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How “green” are the green roofs? Lifecycle analysis of green roof materials

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ABSTRACT

Green roofs can be classified as intensive and extensive roofs based on their purpose and characteristics. Green roofs are built with different layers and variable thicknesses depending on the roof type and/or weather conditions. Basic layers, from bottom to top, of green roof systems usually consists of a root barrier, drainage, filter, growing medium, and vegetation layer. There are many environmental and operational benefits of vegetated roofs. New technology enabled the use of low density polyethylene and polypropylene (polymers) materials with reduced weight on green roofs. This paper evaluates the environmental benefits of green roofs by comparing emissions of NO_2, SO_2, O_3 and PM_{10} in green roof material manufacturing process, such as polymers, with the green roof's pollution removal capacity. The analysis demonstrated that green roofs are sustainable products in long-term basis. In general, air pollution due to the polymer production process can be balanced by green roofs in 13–32 years. However, the manufacturing process of low density polyethylene and polypropylene has many other negative impacts to the environment than air pollution. It was evident that the current green roof materials needed to be replaced by more environmentally friendly and sustainable products.

1. Introduction

The construction industry is vital to provide the necessary infrastructure to satisfy human development needs. This professional sector provides multiple products to enhance the quality of life [42]. Importance of the construction industry is seen in its economic significance to the society and its direct social and environmental impacts [35]. It is recognized that construction practices are one of the major contributors of environmental problems, particularly due to the utilization of non-renewable materials. United States Green Building Council (USGBC) [46] estimated that commercial and residential construction buildings release 30% of green houses gases and consumes 65% of electricity in USA. Due to the well-known environmental issues (i.e. global warming, deforestation, waste generation, etc.), the concept of sustainability has been introduced to the construction sector.

Green construction aims to develop environmentally friendly construction practices that contribute in energy saving, reduction of emissions, re-use, and recycle of materials [39]. These concepts are used in different construction applications such as green roofs, ventilation systems, waste management policies, and recycled materials [52].

Green roofs can be classified by their purpose and characteristics in to two major types: intensive roofs and extensive roofs [8,51]. Intensive roofs need a reasonable depth of soil and require skilled labor, irrigation, and constant maintenance. They are usually associated with roof gardens [20]. Extensive roofs have a relatively thin layer of soil, grow sedums and moss and are designed to be virtually self-sustaining and require minimum maintenance [20]. There is a third type of green roofs called semi-intensive. Semi-intensive green roof is a combination of extensive and intensive, however the extensive type must represent 25% or less of the total green roof's area [51].

Over time, green roofs became popular construction product due to their environmental benefits; nevertheless, their cost disadvantage has been a challenge to the industry [21]. In general, green roof's experts agree that the reasons for these higher costs are usually due to materials lifting with cranes to the roof tops, expensive labor cost, and high insurance premiums. In addition, green roofs add more weight to the roof, which leads to changes of the structural design where columns, beams, and slabs must be modified, resulting a more expensive structure [5]. Green roof's experts justify the need to introduce materials like plastics into the market because it can reduce the overall weight and improve the performance of waterproofing layers without compromising the benefits of green roofs.

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Green roofs layers and materials are similar among manufacturers; however each manufacturer has developed its own system. General data about green roofs systems is available; however, specific content of substances, production process, installation process, and engineering technical information is kept as trade secrets in most cases. Usually manufacturers keep this information confidential to achieve competitive advantage.

This paper has two main objectives:

1. Discuss the importance of different layers of green roof with related materials properties.
2. Discuss the amount of pollution released to the air due to the production process of polypropylene and polyethylene (in green roof materials) and compare with Yang et al. [51] green roof's air pollution removal results.

The importance of this paper relays in determining the sustainability of green roofs, by estimating the number of years that a regular green roof takes to balance the pollution released in its' material production, with the pollution removed by the green roof's plants in the operation phase. The analysis was performed for the polymers, since all the layers, except for the growing medium and vegetation, are generally made out of polymer materials.

2. Research methodology

The data published in this paper was collected through published literature, one-to-one interviews, workshops, and questionnaire surveys.

2.1. Literature review

A comprehensive literature review was conducted to understand the present body of knowledge related to green roofs focusing on the following subjects: 1) environmental benefits, 2) materials, 3) design, and 4) installation.

2.2. Interviews

Open ended interviews were held with green roof's experts in different fields. Experts in installation, designing, and manufacturing provided practical industrial information which was not available in published literature.

2.3. Workshops

The researcher attended industrial workshops on green roofs to understand characteristics, designing, and installation processes of green roofs. Valuable information from the attendees' and informal conversations with presenters were recorded.

2.4. Questionnaire surveys

Formal and structured questionnaire surveys were distributed among green roof experts in Canada. The survey included design, constructability, operation, and market questions.

2.5. SimaPro modeling

The main tool used to determine the environmental impact of green roof's materials was SimaPro. The software's results were used to perform the lifecycle analysis presented in this paper.

3. Environmental benefits of green roofs

Environmental and operational cost-benefits of vegetated roofs are several and can be listed as follows: reduction of energy demand for heating and cooling, mitigation of urban heat island, reduction and delay of storm water runoff, improvement in air quality, replacement of displaced landscape, enhancement of biodiversity, provision of recreational and agricultural spaces, and insulation of a building for sound [7,8,20,31,51].

3.1. Comparison of green roof types

Environmental benefits can be maximized by building one type of green roof or the other; however all three types provide positive environmental benefits. Nevertheless, the installation cost, maintenance, and construction time are depended on the type of the green roof type. Compared to the other two types, extensive green roofs are lighter and require lower maintenance cost. However retention and delay of storm water, temperature control, and agricultural space effects can be lesser as well.

There is a substantial difference of price between the different types of green roofs. While the current cost in British Columbia, Canada for a standard extensive green roof varies from $130/m^2$–$165/m^2$ ($12/ft^2$–$15/ft^2$); the cost of a standard intensive green roof starts around $540/m^2$ ($50/ft^2$). This fact is one of the major reasons that influence owners decisions to build one type or the other [50].

3.2. Heat island effect

The heat island effect explains why urban areas have a higher temperature than rural areas. The reason for this effect is mainly due to dark colors of the buildings' roof tops [21]. Roofs with dark colors absorb energy from the sun and can reach temperatures higher than the ambient temperature. High temperatures on the roof result in increases of energy demand, higher air conditioning costs, and heat-related illnesses [44].

Rural areas are not exposed to this problem due to vegetation. Trees and plants help to control the ambient temperature by evapotranspiration [29]. In open areas plants use solar energy to control temperature by releasing vapor and contributing to the water cycle, while in urban areas there is not enough vegetation to cool down the environment [22,29].

Heat island effect can be mitigated by installing green roofs in urban areas. Rosenzweig et al. [28] suggested that if New York City covers 50% of roof tops with green roofs, the temperature difference between the city and its surrounding may decrease by 0.8 °C.

3.3. Stormwater runoff

Impermeable surfaces in cities are increasing due to urban developments, resulting in decrease storm water infiltration [8]. Green roofs have a water retention capacity that contributes to control the quantity of runoff water that can go into the city's sewer system [7,8,47]. Compared to regular roofing systems, vegetative roofs drain runoff water at a lower rate allowing the city's storm water sewer system to have enough time to transport runoff to the disposal body of water, which reduces the risk of flooding [27,43,49].

The amount of water that can be harvested from rain is important; however the quality of that water is very important as well [8]. Some research studies noted the effect of the roof's materials over the quality of runoff water. Such studies show that regardless of the roofing system, current roofing materials add chemicals or metal compounds to the runoff water [8,11,18,24,43].

Mendez et al. [18] and Nicholson et al. [24] stated that every artificial roofing material affect the runoff, however the water studied from sample green roofs added less chemical compounds and usually met the US EPA standards. However, it is important to note that the Mendez et al. [18] research did not consider the possibility of adding fertilizers and pesticides to protect and enhance plants growth by ordinary owners, resulting in more chemicals in runoff water.

3.4. Air pollution

Pollution management focuses on controlling the sources that release toxic chemicals in the air [34], but does not consider the pollutants that are already in the air [51]. Urban areas usually have higher levels of toxics in the air [17], and urban vegetation may be part of the solution to reduce air contamination to an acceptable level.

Green roofs contribute to reduce air pollution in two ways: (1) controlling temperature variations of a building reduces heating and air conditioning demand, hence less carbon dioxide is released from power plants; and (2) plants' photosynthesis sequester carbon dioxide from the air and store it as biomass [12]. Yang et al. [51] quantified the annual air pollution reduction (1835.23 metric tons of all pollutants) for the City of Chicago completely covered with green roofs. Currie and Bass [6] estimated that 7.87 metric tons of air pollution can be annually reduced by 109 ha of green roofs in Toronto.

4. Layers of a typical green roof

Manufacturers offer different green roof systems to the market to cater different weather conditions and user expectations. As shown in Fig. 1, green roof systems usually have a root barrier, drainage, filter, growing medium, and vegetation [8,26,37].

4.1. Root barrier layer

The root barrier is the first layer above the buildings' roofing assembly that generally is built out of traditional materials like concrete. The main purpose of this layer is to provide a waterproof membrane to the roofing assembly [37]. Leak prevention is one of the most important objectives of any green roof system design. In case of a leak in an operating green roof, all the layers needed to be removed to locate the leak.

Another purpose of this layer, as the name suggests, is to protect the buildings' roofing assembly from plant's roots that could penetrate from green roof's upper layers [38,50]. Roots grow, strengthen, and move through soil seeking water and nutrients for the plant [10]. Over time, without proper protection, roots can penetrate the roofing assembly resulting in cracks and holes where water infiltrates.

There are two different types of root barriers in the market: physical and chemical. Physical barriers consist of a thin layer

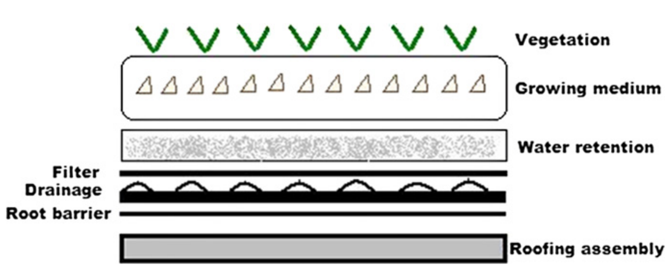

Fig. 1. Cross section of green roof's layers.

(usually about 0.05 cm) of a low-density polyethylene (LDPE) or polyethylene (PP) material that is placed above the roofing assembly [38,50]. Chemical barriers use toxins like copper based products to inhibit root penetration.

4.2. Drainage layer

Green roofs have a water retention capacity; however it is important to provide an empty space between the layers to allow the excess water to freely move out of the roof [37]. It decreases the risk of water leaks to the roofing assembly. In addition, water adds an extra weight to the roof assembly; therefore it is essential to ensure a good drainage to maintain structural capacity of the roof assembly. Effective drainage protects the root barrier from the excess water that can be accumulated in the membrane. Excess water in root barrier encourages plant roots to grow and damage the root barrier and roofing assembly [11].

Drainage materials and material shapes can be different depending on the chosen green roof system, weather conditions, and roofing assembly. Light and thin materials, as polyethylene and polypropylene, are preferred to build extensive green roofs due to weight limitations. Interviewees of green roof manufacturers stated that their preference for polymer based relays are due to its' flexibility to transport in rolls, easy installation, high strength, durability, and low production cost. Usually, the polymer material is bonded to one or both sides of a geotextile that prevents small particles of the growing medium to migrate and block the drainage. Depending on the green roof system and type of drainage, thickness of the layer can vary from 1.0 cm to 1.5 cm [38,50].

Intensive green roofs are designed to hold higher loads than extensive; therefore the drainage layer can be heavier and simpler. Generally the layer is composed of round pebbles which are a natural drainage and filter, and the thickness of the layer can be 4 cm or more [38,50].

4.3. Filter layer

Regardless of the green roof system, the purpose of the filter layer is to prevent the particles of the upper layers from draining with water runoff and block the drainage layer [43]. This layer prevents fine material infiltration to lower layers during the draining process. In addition, the filter layer maintains the integrity of the growing medium and vegetation.

Materials such as polymeric fibers or polyolefins are used to manufacture thin and light filter layer. The filter is bonded to the drainage layer to facilitate easy installation. Since filter layer information is shown as a part of the drainage layer, there is no technical information available to specify its thickness and weight [38,50].

4.4. Water retention layer

The main objective of this layer is to retain water for runoff control [43] and keep the growing medium layer moist [15]. Water is a natural source of nutrients for plants and help vegetation to be healthy to survive on roof tops. In addition, storm water retention by green roofs decreases and delays the runoff water in the city's storm water sewage system [8]. The retention capacity depends on the type of green roof, vegetation, building's roofing assembly, weather conditions, and previous soil's saturation [8,19,23,43]. Stored water in the roof adds an additional weight that the roof structure may not hold; consequently the roofing assembly is the first limitation to select materials and thickness of the water retention layer. Extensive green roofs require less water holding capacity than intensive since the thickness of the growing medium and vegetation is less. On the contrary, intensive green roofs use bigger vegetation with stronger roots that need more water and nutrients to survive and bloom [38,50].

Unlike the other layers, water retention layer is a mat made out of mineral wool or polymeric fibers and is installed just above the filter layer. The thickness of this layer varies, due to the factors discussed above, affecting retention performance and saturated weight. The depth of each mat can vary from 1.0 cm to 6.5 cm [38,50]. Mats can be combined, installing one above the other, to meet the needs of different green roofs.

4.5. Growing medium layer

This layer contributes to thermal performance and water retention [43], besides it supplies nutrients and water that plants need to their biological functions [15]. Additionally, it provides space to plant roots to settle and strengthen, to withstand wind force and other rough weather conditions, on the roof tops. It is important to consider the content and age of the medium since it affects directly the performance of the layer [32].

The natural growing medium is regular soil. However the soil can have clay and organic particles that may be heavy when saturated. Weight limitations of green roof systems led several manufacturers to develop their own growing mediums. Generally, growing medium has a high content of porous minerals and a low content of organic matter to maintain the balance between weight and performance [5]. Nevertheless the content of the medium can be modified to meet the natural requirements of the selected vegetation.

The thickness of the growing medium layer is related to the vegetation as well. Small vegetation like mosses requires less depth of medium to their roots than the depth a shrub may require [48]. The thinnest growing medium in the Canadian market is of 2.5 cm for an extensive green roof system. Intensive green roof systems are designed to grow different types of plants, thus the medium can vary between 20 cm and 120 cm [51].

4.6. Vegetation layer

Vegetation layer is the esthetic layer of green roofs, and perhaps is the symbol that identifies a green roof as an environmental friendly product. Having a bloom and healthy vegetation is the goal of many designers and owners; however the purpose of growing plants on roof tops, besides esthetic, are to mitigate urban heat effect, improve air quality, replace displaced landscape, and enhance biodiversity [5,41]. Moreover plants play an important role in regulating storm water runoff [33] by retention and evapotranspiration processes [25]. Nevertheless Dunnet et al. [9] stated that changes in the physical characteristics of plants influence their environmental contribution.

Environmental conditions at roof tops are different than at ground level, therefore it is recommended to use Crassulacean Acid Metabolism (CAM) plants. CAM plants open their leaf pores to exchange oxygen and carbon dioxide in the darkness allowing the conservation of water under drought conditions [10]. Such characteristics reduce the range of plants that can be used on the roof tops, however Berghage et al. [2] showed that sedums and mosses meet all such requirements, therefore are the most popular type of vegetation on green roofs. Not like sedums, mosses are green and need less care to maintain their physiological functions [48]. Generally these plants do not exceed 10 cm of height.

One of the major goals of intensive green roofs is to provide an open and accessible space for users to enjoy a different environment within the building [20]. Generally plants like grasses, herbs, shrubs, small trees and even small fruit trees or vegetables that can vary their height from 10 cm to more than 100 cm are used in intensive green roofs [3].

5. Physical characteristics of the materials

Green roof's materials usually use polymers for all the layers except for the growing medium. Growing medium should have enough organic matter and porous materials to meet the weight and growing requirements.

5.1. Polymers

Weight limitations in green roofs demanded light but durable materials like polypropylene and polyethylene. The goal of decreasing the weight of green roofs is to facilitate their installation in existing buildings and avoid excessive construction costs of new buildings due to large structural elements. The use of polymers motivated the construction of extensive green roofs, because it allows the roof to decrease thickness and weight, while maintaining environmental benefits similar to intensive green roofs at a lower cost and maintenance.

Lower layers of green roofs are exposed to high stresses due to heavy loads above them. In addition, plant roots of upper layers may damage the water retention and drainage layer. Therefore, materials in these layers should have high tensile and puncture resistance, which polymers are capable of [40].

The broad use of polymers in different industrial applications is due to their multiple beneficial characteristics such as: versatility, low weight, durability, corrosion resistance, insulation capacity, low cost, and ability to be tailored [40]. Additionally, thin and long layers can be produced and packed in rolls that facilitate transport and installation. Moreover, polymers also seems like an environmental attractive material because its' reusing and recycling potential. Generally, drainage and filter layers are manufactured of 40% recycled polypropylene and water retention layer of 100% recycled polymeric fibers [38,50].

5.2. Growing medium

Growing medium specific content is carefully kept confidential by manufacturers. The growing medium content may vary depending on the type of chosen vegetation. All plants need organic matter to grow, nevertheless some types need more than others. Larger plants like small trees and shrubs require more nutrients present in the growing medium. The growing medium for intensive green roofs may have up to 45% of organic content, while extensive's may have up to 30% [10].

Organic content usually is composed of soil with peat moss, bark, sawdust, or leaves to provide enough nutrients to the plants; however decomposing of the organic matter reduces the volume of the growing medium. It may cause harmful exposure of plant's roots [26]. To counteract this problem, the non-organic part of the growing medium should be a mixture of sand, scoria, and porous minerals that are light. It will decrease the consolidation of the medium as well [26,32]. The ultimate goal of manufacturing growing medium is to maintain a proper balance between weight, nutrients for plants, thickness, and durability.

6. Lifecycle analysis of green roof layers

There were many previous cost-benefits analysis of green roofs [6,12,51] by analyzing initial construction costs, reduction of energy demand (to mitigate urban island effect), control and delay of storm water runoff, and removal of air pollution. All the reviewed previous studies noted overall benefits of green roofs. Kosareo and

Table 1
Substances needed and released due to the production process of non-recycled polymers (Based on SimaPro results).

LDPE				PP			
Substance	Media	Unit	Amount released	Substance	Media	Unit	Amount released
Radon-222	Air	Bq	298	Radon-222	Air	Bq	198
Noble gases, radioactive, unspecified	Air	Bq	134	Noble gases, radioactive, unspecified	Air	Bq	91
Heat, waste	Air	MJ	27	Heat, waste	Air	MJ	21
Hydrogen-3, Tritium	Water	Bq	6	Hydrogen-3, Tritium	Water	Bq	4
Carbon dioxide, fossil	Air	kg	2	Carbon dioxide, fossil	Air	kg	1.7
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.9	Oil, crude, in ground	Raw (input)	kg	1
Oil, crude, in ground	Raw (input)	kg	0.9	Gas, natural, in ground	Raw (input)	m^3	0.6
Gas, natural, in ground	Raw (input)	m^3	0.8	Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	0.30
Energy, gross calorific value, in biomass	Raw (input)	MJ	0.4	Energy, gross calorific value, in biomass	Raw (input)	MJ	0.2
Coal, hard, unspecified, in ground	Raw (input)	kg	0.1	Coal, hard, unspecified, in ground	Raw (input)	kg	0.08

Ries [16] compared green roofs types with a conventional stone ballasted roof, nevertheless, this investigation did not focus on analyzing the environmental impacts of manufacturing the materials used in green roof layers. Green roofs are cataloged as a sustainability practice; however the production process of polymers is highly polluting.

6.1. Production process of polymers

Polymers are manufactured in four different processes: 1. continuous extrusion, 2. injection molding, 3. blow molding, and 4. thermoforming. All of these processes has three basic steps: i.e. 1. melting of the raw material, 2. shaping of the molten material, and 3. solidification of the molten to the desired shape [4]. Regardless of the method to produce the polymer, it needs high amount of energy to increase the temperature, to more than 120 °C, to melt the raw material to facilitate the shaping. After providing the desired form, the material must be cold down to accelerate solidification [13]. The energy sources and chemicals in the manufacture process of polymers release toxic substances to the air. Air pollution and energy consumption are essentials in lifecycle analysis.

6.2. Input of the lifecycle analysis software

The lifecycle analysis presented in this paper used SimaPro 7.1 software. The damage oriented method Eco-Indicator (H) V2.06 was applied. This method quantifies the amount of raw materials and substances released to different media, such as air, water and soil, to produce 1 kg of polymer. The software was used to analyze two options: i.e. recycled and non-recycled materials. Polyethylene low density (PE-LD) production mix at plant (RER) and polypropylene granulate (PP) production mix at plant (RER) were selected as the specific polymer materials for the root barrier and drainage, filter, and water retention layers. The recycling process includes mixing the polymer with chemical additives. Nevertheless, these substances don't produce any considerable effect on the durability and lifespan of the polymers [36]. Therefore, using non-recycled or recycled materials as green roofs layers depends just on their availability and price in the market. Polymers take long time to biodegrade in landfills [4], hence it is preferable to recycle and introduce them again in the market, than produce new ones.

For the lifecycle analysis of low density polyethylene and polypropylene, densities of 0.92 g/cm^3 and 0.95 g/cm^3 respectively in 20 °C., were used [36]. The drainage layer (polymeric fibers) typically has same density and production process of polypropylene. Hence it was analyzed as polypropylene.

6.3. Output of the lifecycle analysis software

Table 1 and Table 2 rank the amount of substances used in the production process of LDPE and PP for non-recycled and recycled process respectively.

The column "media" shown in Table 1 identify the amount of substances that are released to the environment, or the amount of raw materials needed for the production process. The first five released substances are the same for both polymers. Data shows

Table 2
Substances needed and released due to the production process of recycled polymers (Based on SimaPro results).

LDPE				PP			
Substance	Media	Unit	Amount released	Substance	Media	Unit	Amount released
Radioactive species	Air	Bq	3,639,724	Additives	Raw (input)	kg	3,763,977
Radioactive species	Water	Bq	33,441	Scandium	Air	kg	3,729,724
Radon-222	Air	Bq	297	Acids	Raw (input)	kg	317
Noble gases, radioactive, unspecified	Air	Bq	133	Waste in bioactive landfill	Solid waste	kg	21
Heat, waste	Air	MJ	27	Phosphate	Water	kg	1.8
Hydrogen-3, Tritium	Water	Bq	6	Formaldehyde	Air	kg	0.5
Energy, potential (in hydropower reservoir), converted	Raw (input)	MJ	3.5	Fluoride	Air	kg	0.40
Carbon dioxide, fossil	Air	Kg	2	Boron	Water	kg	0.10
Oil, crude, in ground	Raw (input)	Kg	0.9	Hydrocarbons, aliphatic, unsaturated	Air	kg	0.08
Gas, natural, in ground	Raw (input)	m^3	0.8	Glyphosate	Soil	kg	0.05

that the production process of polymers is highly pollutant, where 2 kg and 1.7 kg of carbon dioxide (CO_2) is released to produce 1 kg of LDPE and PP respectively. The amount of mass of CO_2 released doubles the amount of product manufactured.

In addition, the amount of raw material and energy to manufacture 1 kg of polymers is considerably high. Energy (from different sources) in the production process needed for extrusion, blow molding, injection molding, and thermoforming. All these processes require high pressures and temperatures. Crude Oil represents the biggest raw material contributor to manufacture polymers. To produce 1 kg of LDPE and PP, 0.8 kg and 1 kg of crude oil is required respectively, which is on 1:1 relation. Use of this fossil source causes extreme pollution in production process [45].

Table 2 shows that the same amount of oil and gas are needed for the non-recycled and recycled processes of LDPE. In addition, the same amount of carbon dioxide, radon 222, noble gases, and heat are emitted to the air in both processes. However, the recycled process releases other substances, such as scandium and phosphate, which are not released in the non-recycled process. Even though many emissions and input of the recycled and non-recycled process are the same, the recycled process can be considered more polluting for specific media and substances, since it releases much more radioactive substances to air and water.

Recycled PP doesn't need the same amount of oil and gas as an input compared to non-recycled PP; however the process requires additives and acids. Additionally, large quantities of scandium and waste (bioactive landfill) are produced to manufacture 1 kg of the recycled polymer. Compared to the non-recycled material, the recycled is generating more waste in the overall production process. Although the recycling process of polymers releases some radioactive materials, which are not released in non-recycled polymer production, overall recycled polymer production process has a lower environmental impact.

6.4. Application of data to different scenarios

To have a comparative analysis in this paper, the same problem addressed by Yang et al. [51] is considered. Yang et al. [51] investigations quantified the air pollution removal of green roofs for the entire area of the city of Chicago. This paper analyses the air pollution created due to the production process of the polymers, which are used to manufacture green roof's layers. Yang et al. [51] considered the air pollution removal in four substances: 1. Nitrogen Dioxide (NO_2), 2. Sulfur Dioxide (SO_2), 3. Ozone (O_3), and 4. particles of 10 μm or less (PM_{10}). For comparative purposes this paper analyzes the same substances with two scenarios:

(1) Green roof materials are manufactured with non-recycled polymers.
(2) Drainage and filter layers are manufactured with 40% recycled polypropylene and water retention layer is manufactured with 100% recycled polymeric fibers [38,50].

The city of Chicago has an area of 588.3 km^2 (58,830 ha) and 27.86% of that area is roof surfaces [14]. Yang et al. [51] estimated 0.198 km^2 (19.8 ha) of the roof area are green roofs, moreover noted that 32.58% of that area represents extensive green roofs (and 67.42% to intensive/semi-intensive green roofs).

Yang et al. [51] investigation quantified the air pollution removal by assuming all the roof tops of the city of Chicago as green roofs. To model the roof area that is not currently considered as a green roof (remaining roof area) Yang et al. [51] analyzed three scenarios:

(1) the remaining roof area has the same current ratio of extensive and intensive green roofs
(2) the remaining roof area has extensive green roofs, and
(3) the remaining roof area has intensive green roofs.

Table 3 shows the distribution of areas organized by the type of green roofs under three scenarios.

The weight of polymers used to build a typical green roof is needed to estimate the amount of pollutants released to air due to the production process of polymers. As mentioned, this paper analyses the polymer materials in root barrier, drainage, and water retention layer, of green roofs (shown in Fig. 1). Properties of the materials and the thickness of each layer considered for the life-cycle analysis are shown in Table 4.

The volume of polymers was obtained by multiplying the areas shown in Table 3 with the thickness shown in Table 4. The weight of each layer, shown in Table 5, was calculated by multiplying the volume with the density of each layer (shown in Table 4).

Pollution is mainly caused by the emissions in the production process of polymers; therefore the weight shown in Table 5 is organized by the type of polymers (Table 6).

Results in Table 7 show the amount of substances released to the air for each kilogram of recycled and non-recycled polymers. SimaPro 7.1 was used for the analysis.

Table 7 shows that low density polyethylene's production process, for both recycled and non-recycled polymer, is more pollutant than polypropylene's. Polyethylene is used to manufacture the layer that requires the lowest quantity of material (root barrier). The total amount of substances released to the air for the option of non-recycled polymers is calculated by multiplying the information in Table 6 and Table 7. Calculations for the recycled polymers option was more complicated since the drainage and filter layers have 40% and 100% recycled PP respectively.

Table 3
Area of green roof for the different scenarios (Based on Yang et al. [51]).

	Area (ha)		
	First scenario	Second scenario	Third scenario
Extensive	5339.86	16,376.70	6.45
Intensive/semi-intensive	11,050.20	13.35	16,383.60
Total	16,390	16,390	16,390

Table 4
Materials and properties considered for green roof's layers.

Layer	Material	Density (g/cm^3)	Thickness (cm)	
			Extensive	Intensive
Root barrier	Low density polyethylene	0.92	0.05	0.05
Drainage	Semi-Crystalline polypropylene	0.95	1.5	4.0
Water Retention	Polymeric fibers	0.95	1.0	1.5

Table 5
Weight of polymers for each layer.

		Weight (ton)		
		First scenario	Second scenario	Third scenario
Extensive	Root barrier	24,563.36	75,332.82	29.67
	Drainage	760,930.05	2,333,679.75	919.13
	Water Retention	507,286.70	1,555,786.50	612.75
Intensive/semi-intensive	Root barrier	50,830.92	61.41	75,364.56
	Drainage	4,199,076.00	5073.00	6,225,768.00
	Water Retention	1,574,653.50	1902.38	2,334,663.00

Table 6
Total weight of polymers under different scenarios.

		Weight (ton)		
		First scenario	Second scenario	Third scenario
Extensive	Low Density polyethylene	24,563.36	75,332.82	29.67
	Polypropylene	1,268,216.75	3,889,466.25	1531.88
Intensive/ semi-intensive	Low Density polyethylene	50,830.92	61.41	75,364.56
	Polypropylene	5,773,729.50	6975.38	8,560,431.00

Table 7
Amount of substances released to the air per 1 kg of polymer (Derived from SimaPro results).

Substance	Unit	Weight (kg)			
		Non-recycled		Recycled	
		LDPE	PP	LDPE	PP
NO_2	Kg	3.80E-03	3.30E-03	−2.22E-03	6.75E-260
SO_2	Kg	5.03E-03	3.79E-03	5.03E-03	0
O_3	Kg	4.16E-09	2.88E-09	4.16E-09	6.75E-260
PM_{10}	Kg	4.75E-04	4.06E-04	4.75E-04	6.75E-260
	Total of pollutants (kg)	9.31E-03	7.49E-03	3.29E-03	2.03E-259

It is assumed that 60% of the total weight of drainage layer is produced with non-recycled polymers and the remaining with recycled polymers.

The amount of pollution released is calculated by multiplying the 60% of the drainage layer weight (Table 5) with the amount of toxic substances shown in Table 7. Similarly, the remaining was estimated by multiplying the remaining weight (40%) with the toxic substances shown in Table 7.

The same process was followed for every scenario. Obtained results are shown in Table 8.

Table 9 shows the amount of pollution released for the two options described above.

Table 10 shows the number of years required, in the operation phase of the green roofs, to balance the air pollution in the materials' production phase.

7. Discussion

Results of the total pollutants released show that non-recycled LDPE releases 2.8 times more toxic substances to air than recycled LDPE (Table 7). Additionally, the recycling process removes NO_2 from the air than releasing it because it is required in the production process. Analyzing just the amounts of the four toxic substances (NO_2, SO_2, O_3 and PM_{10}) released from the recycled LDPE is lower than the emissions of non-recycled process.

Toxic emissions released to air decreased by the use of layers manufactured out of recycled polymers in 2.3, 2.7 and 2.2 times for the first, second, and third scenario respectively. Pollution is considerably decreased; if 100% recycled PP is used in the drainage layer (instead of using 40%).

Yang et al. [51] estimated that the total amount of air pollution removal per year for every scenario. Table 9 shows the amount of pollution released for non-recycled and recycled polymers for every selected scenario. It is evident that the manufacturing process of non-recycled polymers pollutes more than the recycled polymers.

Toxic substances released to air are 1820 kg per ha and 3960 kg per ha for extensive and intensive green roofs, with the non-recycle option, respectively (shown in Table 9). The recycled option released 680 kg per ha for extensive green roofs and 1750 kg per ha for intensive green roofs. These rates are compared with the air pollution removal rate of green roofs reported by Yang et al. [51]; which is 85 kg per ha per year in Chicago. Currie and Bass [6] reported the air pollution removal rate of green roofs as 72 kg per ha per year in Toronto. These removal rates allowed calculating the amount of years required to balance pollution for every scenario and option analyzed in this paper. From the results in Table 9, it is notable that the non-recycled materials need more time to balance pollution created in the material production. Table 10 evidences that the use of non-recycled polymers increase toxic releases to the environment.

Extensive green roofs release least amount of toxic substances for both, recycled and non-recycled materials. This result was expected since the layers of extensive green roofs are thinner than the intensive type, hence less material is required. In terms of 4 toxic substances (NO_2, SO_2, O_3 and PM_{10}, extensive roofs manufactured with recycled plastics are the best option. Kosareo and Ries [16] determined, that intensive green roof is the best option from a lifecycle perspective. However, the only difference between the extensive and intensive green roof used for their study is the thickness of the growing medium. Variations in the growing medium won't affect the toxic emissions of the manufacturing process of the polymers. This paper considered different thickness for the drainage and water retention layer, which is the reality. These variations directly affect the toxic substances released to the air in the manufacturing process.

In terms of SO_2, Kosareo and Ries [16] determined that intensive green roofs are better than extensive. This suggests that they used different plants for intensive green roofs and for extensive green roofs in the analysis. This study used the same type of plants for both types of green roofs, since the air pollution removal rate

Table 8
Total amount of pollutants released to the air (Derived from SimaPro results).

		Weight (ton)					
		First Scenario		Second Scenario		Third Scenario	
		Non-recycled	Recycled	Non-recycled	Recycled	Non-recycled	Recycled
Extensive	NO_2	4272	1598	13,103	4900	5	2
	SO_2	4927	1853	15,110	5682	6	2
	O_3	3.8E-03	1.4E-03	1.2E-02	4.3E-03	4.5E-06	1.7E-06
	PM_{10}	526	197	1615	604	6.36E-01	2.38E-01
Intensive/semi-intensive	NO_2	19,219	8495	23	10	28,495	12,595
	SO_2	22,123	9798	27	12	32,801	14,527
	O_3	1.7E-02	7.5E-03	2.0E-05	9.0E-06	2.5E-02	1.1E-02
	PM_{10}	2368	1047	3	1	3511	1552
	Total (ton)	53,436	22,988	29,880	11,210	64,819	28,679

Table 9
Amount of pollution released (Derived from SimaPro results).

	Air pollution removal (ton/yr) Yang et al., 2008	Pollution released (ton)	
		Non-recycled materials (option 1)	Recycled materials (option 2)
First scenario	1835.2	53,435.80	22,987.73
Second scenario	1405.5	29,880.49	11,210.08
Third scenario	2046.9	64,818.54	28,679.10

reported by Yang et al. [51] is an average rate for green roofs. The air pollution removal depends on the air pollution concentration, weather, type, and age of the plants [51]. Intensive green roofs usually have bigger plants that sequester more contaminants from air due to their natural metabolism [2]. Therefore, intensive green roofs will have a higher air removal rate and have a better performance in the lifecycle analysis.

Difference in above results show uncertainties in green roof performance. Weather, thickness of layers and types of materials and plants are characteristics that vary among green roofs. The choice of these characteristics affects the pollution released in the manufacturing process and influences the environmental performance of green roofs.

Lifespan of green roofs depends on the maintenance, type of green roof, and weather conditions. Acks [1] noted the expected operating life of green roofs as 55 years, while Kosareo and Ries [16] as 45 years, Saiz et al. [30] as 50 years, and Clark et al. [5] as 40 years. Based on these studies, it can be concluded that green roof's lifespan varies between 40 and 55 years. All the analyzed three scenarios, for the two studied options, balanced the pollution created by material manufacturing process in the full lifespan of green roofs. However, it required almost 2/3 and 1/3 of the lifespan of green roofs, with non-recycled and recycled materials, respectively.

The typical disposal phase of green roofs includes dissemble of all the layers and transport them to landfills. The growing medium can be easily re-used in any other purpose and plants biodegrade fast; but not the polymers. Polymers degrade very slowly [4] and on a volume basis represent the 20% of landfills input [36]. Therefore, recycling or reusing these materials becomes an attractive option. Additionally, recycling and reusing avoid the production of new materials. From an environmental point of view, it is recommendable the use of recycled polymers as green roofs layers; even though the recycling process has a negative environmental impact.

It is still beneficial to install green roofs with polymers; however, it is essential to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs. Some industrial and construction processes discard materials that do not meet the designed quality or intended purpose. Introduce these waste materials into green roof construction is the next immediate challenge.

Table 10
Years needed to balance pollution.

	Years		Non-recycled/recycled
	Non-recycled materials	Recycled materials	
First scenario	29	13	2.23
Second scenario	21	8	2.62
Third scenario	32	14	2.28
		Average	2.37
		Variance	0.05

8. Conclusions

Results demonstrate that there are more advantages than disadvantages of building green roofs to reduce air pollution. Positive environmental impacts emphasize the importance of green roofs as a sustainable option for the construction industry and society. The analysis presented in this paper considered four main polluting substances (NO_2, SO_2, O_3 and PM_{10}); however the production process of polymers releases more toxic substances to different media. Investigations needed to be conducted to enhance the overall air pollution potential of green roofs.

The pollution released to the air due to the polymer's production process can be balanced by green roofs in long term; however it is important to point that the manufacturing process of low density polyethylene and polypropylene has high negative impacts to the environment. The analysis concluded that it is still beneficial to install green roofs with polymers; however, it is essential to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs. The use/re-use of waste materials is a mandatory step in green construction.

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