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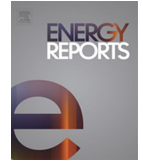
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Environmental impact assessment of green roofs using life cycle assessment

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Abstract

The main objective of this study was to analyse the environmental impacts of roof top greenery systems for a building in Sydney, Australia, using the Life Cycle Assessment (LCA). SimaPro software was used for the simulation. The input data for SimaPro on roof barrier, protection layer, drainage layer, filter layer, substrate, plants, etc., were taken from Sydney City Council and relevant literature. The environmental impacts of major pollutants such as Abiotic depletion, Global warming (GWP100), Ozone layer depletion (ODP), Human toxicity, Freshwater aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity, Photochemical oxidation, Acidification and Eutrophication released from raw materials consumption and operation are compared between green roof and non-green roof. The results indicate that green roofs impact about 3 times positively in the environment compared to non-green roofs. Most of the emissions reductions were found to be in the range of 35% to 83%, however, ozone layer depletion is almost nullified when any of the green roofs are installed. It was also found that environmental impacts of both extensive and intensive green roofs are comparable; however, intensive green roofs perform slightly better and are recommended for urban life systems.

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Keywords: Green roof; Environmental life cycle analysis; SimaPro

1. Introduction

Industrialisation, increase in luxury of the people and deforestation has been causing a lot of damage to our natural environment, and human and animal life over time. Implementation of green infrastructure (GI) initiatives have been emerging as thriving measures in bringing back the urban living spaces in many developed and developing countries across the world [1]. There are several types of GI in practice. The Green Roof, otherwise called a living roof, is one of the GI practices, which have many advantages besides a few disadvantages. This has been in practice for centuries; however, it has received more attention in recent years, particularly in Australia, due to its

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environmental, energy and economic benefits. It reduces air conditioning energy consumption in both winter and summer by keeping a building hot during winter and by acting as a barrier for the heat of the sun during summer [2]. It reduces: (a) life cycle expenses of the roof as green roofs are approximately 3 times more durable than conventional roofs, (b) construction wastes leading to the reduction in construction costs, and (c) sound propagation by acting as insulation medium due to making the roof thicker. Due to better amenity, buildings with green roofs would attract higher rent and higher occupant retention. Environmental benefits include: (a) by acting as a medium which can hold the moisture and water content, it reduces the passage of storm water, consequently reducing erosion, (b) it improves the air quality, and (c) it diminishes the urban heat island effect because, during the summer season, urban areas are hotter than the rural areas. Social benefits include that it increases the educational opportunities, employment opportunities, provides space for food production and provides green space for recreational use. The green roofs protect and extend the roof life against the high temperature and fluctuations, act as insulation to sound. They also allow the improvement in the air quality by capturing carbon dioxide. In general, there are two-types of green roofs. These are intensive (Fig. 1) and extensive (Fig. 2) green roofs. The growing medium is thicker for intensive (more than 300 mm) than for extensive (less than 300 mm) green roofs. Intensive green roofs need a deep soil layer and skilled labour, and higher maintenance than extensive green roofs. The different layers of the green roof are a vegetation layer, substrate layer, water retention layer, filter layer, drainage layer, root barrier layer and protection layer.

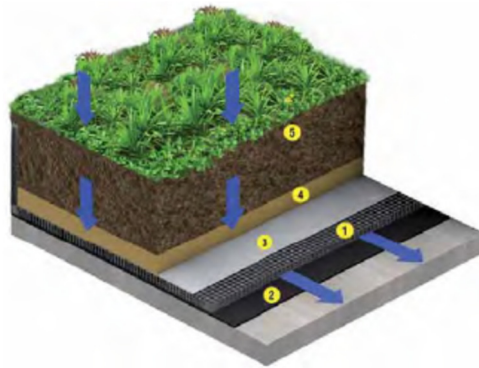


Fig. 1. Typical intensive green roof system. (1) The drainage system (2) Water proofing membrane (3) Filter fabric (4) Sand and (5) Lightweight growing medium [3].



Fig. 2. Typical extensive green roof system. (1) Waterproofing membrane (2) Drainage system (3) Filter fabric (4) Cellular confinement cells (5) Lightweight growing medium [3].

There are lots of buildings which are old and low rise that do not have green roofs. Green roofs on low-rise buildings give more benefits than on the tall buildings, hence a low-rise building was selected for this study. In this study, environmental impacts of both types of green roofs are compared with the non-green roof system. The life cycle of the green roofs was set to 25 years. The major objectives were to evaluate and quantify the environmental

impacts of green roofs and to develop a simple model and the database for an LCA of green roof systems using SimaPro simulation software.

2. Materials and methods

As per ISO 14040, there are different methods of LCA [4]. Each method has different categories of impact, so a proper method needs to be chosen [5]. In this study, CML2 baseline 2000 v2.1 was chosen as a method of impact assessment [6]. The impact categories investigated in this study include Depletion of abiotic resources (kg Sb eq); Climate change (kg CO₂ eq); Stratospheric ozone depletion (kg CFC-11 eq); Human toxicity (kg 1,4-DB eq); Fresh-water aquatic eco-toxicity (kg 1,4-DB eq); Marine eco-toxicity (kg 1,4-DB eq); Terrestrial ecotoxicity (kg 1,4-DB eq); Photo-oxidant formation (kg C₂H₄); Acidification (kg SO₂ eq) and Eutrophication (kg PO₄ eq) [7]. A brief description on each category is given below.

- Abiotic depletion is the depletion of the resources that come from the non-living, non-organic materials like land, freshwater, air, etc.
- The global warming potential, the characterisation factor of climate change, mainly a measure of CO₂ eq.
- Chlorofluorocarbons (CFCs) are one of the Ozone depletion substances. Generally, for each heavy metal toxicity, the Human toxicity potentials (HTP) is expressed or measured with a reference unit of kg 1,4 dichlorobenzene (1,4-DB) eq.
- Environmental toxicity is the criterion which measures impacts on freshwater systems and land (terrestrial). These are also measured in kg, 1,4 dichlorobenzene eq.
- Marine ecotoxicity relates to discharges into marine waters.
- Photochemical ozone creation/summer smog measures the release of substance into air like NO_x, volatile organic compounds. It is expressed in units of kg C₂H₄ eq.
- Acidification is the release of Acidic gases such as SO₂. Generally, these acidic gases react with water to form acidic rain. This process is known as acid deposition.
- Nitrates and phosphates are useful to life when they are in limited concentrations, however, increased concentrations in water induce the growth of algae and abets in decreasing the amount of oxygen in water. This is called Eutrophication. This is measured in kg PO₄ eq.

The outcomes of this study will help the respective authorities to understand and identify the significant factors that can promote the applications of green roof systems.

The LCA methodology includes four steps, namely selection of building structures where green roofs are installed, collecting the input data for LCA of the raw materials used for green roofs, simulation of the green roof models in LCA using SimaPro software to examine the environmental effects and analysing the simulation results critically. The materials required for the construction of roof components were taken from the literature and Sydney City Council Green Roof Resource Manual [8–11]. The data for the LCA was collected as per the type of the raw materials needed for construction of green roofs; the details of by-products, co-products and wastes released during the manufacturing process; and the emissions into the air during the manufacturing and use of the raw materials for installation of green roofs. The SimaPro software database was used for examining the impact and processing of the raw materials. The simulation was done separately for the non-green roof, extensive green roof and intensive green roof. The calculation for total air pollutants were done using the Big-leaf resistance model [12]. The total air pollutants removal at a given place in a certain period was calculated using:

$$Q = LT V_d C \times 10^{-8} \quad (1)$$

where Q is the amount of the air pollutant removed by the particular area of green roofs in a certain time (g), L is the total green roof area (m²), T is the time (s), V_d is the dry deposition velocity of an air pollutant (m/s) and C is the concentration of that pollutant in the air (μg/m³).

As mentioned earlier, the materials and components used for the construction of green roof systems were the roof barrier, protection layer, drainage layer, filter layer, soil/substrate and plants/vegetation. The simulation for the selected pollutants were done using [13] methodology “CML2 baseline 2000 v2.1” of SimaPro software. It must be noted that the transportation and the local demolition of the roofs were not considered in this study. Tables 1, 2 and 3 details the unit weight of the different materials required for the respective types of the roofs. Gravel and sand mixture densities considered were 1650 kg/m³ and 1522 kg/m³, respectively.

Table 1. Materials required for the construction of extensive green roof and their unit weights.

Components of extensive green roof	Thickness of the layer (mm)	Materials included	Unit weight (kg/m ²)
Roof barrier	1 mm	PVC	0.016
Protection layer	–	Polypropylene sheet	0.30
Drainage layer	25 mm	Polystyrene	1.75
Filter layer	–	Polypropylene sheet	0.10
Soil	150 mm	Gravel (100 mm)	152.2
		Sand (100 mm)	12.8
		Kaolin (50 mm)	51.3
Plant	–	Sedums	10

Table 2. Materials required for the construction of intensive green roof and their unit weights.

Components of intensive green roof	Thickness of the layer (mm)	Materials included	Unit weight (kg/m ²)
Roof barrier	0.4 mm	HDPE	0.385
Protection layer	–	Polypropylene sheet	0.60
Drainage layer	100 mm	Gravel (50 mm)	76.1
		Bentonite (25 mm)	20
		Kaolin (25 mm)	25.63
Filter layer	–	Polypropylene sheet	0.60
Soil	1500 mm	Gravel (1000 mm)	1522
		Sand (1000 mm)	128
		Kaolin (500 mm)	513
Plant	Up to 3000 mm		30

Table 3. Materials required for the construction of conventional roof and their unit weights.

Components of non-green roof	Thickness of the layer (mm)	Materials included	Unit weight (kg/m ²)
Insulation layer	50	Polystyrene	3.5
Finishing layer	250	Asphalt	555.5

3. Results and discussions

The environmental impacts of materials used, starting from the production of materials from raw materials to the building construction materials, for different types of roofs were investigated first. It was found that the impacts of the materials used for the conventional type of roof are higher than for the green roofs. It should be noted that the normal life cycle of the conventional roof is lower than for green roofs, which indicates that replacement or renovation is required more frequently for a conventional roof than for a green roof. This increases the environmental burden of a conventional roof. It is also to be noted that, as the quantity of materials used in intensive green roofs is higher than in extensive green roofs, the environmental impacts of materials production of the latter are lower than for the intensive green roof. If only the impacts of material production is taken into consideration, extensive green roofs are better. The environmental impacts of the operational energy for different types of roof systems were calculated based on the U-Value of the respective roofs. This was focused mainly on the air conditioning system operation which is affected by the roofing system. The cooling load due to the air conditioning system, the lighting load, operation of a normal fan and other electrical equipment were considered in calculating the environmental impacts. [Table 4](#) shows the environmental impact values for the same operational scenario on the energy under different types of roof systems. [Table 5](#) shows comparison of total environmental impacts of all the three types of roof systems.

[Table 6](#) shows the percentage reduction in various impact categories on the environment using different types of green roofs.

It can be clearly seen from this table that the terrestrial ecotoxicity decreases by 36%–37% when the green roof is used and the Human toxicity decreases by 74%. The important point to be noted is that the ozone layer depletion

Table 4. Environmental impacts comparison of total operational energy for three types of roof systems.

Impact category	Units	Extensive green roof	Intensive green roof	Non-green roof
Abiotic depletion	kg Sb eq	4.03×10^3	3.89×10^3	4.08×10^3
Global warming (GWP100)	kg CO ₂ eq	5.09×10^5	4.90×10^5	5.14×10^5
Ozone layer depletion (ODP)	kg CFC-11 eq	0.01	0.01	0.01
Human toxicity	kg 1,4-DB eq	1.43×10^5	1.38×10^5	1.45×10^5
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	2.06×10^4	1.99×10^4	2.09×10^4
Marine aquatic ecotoxicity	kg 1,4-DB eq	6.56×10^8	6.32×10^8	6.63×10^8
Terrestrial ecotoxicity	kg 1,4-DB eq	2.37×10^3	2.28×10^3	2.39×10^3
Photochemical oxidation	kg C ₂ H ₄	104.63	100.75	105.69
Acidification	kg SO ₂ eq	2.87×10^3	2.77×10^3	2.90×10^3
Eutrophication	kg PO ₄ eq	184.47	177.65	186.35

Table 5. Comparison of total environmental impacts of all the three types of roof systems.

Impact category	Units	Intensive green roof	Extensive green roof	Non-green roof
Abiotic depletion	kg Sb eq	4132.6	4340.81	18 248.94
Global warming (GWP100)	kg CO ₂ eq	520 201.76	566 494.19	839 582.04
Ozone layer depletion (ODP)	kg CFC-11 eq	0.01195	0.02	3.02
Human toxicity	kg 1,4-DB eq	147 877.83	150 329.17	571 058.07
Freshwater aquatic ecotoxicity	kg 1,4-DB eq	20 761.49	21 177.62	122 180.31
Marine aquatic ecotoxicity	kg 1,4-DB eq	6 58 343 355	6 55 231 560	1 033 708 457
Terrestrial ecotoxicity	kg 1,4-DB eq	2377.46	2421.66	3772.01
Photochemical oxidation	kg C ₂ H ₄	106.74	112.31	293.84
Acidification	kg SO ₂ eq	2921.36	3077.44	5051.06
Eutrophication	kg PO ₄ eq	188.12	202.24	365.59

Table 6. Percentage reduction of the categories of environmental impacts.

Impact category	Intensive green roof	Extensive green roof
Abiotic depletion	78%	75%
Global warming (GWP100)	39%	33%
Ozone layer depletion (ODP)	100%	100%
Human toxicity	74%	74%
Freshwater aquatic ecotoxicity	83%	83%
Marine aquatic ecotoxicity	36%	36%
Terrestrial ecotoxicity	37%	36%
Photochemical oxidation	64%	61%
Acidification	44%	39%
Eutrophication	49%	45%

is almost nullified when any of the green roof systems is used. In addition to these benefits, the global warming emissions decrease by around 35%–39% when green roofs are used; however, the intensive green roof reduces more. When compared with the life cycle of 25 years for the green roofs, it is evident that the total environmental impacts of the intensive green roofs are lower than for extensive green roofs in several categories of environmental effects. Hence, the most recommended roof type as per environmental issues are intensive green roofs. Based on the simulated results, it was found that the green roofs impact very heavily, about 3 times, on the environment positively. Overall, the atmospheric pollution reduction was found to be in the range of 35% to 100%. It was also found that environmental impacts of both types of green roofs, i.e., extensive or intensive green roofs, are comparable; however, intensive green roofs perform slightly better. In general, green roofs have lower environmental impacts than traditional roofs which is well supported by other studies available in the literature. For example, Speak et al. [14] reported that the green roofs can reduce air pollutants by 0.41–3.21 g/m² in Manchester (UK). Yang et al. [12] reported that approximately 1767 kg of air pollutants can be removed by the green roofs per year in Chicago; Currie and Bass [15] calculated that 7870 kg of air pollutants can be removed annually by green roofs in Toronto. However, there are different methods being used in calculating the quantity of air pollutants removed such as the UFORE Model, Dry deposition velocity model, big-leaf resistance model, etc. The main emissions during the manufacture

of the materials for the green roofs are SO₂, NO₂, O₃, PM₁₀, etc. [16]. The main pollutants present in air are CO₂, O₃, SO₂, NO₂, PM_{2.5}, and PM₁₀ [17]. Tong et al. [17] reported that about 7%–33% of PM_{2.5} concentrations can be reduced at 26 m above the ground level of a building with green roofs. Jayasooriya [18] reported in his thesis that a total roof area of 288 788 m² replaced with an intensive green roof in Brooklyn Industrial Precinct can reduce 109 kg of NO₂, 30 kg of SO₂, 443 kg of PM₁₀, 10 kg of CO, 14 kg of PM 2.5 and 357 kg of O₃ per annum.

4. Conclusions and recommendations

The results show that green roofs are useful in mitigating the environmental impacts. Overall, the green roof can reduce atmospheric pollution from 35% to 100%. Intensive green roofs would help mitigate the environmental impacts more than extensive green roofs. Therefore, the intensive green roofs are recommended for the urban life systems for low-rise buildings in Sydney or in similar climate, which has more coastal area. There is a need to study the same benefits with the change in raw materials to those which have less carbon footprint. Life cycle cost analysis is also an important criterion to give a clear idea of whether to opt for green roofs.

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