roofs with Sedum plants for 12 and 14-month periods by measuring the amount of biomass found in the plant. Nadoushani and Akbarnezhad (2015) studied structures of different heights and with different lateral load resistance systems, and then examined their carbon footprint in different areas of construction, transportation, and energy consumption. Ondoño et al. (2016) studied nitrogen and carbon sequestration of green roofs with grass vegetation for a 9-month period by quantifying the element composition. In a study by Huang et al. (2017) on the carbon footprint of urban structures and the carbon emissions reduction potentials, they reported that the building sector is one of the main producers of greenhouse gases at the urban level and pointed out the necessity of having a comprehensive plan to reduce greenhouse gas emissions in the construction sector. In a case study carried out by Yang et al. (2018), they estimated the carbon footprint of a building by Building Information Modeling and Life Cycle Assessment. In another study, Collazo-Ortega et al. (2017) used the conventional IRGA method to measure CO_2 sequestration of green roof vegetation. A study by Fenner et al. (2018) on the carbon footprint of the construction industry stated that buildings are one of the primary sources of CO_2 production and that carbon footprint of buildings can be divided into three parts: construction, transportation, and energy consumption. Gamarra et al. (2018) studied the water use, energy use, and carbon footprint of a school in a hot and dry climate. They stated that schools have a high potential for energy savings and creating desirable environmental impacts in urban spaces.

It is a fact that green roofs can affect the climate at a micro scale (urban spaces) and have a positive impact on the carbon footprint of buildings, but so far these roofs have been mostly used to reduce energy loss and thermal islands effects, and there have been only a few studies on the effect of green roofs on the carbon footprint of buildings. In most studies, the amount of CO_2 sequestrated by a green roof has been measured and reported, while the amount of CO_2 emitted by green roof construction has been underestimated. It should be stressed that adding any new components to a building has an impact on the amount of carbon to be emitted during the construction process and this is also true for green roofs, which in fact require more materials than traditional roofs, both in the roofs themselves and in the underlying structure. However, the carbon sequestration that takes place during the growth of green roof vegetation will naturally have short- and long-term effects on the carbon footprint of the building. The purpose of this research was to (*i*) determine the amount of carbon released during green roofs as compared to conventional roofs and (*ii*) compare different green roofs suitable for dry and cold climates (similar to north-eastern Iran) in terms of carbon sequestration.

2. Materials And Methods

2.1. Study location

Iran has a variable climate that is generally temperate but frequently turns dry and cold. The average daytime maximum and minimum temperature across Iran is 24 and 2°C respectively. This country has also had a mean precipitation of 204.2 mm (Iran Meteorological Organization, 2019). According to the Master Plan, the total area of land allocated for construction is currently 70.7 million m^2. Based on the rule of Ministry of Roads and Urban Development, a residential structure cannot occupy (on average) more than 69% of the land parcel on which it sits, thus the total area of roofs must be calculated accordingly.

2.2. Materials

Since this study intends to investigate the effect of green roofs on the carbon footprint of buildings, the type of roof structure is of particular importance for this investigation. The analyses of this research were conducted for a residential building with an area of 160 m^2 that is located in Mashhad. The roof of this building was assumed to be flat and consist of four layers including (from top to bottom): (*i*) green roof, (*ii*) 0.01 m thick waterproofing layer, (*iii*) 0.25 m thick glass wool layer, (*iv*) 0.013 m thick structural support (plasterboard). Figure 1 schematically shows the layers of the whole roof, and the details of green roof layer.

Figure 1. Schematic composition of the green roof layer

The green roof itself, *i.e.* the outermost layer, was assumed to consist of vegetation, a 0.2 m thick layer of soil, and a drainage system. Given the dry climate of the area, the plants to be used in this green roof must exhibit good resistance to water stress. Glass wool is made of very fine glass fibers and is typically used in insulation. Table 1 shows the thermal conductivity, specific heat, and density of the different layers considered in the roof. The reasons for using these particular layers are: (*i*) the availability of these materials in the study area, (*ii*) the cold weather in winter, and (*iii*) energy loss prevention in both the cold and warm seasons.

Table 1
Physical characteristics of the layers considered for the roof
(Mirzababaie and Karrabi 2019)

Material	**Conductivity (w/m.k)**	**Specific heat (J/kg.k)**	**Density (kg/m^3)**
Green roof	Variable	Variable	Variable
Asphalt	0.7	1000	2100
MW glass wool	0.04	840	12
Air gap	0.3	1000	1000
Plaster board	0.25	896	2800

The plant species considered in green roofs are *Sedum acre L*, *Sedum spectabile Boreau*, *Frankenia laevis*, *Vinca major*, *Phyla nodiflora*, *Potentilla reptans*, *Carpobrotus edulis*, and *Aptenia cordifolia*. They were chosen because of their resistance to cold and water stress, which would be expected in the studied area (Weinstein 1999; Bird 2004; Rickard 2011). Plants used in the study were six-month-old seedlings grown in pots (18 cm wide, 25 cm deep) maintained in greenhouse conditions with 16 hours of daylight, 8 hours of darkness, and at a temperature of 22 ± 5°C. Plant height ranged from 15 to 20 cm. The growing media was composed of equal portions (by volume) of sand, compost, and native soil. The source of utilized compost was from landscape waste.

2.3. Methods

The effect of the green roof on carbon footprint was investigated using the software Design Builder v.5.5 (DBS company, UK), which is able to model the amount of carbon produced during construction with different materials based on the EnergyPlus software. The construction of a building with a green roof and without it (with a traditional roof) was simulated and the differences in results were examined to determine the additional resources needed to build the green roof. In general, there are three methods to quantify carbon emissions: (*i*) computing the embodied carbon alone, (*ii*) computing the quantities of six gases defined in the Kyoto Protocol, namely CO_2, methane, nitrogen oxide, sulfur hexafluoride, hydrofluorocarbon, perfluorocarbon, or the equivalent CO_2, (*iii*) measuring other gases specified by the Intergovernmental Panel on Climate Change (Chen et al. 2019; Xu et al. 2019).

Green roofs reduce the carbon emission in three ways: (*i*) the energy consumption by preventing energy loss during the warm and cold seasons, (*ii*) the heat island effect, and (*iii*) plant photosynthesis (Getter et al. 2009; Whittinghill et al. 2014). There are various methods to measure the amount of carbon absorbed by plants, including cumulative biomass measurement, oxygen-carbon balance model, and IRGA (measuring the amount of gas exchanged through leaves) (Yin et al. 2010; Whittinghill et al. 2014). In this research, the carbon footprint of the building with and without the green roof was quantified in two ways: the amount of CO_2 emitted and the equivalent CO_2 of non-CO_2 emissions. The amount of CO_2 absorbed was measured based on the daily photosynthetic amount of each plant using the LCA4 infrared gas analyzer (ADC Bioscientific Limited, UK). All the experiments were carried out in triplicate. One-way analysis of variance (ANOVA) at the confidance level of 95% was also fullfilled using the R software. After studying the intensity of solar radiation in Mashhad over a 25-year period according to the data collected from the Iranian Meteorological Organization, the light intensities of 1000, 1500 and 2000 $\mu mol/m^2.s$ were considered as the basis of IRGA.

3. Results And Discussion

3.1. Carbon produced during the construction of the green roof

According to the United States Environmental Protection Agency (US-EPA), the carbon footprint of construction activities will increase by adding any new materials in the construction phase of the buildings (EPA, 2018). Consequently, the implementation of green roofs as new components in the building and due to the manufacturing, transportation, and installation of various equipment increases the amount of CO_2 released. Table 2 shows the amount of CO_2 to be released during the construction of the considered building with either the green roof or a traditional roof, in both direct and equivalent formats.

Table 2
Carbon emissions due to the construction of the considered building with the green roof and with the conventional roof

Types of roof	Embodied carbon ($kg\ CO_2/m^2$)	Equivalent CO_2 ($kg\ CO_2/m^2$)
Traditional roof	19.61	20.72
Green roof	21.80	23.13
Difference	2.19	2.41

The results show that, because of the use of extra materials and equipment in the green roof (drainage system, soil layer, etc.), building this roof will increase the carbon footprint of the construction. Similar to the method used by previous studies, e.g. Nadoushani and Akbarnezhad (2015) and Mirzababaie and Karrabi (2019), in the present study, the embodied carbon term is related to the direct emission of CO_2 itself, but the other greenhouse gas emissions such as the methane were reported by their CO_2 equivalent amount. The difference between building the green roof and building a traditional roof in terms of direct CO_2 emission and equivalent CO_2 emission was calculated as respectively 2.19 kg/m^2 and 2.41 kg/m^2, which, if multiplied by the net area of the roof (143 m^2), gives a total difference of 313.17 kg and 344.63 kg, respectively. The sum of direct CO_2 emission and equivalent CO_2 emission (from other greenhouse gases) was calculated as 657.8 kg or 4.6 kg/m^2.

3.2. Carbon sequestration measurement by IRGA

In essence, green roofs have a positive effect on the carbon footprint by absorbing air carbon. CO_2 sequestration by the green roof gradually offset the extra carbon emission of the construction process and the positive effect continues throughout the life of the building. Plants grown on green roofs continuously absorb CO_2 for photosynthesis, during which CO_2 is consumed to produce glucose (six molecules of CO_2 are needed to produce one molecule of glucose). The CO_2 that plants release during the night should also be considered in carbon footprint calculations. In general, plants return 50% of the absorbed CO_2 to the atmosphere during respiration. They also transfer 90% of the remaining amount (*i.e.* 45% of the total carbon absorbed) to soil microbes, which eventually returns to the atmosphere upon their death. This means that only 5% of CO_2 initially absorbed by the plant is actually consumed (Guo and Lee 2006). Figure 2 shows the CO_2 absorption (photosynthesis rate) measured by the infrared gas analyzer for the eight considered plant species at the light intensities of 1000, 1500, and 2000 μmol/m^2.s.

Figure 2. CO_2 uptake (photosynthesis rate) of the eight considered plant species at the light intensities of 1000, 1500, and 2000 μmol/m^2.s

The results show that plant species *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis*, and *Vinca major* have higher CO_2 uptake rates than the others and therefore a higher potential to offset the extra carbon produced during the construction of the green roof. The CO_2 uptake of plants increased with light intensity, but this increase was not linear. For example, for *Sedum acre L* and *Vinca major*, a change in light intensity from 1500 to 2000 μmol/m^2.s led to a greater increase in CO_2 uptake than the change from 1000 to 1500 μmol/m^2.s. This suggests that these plants perform better during sunny hours (around noon) and in warmer seasons (in summer), when the light intensity is higher. In contrast, species *Carpobrotus edulis, Sedum spectabile boreau*, *Aptenia cordifolia*, and *Phyla nodiflora* showed a roughly proportional increase in CO_2 uptake as the light intensity increased from 1000 to 2000 μmol/m^2.s. Species *Frankenia laevis* was found to be particularly responsive to light intensity, which was reflected in a dramatic increase in CO_2 uptake. The CO_2 uptake of this plant at a light intensity of 1000 μmol/m^2.s is similar to that of *Vinca major* and much lower than that of *Sedum spectabile boreau*, but at light intensities of 1500 and 2000 μmol/m^2.s it outperforms *Sedum spectabile boreau* and closes the gap with *Sedum acre L*. The performance of different *Sedum* species has been researched in several works, including Getter et al. (2009), Collazo-Ortega et al. (2017), and Mirzababaie and Karrabi (2019), which have shown its suitability for use in green roofs from the perspective of cold and water stress resistance. The results of this study indicate that these plant species also have a very good CO_2 uptake performance, which makes them an even better option for use in green roofs. As shown in Fig. 2, although *Potentilla reptans* and *Phyla nodiflora* have an excellent cold and drought resistance, they lack CO_2 uptake performance, which makes them ill-suited for the cases where the primary purpose of the green roof is to reduce CO_2 emission, like high-traffic urban areas and industrial zones with high potential air pollution. Among the eight examined plants, *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis*, and *Vinca* *major*, which had a high CO_2 uptake as well as the necessary level of drought and cold resistance for survival in the study area, were chosen for use in the remainder of the work.

3.3. Compensation of extra carbon emission

The results obtained from IRGA was used to compute the annual CO_2 uptake of the roof with *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis*, and *Vinca major* and also the time it takes for the roof to offset the extra carbon produced in the construction process in each case. The results of these calculations are presented in Table 3.

Table 3
Annual CO_2 uptake of the roof with chosen plant species and the time required to compensate for the extra carbon footprint

Plant species	CO_2 uptake (kg/year.m^2)			The time needed to compensate for the extra carbon emission (day)		
	Light intensity (μmol/m^2.s)			Light intensity (μmol/m^2.s)		
	1000	1500	2000	1000	1500	2000
Sedum acre L	3.85	4.31	6.29	431	384	264
Sedum spectabile boreau	2.39	3.04	3.79	690	545	438
Frankenia laevis	0.90	3.17	4.47	1830	522	369
Vinka major	0.90	1.23	1.91	1830	1350	870

The highest CO_2 uptake was observed for *Sedum acre L* under a light intensity of 2000 μmol/m^2.s. With this plant and under this light intensity, it will take the green roof just 264 days to offset the extra carbon produced during construction and start to yield a net positive effect on carbon release in the environment. The condition under which it would take longer (1830 days) to offset the extra carbon is the use of *Vinca major* under a light intensity of 1000 μmol/m^2.s. As shown in Table 3, the CO_2 uptake rate of the selected plant species at different light intensities ranges from 0.9 to 6.3 kgCO_2/m^2.year. In the study carried out by Whittinghill et al. (2014) on the carbon uptake of various types of *Sedum* when used as green roof vegetation, the uptake rate over a 12-month period was 3.9 kgCO_2/m^2. Collazo-Ortega et al. (2017) reported a carbon uptake of 1.8 kgCO_2/m^2.year for green roofs with *Sedum dendroideum* and *Sedum rubrotinctum*. The variations in reported CO_2 uptake values may result from difference between the studies in terms of light intensity, plant species, and climate.

3.4. Short-term carbon footprint

In a study by Silva et al. (2015), they stated that maintaining a green roof, including its vegetation, soil layer, drainage system, irrigation system, and thermal insulation, normally requires no activity with significant carbon production in the first 5 years. Following the approach taken by Silva et al., the present study assumed that there would be no extra carbon production due to the maintenance of the green roof during the first five years. Figure 3 shows the CO_2 uptake of the green roof with each of the four selected plant species in the years following construction.

Figure 3. CO_2 uptake of the green roof with a) *Sedum acre L*, b) *Sedum spectabile boreau*, c) *Frankenia laevis*, and d) *Vinca major*

The amount of CO_2 uptake by selected plants is measured based on their photosynthetic rate under three light intensities. The CO_2 absorption process for each plant includes two time periods during the short-term operating phase of the building: (*i*) the time required to compensate for the extra CO_2 emission due to the implementation of the green roof and (*ii*) the remaining time period when the positive effects on carbon footprint occur. As shown in Fig. 3, under higher light intensities and due to the better CO_2 sequestration, it takes less time for the green roof vegetation to compensate the extra CO_2 emission. The results show that for lower light intensity ranges (1000–1500 μmol/m^2.s), *Sedum acre L* and *Sedum spectabile boreau* have the best CO_2 uptake performance. For higher light intensities (1500–2000 μmol/m^2.s), the best CO_2 uptake performance belongs to *Sedum acre L* and *Frankenia laevis*. The best improvement in CO_2 uptake as light intensity increased from 1000 to 2000 μmol/m^2.s was observed in *Frankenia laevis*, which showed increased CO_2 absorption 5 times. The next best results in this respect were seen in the plant species *Vinca major* with 2.1 times increase, *Sedum acre L* with 1.6 times increase, and *Sedum spectabile boreau* with 1.5 times increase (Fig. 4). This result demonstrates the relatively stable CO_2 uptake behaviour of *Sedum acre L* and *Sedum spectabile boreau* under different light intensity conditions.

Figure 4. Variations of CO_2 uptake in different light intensities for the selected plants

According to Fig. 4, the CO_2 uptake of the roof with *Sedum acre L* increases more sharply as the light intensity increases, as it shows greater increase in the second 500-unit increase of light intensity (from 1500 to 2000 μmol/m^2.s) than in the first one (from 1000 to 1500 μmol/m^2.s). The green roof with *Vinca major* shows the same trend, *i.e.* it has a better CO_2 uptake performance under sunny conditions. In contrast, for the roof with *Sedum spectabile boreau*, there is no significant change in the trend of CO_2 uptake as the light intensity increases from 1000 to 1500 μmol/m^2.s and from 1500 to 2000 μmol/m^2.s. For the roof with *Frankenia laevis*, the increase in CO_2 uptake in the first light intensity interval (1000–1500 μmol/m^2.s) is greater than in the second one (1500–2000 μmol/m^2.s). The poor CO_2 uptake performance of *Frankenia laevis* in low light intensities make this plant ill-suited for areas with few sunny hours and sunny days and for use in green roofs whose main purpose is CO_2 absorption. The four examined plants can be divided in two groups based on the climatic conditions of the area where the roof is to be built: the first group comprises the plants that are best to be used in areas where there are more cloudy days than sunny days, and the other group is the plants that exhibit better performance in areas with higher light intensity.

3.5. Long-term carbon footprint in Iran

In recent years, many developing countries, including Iran, have shown increasing interest in the promotion of environment-friendly building technologies *i.e.* green roofs, as a step toward sustainable development in the building sector. According to the Paris Agreement (UNFCCC), between 2021 and 2030, Iran is obligated to reduce its greenhouse gas emissions by either 4% or 12% depending on whether international sanctions are lifted from this country (Umemiya et al. 2020). Therefore, in the next step, the potential impact of green roofing on Iran's total CO_2 emission was evaluated in three hypothetical scenarios where 25, 50 and 75% of the urban roofed space in the country has green roofing. According to the statistics published by the Ministry of Roads and Urban Development of Iran, by 2030, the total area of roofed buildings in the urban areas of Iran will reach 4.9×10^7 m^2. Assuming that 15% of this total area is access space (La Roche and Berardi 2014; Statistical Center of Iran 2018), green roofs can be built on 85% of this area, i.e. 4.1×10^7 m^2. Based on this assumption, the impact of the three mentioned green roofing scenarios on CO_2 emission was estimated to determine how much this technology can contribute to Iran meeting its obligations under the Paris Agreement by 2030. The results are presented in Fig. 5.

Figure 5. Annual CO_2 reduction due to the extent of green roofing a) *Sedum acre L*, b) *Sedum spectabile boreau*, c) *Frankenia laevis*, and d) *Vinca major*

As shown in Fig. 5, the greatest reduction in CO_2 emission (1.9×10^5 tons/year) will take place if 75% of the roofed surfaces in urban areas is covered with green roofs with *Sedum acre L* and receives the maximum light intensity (2000 μmol/m^2.s). On the contrary, the smallest reduction in CO_2 emission will occur if 25% of these roofed surfaces is covered with green roofs with *Frankenia laevis* and *Vinca major* and receives light with an intensity of 1000 μmol/m^2.s.

Considering that the building sector is one of the major producers of greenhouse gas emission in Iran (accounting for 30% of total greenhouse gas production (Jeong et al. 2012; Statistical Center of Iran 2018), this sector is expected to have an at least 30% share in the total greenhouse gas emission reduction of the country. Since the signing of the Paris Agreement (2012), Iran has largely remained under international sanctions, and according to many experts, can be expected to remain sanctioned for the foreseeable future, possibly well after 2030. Thus, according to this agreement, by 2030, Iran should reduce its greenhouse gas emission by 4%. Based on the average per capita CO_2 production in Iran (8.3 tons), this 4% amounts to 27.1 million tons of CO_2, of which 8.12 million tons should be in the building sector. The results of this study show that in the absolute best-case scenario, nation-wide use of green roofs will allow Iran to meet 2.4% of its international obligations in the building sector. However, it must be noted that any decrease in CO_2 emission is favorable from an environmental point of view and contributes to the long-term reduction of the country's carbon footprint.

To benefit from the advantages of green roofs for a long time, they should be designed and constructed meticulously and maintained with great care. This operation should be able to mitigate the risks that threaten the integrity of the roof, including the decay of components and loss of vegetation, so as to prolong the lifetime of this environment (Peck and Kuhn 2003). Some of the green roof maintenance activities and operations have a noticeable carbon emission, which inevitably leaves a negative impact on the overall carbon footprint of the roof. Therefore, taking into account the amount of carbon that will be produced due to maintenance activities during the life of a green roof can improve the accuracy of the estimation in regards to the actual carbon footprint of the roof. So far, only a few studies have been conducted on the carbon footprint of long-term green roof maintenance operations. Therefore, more extensive and comprehensive studies are still needed to determine the amount of carbon released in each operation and the consequent effect on the overall carbon footprint of the structure. It is noteworthy that, in this study, the process of carbon dioxide absorption is considered a linear function with respect to time. However, determining the linear or nonlinear function of CO_2 uptake by plants used on green roofs could provide a better perspective on carbon footprint, particularly over a long period of time.

4. Conclusion

This study intends to investigate the CO_2 uptake of eight plant species namely *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis*, *Vinca major*, *Phyla nodiflora*, *Potentilla reptans, Aptenia cordifolia* and *Carpobrotus edulis* when used as green roof vegetation and determine the time it takes for the roof to offset the extra carbon produced during the construction process for each case. This investigation used Design Builder to model a building with a roof area of 160 m^2 in cold and dry climates, such as in Mashhad (Iran). The results showed that the total sum of direct CO_2 emission and equivalent CO_2 emission (due to other greenhouse gases) to be released during the building of this residential house is 657.8 kg or 4.6kg/m^2. After measuring the CO_2 uptake of the considered plants by IRGA at light intensities of 1000, 1500, and 2000 μmol/m^2.s), four species of *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis* and *Vinca major* were found to be more suitable for the considered building and area. The results obtained by simulating the green roofs with these four-plant species are presented below:

- The shortest time it takes for green roofs with *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis*, and *Vinca major* plants to offset the extra carbon produced during the construction process are respectively 264, 438, 369, and 870 days under a light intensity of 2000 μmol/m^2.s;
- Under all considered light intensities, *Sedum acre L* had the highest and *Vinca major* the lowest CO_2 uptake. Therefore, among the plant considered in this study, which are the most widely used green roof plants in the studied area, the best plant for green roof vegetation is *Sedum acre L*, which combines excellent response to the environment in question with a desirable CO_2 sequestration capability in both sunny and cloudy days;
- Since green roofs with *Sedum acre L*, *Sedum spectabile boreau*, *Frankenia laevis* and *Vinca major* plants do not require any maintenance activity with significant carbon emission in the first five years,

their CO_2 uptake under a moderate light intensity (1500 μmol/m^2.s) is respectively 4.31, 3.04, 3.17, and 1.23 kg/m^2.year;

- The CO_2 uptake results of *Frankenia laevis* showed that this plant performs considerably better under high light intensities. Therefore, it will be a better choice for areas with more sunny hours or longer warm seasons, which fall in the category of hot and dry climate.

When discussing the effect of green roofs on the carbon footprint of a building, it should be remembered that repair and maintenance operations are essential to take advantage of all benefits of these roofs for the longest possible time. However, many of the necessary maintenance activities contribute to carbon production and have a negative impact on the overall carbon footprint of the assembly. Therefore, careful attention on the quantities of carbon released because of these activities may provide better insight into the effect of green roofs on the carbon footprint of buildings.

Declarations

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Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

MK and JN devised the project, the main conceptual ideas and proof outline. **MRS** carried out the experiment and simulations. **MK** supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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Competing Interests

The authors declare that they have no competing interests

Availability of data and materials

All data generated or analysed during this study are included in this published article

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Figures

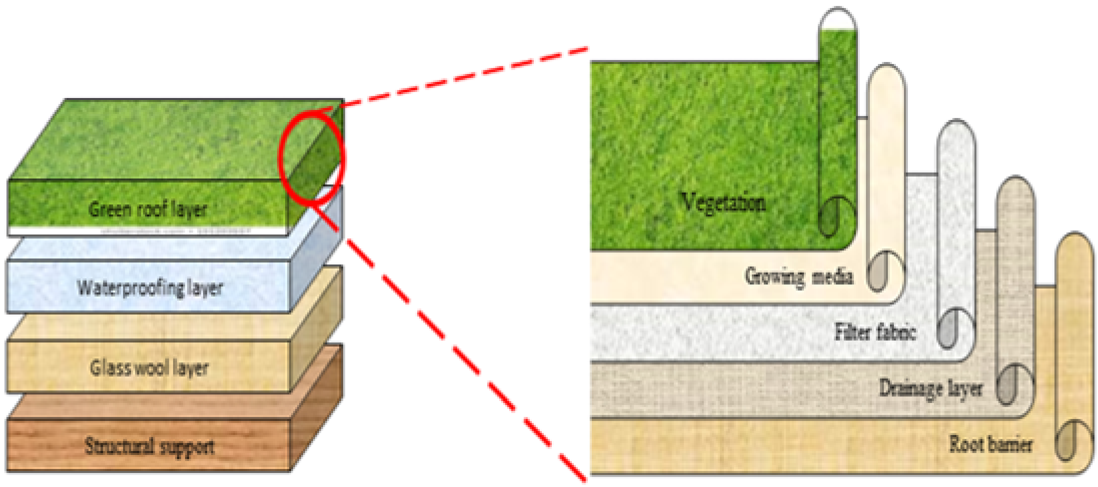

Figure 1

Schematic composition of the green roof layer

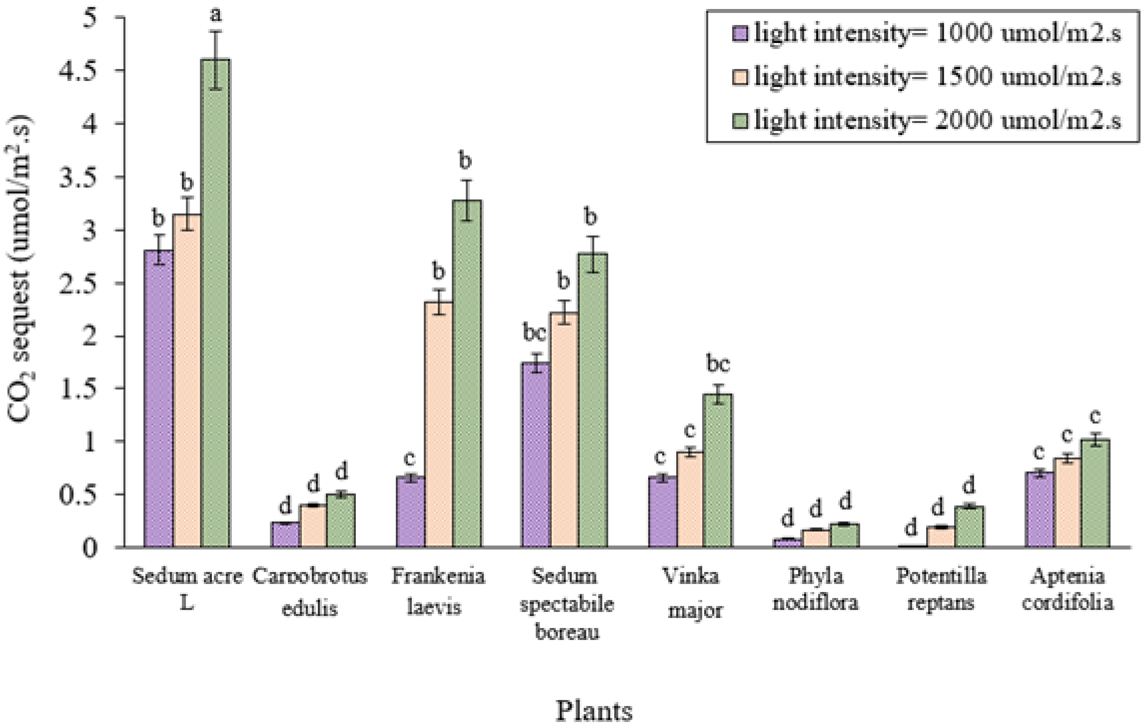

Figure 2

CO_2 uptake (photosynthesis rate) of the eight considered plant species at the light intensities of 1000, 1500, and 2000 μmol/m2.s. Significant differences in CO_2 uptake values are indicated by small letters.

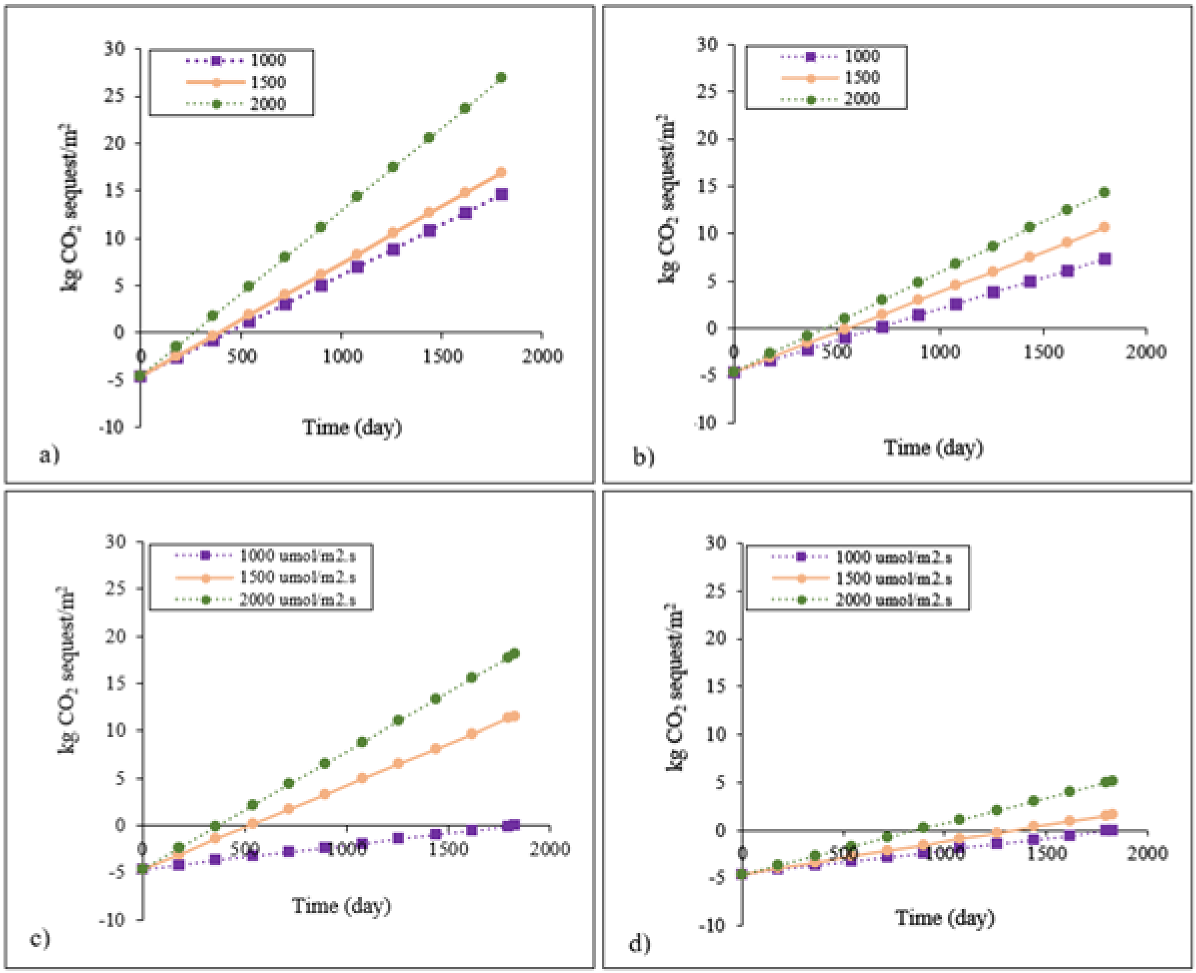

Figure 3

CO2 uptake of the green roof with a) Sedum acre L, b) Sedum spectabile boreau, c) Frankenia laevis, and d) Vinca major

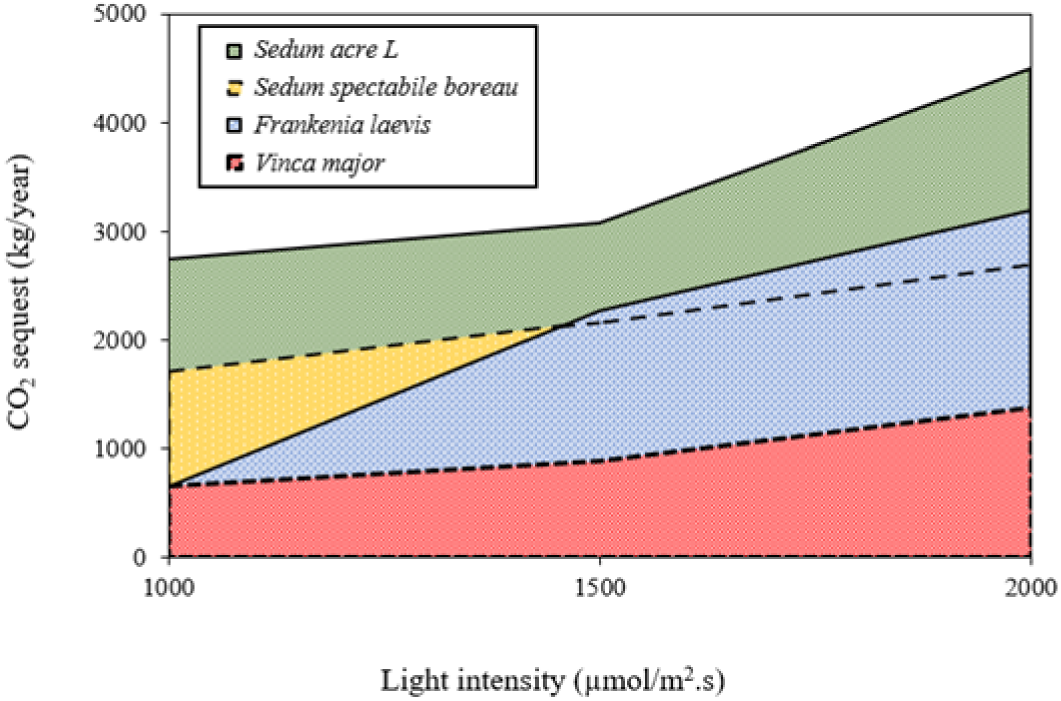

Figure 4

Variations of CO2 uptake in different light intensities for the selected plants

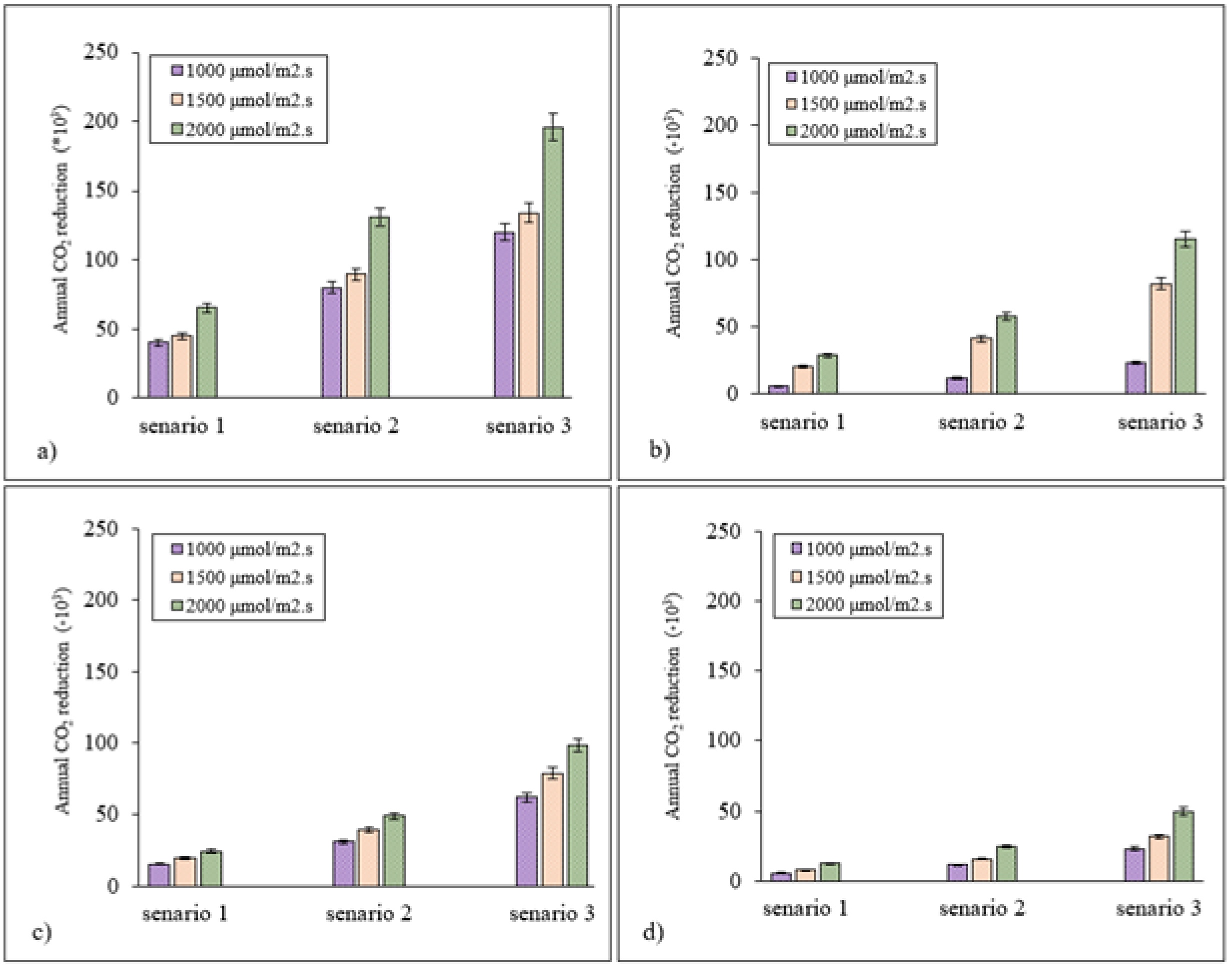

Figure 5

Annual CO2 reduction due to the extent of green roofing a) Sedum acre L, b) Sedum spectabile boreau, c) Frankenia laevis, and d) Vinca major