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AIR POLLUTION REMOVAL AND CONTROL BY GREEN LIVING ROOF SYSTEMS

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Abstract: Cities are open and dynamic urban ecosystems, which consume, transform and release matter and energy. By erecting buildings change in the flow of energy and matter through the urban ecosystems occurs creating multiple environmental problems. Those problems are amplified by transportation and production systems, which influence the elements of the ecosystem negatively. Air pollution in the urban environment, as one of the problem, is a major threat to human health. Conventional air pollution management programs focus on controlling the source of air pollutants but do not address the pollutants already in the air. Green roof implementation strategy is an innovative approach that can be adopted to remove existing air pollutants thereby reducing air pollution concentrations to an acceptable level, as vegetation plays important roles on remediating air pollution after the emission occurs. The green roof can be used to supplement the use of urban trees in air pollution control, especially in situations where land is not available and public funds are insufficient. This review paper presents collected data comparing the findings from different research conditions and approach, to explore the important role that the green living roofs can play in the dense urban areas, mainly considering the impact on air quality. Pollution level, type of green roof involved in researches, and different material selection, for both plants and soil, have considering the influence on the performance of the green roof as a passive natural air filtration system.
Keywords: green roof, air pollution, environment, building

INTRODUCTION

Change in the flow of energy and matter through the urban ecosystems occurs by altering the surface cover of an area. Urban areas invade natural landscapes creating a deficiency of green spaces and multiplying environmental problems impacting the entire planet. Those problems are amplified by modern anthropogenic sources such as transportation (vehicular traffic fuel combustion, particularly diesel, and vehicular component wear) and production systems, which influence the elements of the ecosystem negatively. A focus on decreasing energy consumption should progressively reduce air pollution from power generation and industry. Transitional nations, with increasing traffic amounts, need to focus on preserving the health of their citizens. Concerns about black smoke and air acidification (sulfur dioxide, SO_2) from coal burning have been replaced by new concerns about particle pollution and nitrogen dioxide (NO_2) from transport, and the air pollution that forms through chemical reactions between other pollutants in the atmosphere. City residents are at most risk from being exposed to urban particulate pollution. Particles smaller than 10 μm diameter (PM_{10}) can penetrate deep into the pulmonary passages where any transition metals present can release free radicals in lung fluid and cause cellular inflammation [1]. Conventional air pollution management strategy effectively reduces the emission of new air pollutants focusing on controlling the source but does not address the issue of pollutants already spreading.

By combining nature and built areas in their designs urban planners can respond to these serious human health and welfare issues and restore the environmental quality of dense urban areas. Greening the building envelope is innovating technology in architecture that can regain losses of natural environment produced by erecting buildings. As vegetation plays important roles on remediating air pollution after the emission occurs adapting the existing building envelope into a green living system would be an efficient and sustainable solution for improving the environmental balance of cities. Greening horizontal surfaces with intensive and extensive green roofs could remove existing air pollutants thereby reduce air pollution concentrations to an acceptable level.

GREEN LIVING ROOF SYSTEMS

Living architecture is the integration of the living, organic systems characterized by green walls and green roofs, with the inorganic and lifeless structures that have come to dominate modern architecture.

The model of the green roof consists of three main components: structural support, the soil layer, and foliage layer. The structural support includes all the layers between the inner plaster and the drainage layer or filter layer. The soil layer is complex with the solid phase (organic and mineral material), the liquid phase (water) and the gaseous phase (water vapor and air). The foliage layer (canopy) is composed of the leafs and the air within the leafs and depends on the plant selection. Depending on its complexity several more layers could be present. The drainage layer provides water for upper layers in relatively small space and with lightweight; excess water overflows and easily passes underneath it away and down the roof drain. The growing medium, filter and protection layer act to support plants and protect lower levels.

There are two main classifications of green roofs: Extensive Green Roofs (EGR) and Intensive Green Roofs (IGR).

The extensive green roofs (EGR)

Extensive Green Roofs are lightweight in structure with a thinner substrate and feature succulent plants like sedums that can survive in harsh conditions (Figure 1). Extensive green roofs are used mainly for environmental benefit, require little maintenance once they are established and are generally cost effective, particularly in commercial and public buildings with long life spans.

Figure 1. EGR, Headquarter Honda, Clermont, FL, USA (left) IGR, Delft University of Technology Library, Delft, The Netherlands (right)

The intensive green roofs (IGR)

Intensive Green Roofs may require irrigation during dry periods having a thicker soil layer than extensive ones. Because of their thicker soil, these roofs require greater structural support (Fig. 1). IGR allow a greater variety and size of plants such as shrubs and small trees but have higher initial costs and maintenance.

THE ROLE OF GREEN LIVING ROOF SYSTEMS IN THE REMOVAL OF AIR POLLUTION

In the reduction of air pollutants, an important role is played not only by trees but also by the structure, texture, and localization of green infrastructure components. Vegetation has been found to be significant sinks for gaseous, aerosol, particulate and rain-borne pollutants. Four processes are responsible for deposition onto the large surface area provided by leaves [2]:

- sedimentation under gravity,
- diffusion,
- turbulent transfer giving rise to impaction and
- interception

The ability to remove air pollutants can be affected by tree crown morphology and city design [3]. The large leaf area and turbulent air movement caused by their structure make trees particularly effective for particle removal. Adapting flat roof surfaces into green living systems is an efficient and sustainable solution as there are limited opportunities to implement urban greenery in ground areas. Roof area fraction may vary from 20% to 25% for less or more dense cities. A study in Toronto found that 58 metric tones of air pollutants could be removed if all the roofs in the city were converted to green roofs, with intensive green roofs having a higher impact than extensive green roofs [4].

Vegetation removes pollutants directly and indirectly. Plants take up gaseous pollutants through their stomata, intercept particulate matter with their leaves, and are capable of breaking down certain organic compounds such as poly-aromatic hydrocarbons in their plant tissues or in the soil. The city of Los Angeles conducted the report and it was estimated that 2000m^2 of uncut grass on the green roof can remove up to 4000kg of particulate matter showing that one square meter of the green roof could offset the annual particulate matter emissions of one car.

Over 889 tons per year of NO_2, 0.5% of that area's emissions, would be removed in Detroit, MI if 20% of all industrial and commercial roof surfaces convert to EGR [5]. Assuming the NO_2 uptake rates by green roof plants were constant Corrie et al. [6] estimated the annual reduction of NO_2 by green roofs in Chicago and Detroit. Their study showed by covering 20% of the roof surface in Chicago the reduction of NO_2 was between 806.48 and 2769.89 metric tons depending on the type of plants used.

Measuring the concentrations of acidic gaseous pollutants and particulate matters on a 4000m^2 roof in Singapore before and after the installation of a green roof Tan and Sia [7] found that after installation of the green roof the levels of particles and SO_2 in air above the roof were reduced by 6% and 37%, respectively. This field measurement proved that green roofs can reduce certain air pollutants but it is difficult to extrapolate their results to other places or to a larger scale.

Using the Urban Forest Effects (UFORE) dry deposition model developed by the USDA Forest Service Currie and Bass [8] studied the effects of green roofs on air pollution in Toronto. The model quantified levels and hourly reduction rates of NO_2, SO_2, CO_2, PM_{10} and ozone as well as their economic value. UFORE calculations were based on vegetation cover, hourly weather data, and data on the concentration of pollutants. Trees and shrubs were more effective in removing contaminants than herbaceous perennials largely due to greater leaf surface area. Although intensive green roofs with trees and shrubs are more favorable in terms of reducing pollution, extensive green roofs can play a supplementary role in regards to air quality.

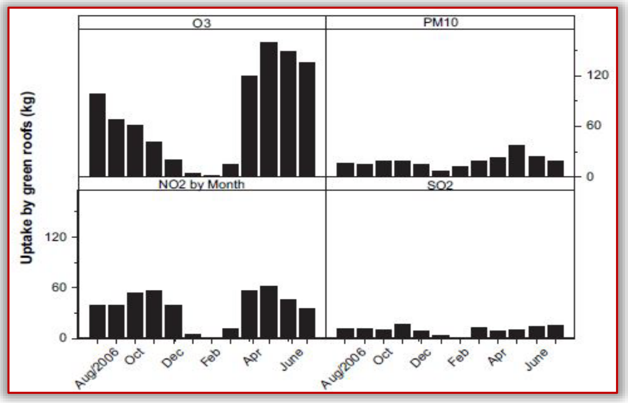

Figure 2. Monthly uptake of air pollutants by green roofs in Chicago between August 2006 and July 2007.

Using also the UFORE dry deposition model the research in Chicago was conducted [8]. The total air pollution removal by 19.8ha of green roofs was 1675kg between August 2006 and July 2007 (Fig. 2). If the reported 2787ha of green roofs were all completed and had the same ratio of extensive vs. intensive green roofs, the air pollutants removed could reach 2388kg. The 19.8ha of green roof consisted of 63% short grass and other low-growing plants, 14% large herbaceous plants, 11% trees and shrubs, and about 12% various structures and hard surfaces. Among the four air pollutants, the uptake of O_3 was the largest, 52% of the total uptake followed by NO_2 (27%), PM10 (14%), and SO_2 (7%). If all remaining roofs in Chicago were planted with intensive green roofs, the direct removal of air pollutants could reach as high as 2046.89 metric tons.

Indirectly lowering surface temperatures by providing shade use of energy for air conditioning is less, due to reduced energy the emission of pollutants from power plants decreases. Calculations showed [9] that emissions from coal-fired power plants could be reduced by 350 tons of NOx per day in Los Angeles by reducing the need for air conditioning. Vegetation also lowers the ambient air temperature by changing the albedos of urban surfaces and through transpiration cooling, which in turn decreases photochemical reactions that form pollutants such as ozone in the atmosphere. A green roof program covering 50% or more of roof space in a city, when implemented in coordination with other large-scale greening efforts like street tree planting, could result in city-wide cooling throughout the day and during peak summertime energy demand periods.

Carbon sequestration

When green coverage is less than 10%, the concentration of CO_2 in the air would be 40% higher than the one with 40% coverage rate, and when the coverage rate reached 50%, the concentration of CO_2 in the air can maintain a normal rate of 320 ppm. Carbon is a major component of plant structures and is naturally sequestered in plant tissues through photosynthesis and into the soil substrate via plant litter and root exudates. The carbon fixation and oxygen release capabilities of the green roof depend on the plant selection. Trees, bushes, and shrubs are better in controlling the CO_2 concentration at certain level improving the environment and maintaining oxygen balance than the grass.

Getter et al. [10] quantified the carbon sequestered by four species of Sedum in a 6.0cm substrate depth extensive green roof in Michigan over a period of two years. At the end of the study, above-ground plant material and root biomass stored an average of 168g C /m^2 and 107g C /m^2, respectively, with differences among species from 64g C /m^2 to 239 g C /m^2 for *S. acre* and *S. album*, respectively. Increasing substrate depth would not only provide a larger volume for carbon storage, it would also enable a wider plant palette that could include larger perennials and even trees.

In Hong Kong, [11] in summer, on a typical sunny day, the CO_2 absorption rate of a plant in the daytime is much higher compared with the CO_2 emission rate at night. The research showed that the extent of the green roof effectiveness depends on factors such as the ambient airflow condition, the green roof position, and the plant's condition and that the green roof can reduce the CO_2 concentration in the nearby region by nearly 2%.

Table 1. Peer-reviewed journal articles written in English on the effects of green roofs on air pollution [12].

Reference	Location	Topic
Clark et al., 2008a	Michigan, USA	Estimates that NOx reduction would provide an annual benefit of $895-3392 for a 2000 ft^2 green roof and would lead to a mean NPV (net present value) for the green roof that is 24.5-40.2% less than the mean conventional roof NPV.
Currie and Bass, 2008	Toronto, Canada	Effect of various vegetation scenarios (trees, shrubs, green roofs, and green walls) on air pollution estimated using the UFORE model. Results indicate that intensive green roofs would have the greatest impact, but extensive roofs could augment the effect of trees and shrubs.
Getter et al., 2009	Michigan, USA	Measured carbon sequestration of sedum-based extensive green roofs over time, included carbon cost embedded in green roof materials, and calculated the reduction in CO_2 given off from power plants due to energy savings.
Yang et al., 2008	Illinois, USA	Estimated level of air pollution removal in Chicago using a dry deposition model. Annual removal of pollutants per hectare of green roof was 85 kg ha^{-1} yr^{-1} with the highest and lowest removal during May and February, respectively. Would remove 2046.89 metric tons if all rooftops in Chicago were covered with intensive green roofs.

Sterilization

Garden plants as the major species in urban greening have the important role in reducing the amount of environmental harmful pathogenic microorganisms and improving the urban environment's ecological value and adding social benefits. Plants can sterilize and inhibit the bacteria and other pathogenic microorganisms in their living environment to varying degrees. High green coverage rate helps to reduce the bacterial content in the air. Some tree species produce essential oils called phytoncides, which when inhaled, improve mental well-being.

PLANTS SELECTION

The process of pollution removal is depended on distinguishing features of various plant species, their habit, habitat, leaf physical parameters and weather conditions present in the areas. The tolerant species can be used for reducing the level of pollution and sensitive species as bio-indicators for monitoring ambient air quality. The mix of both types can be used for developing green belt in polluted areas. Because plant species possess varying abilities to remove air pollutants and reduce emissions they can be selected to maximize improvements in air quality. Using a better adapted and tolerant floral species in green living roof systems would help to enhance the ecosystem services and reduce the detrimental effects of pollution on the environment.

Reductions in particulate matter, ozone, NOx, and SOx occur while plants are actively growing and in-leaf so evergreen conifers may provide a greater benefit than deciduous species because they retain their leaves year-round.

Table 2. Annual removal rate of air pollutants per canopy cover by different vegetation types in Chicago between August 2006 and July 2007 [8].

Type of vegetation	SO_2 [g/m²yr]	NO_2 [g/m²yr]	PM_{10} [g/m²yr]	O_3 [g/m²yr]	Total [g/m²yr]
Short grass	0.65	2.33	1.12	4.49	8.59
Tall herb. plants	0.83	2.94	1.52	5.81	11.10
Deciduous trees	1.01	3.57	2.16	7.17	13.91

CONCLUSIONS

Air pollution in the urban environment is a major threat to human health. The green living roof systems can be used to supplement the use of urban trees in air pollution control, especially in situations where land is not available and public funds are insufficient. As a strategy to remove air pollutants, intensive green roofs IGR with trees and shrubs are comparable to urban forests and play a much larger role in improving air quality than grasses or succulents that are often found on extensive green roofs EGR.

Beside carbon sequestration by plants and the substrate in the green living roof systems, there is also a reduction in CO_2 given off from power plants due to the green roof's ability to insulate individual buildings and reduce the urban heat island. Reductions in particulate matter, ozone, NOx, and SOx occur while plants are actively growing and in-leaf. Green roofs perform better when designed as ecosystems to promote biodiversity instead of monocultures. Plants need to be evaluated in various locations and climatic regions, as well as for management and maintenance practices.

In addition, viewing green vegetation and nature has beneficial health effects as well as improved health and work productivity. Green roofs improve urban air quality and by extension public health and quality of life.

Note

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