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Environmental Benefits of Green Roof Gardens: Reducing Air Pollution and Improving Urban Air Quality

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ABSTRACT

Urban vegetation reduction and higher levels of atmospheric pollutants are due to rapid global urbanization, which has altered nature, creating impervious urban built environments. Green roofs, which is the technology used to introduce vegetation into the building surface, have been virtually invented as a solution to enhance urban environmental quality in an alternative and innovative manner. This study aims to examine the possibilities through which Green Roofing systems can help to reduce air pollution and carbon in densely populated cities especially Lahore, Pakistan. Green roofs are said to be the "future lungs" of cities, and how they can create vegetation in highly urbanised building sites, thus reinforcing the bond between built and natural environments is examined. This study explores three green roof sites, based on a comparative isosceles triangle case-study approach: Chicago, USA; Lahore, Pakistan; and Washington, D.C. USA. The results of this study examine the environmental benefits of green roofs that have been reported in relation to the removal of air pollutants, carbon sequestration and the improvement of the urban environment. The results showed the potential of the Green Roof in terms of bringing up vegetational cover and ecosystem service to urban sustainability, especially in a location where the availability of the green space at ground level is limited. The study also covers the viability of green roof technology, highlighting its feasibility as a potential nature-based solution for mitigating environmental stresses in fast-growing cities like Lahore. Finally, the study examines the contribution of green roofs in the context of the "future lungs" of cities and suggests possibilities and limitations in further use in urban areas.

Introduction

The increasing urbanization pace has undergone significant alteration of the physical and environmental natures and attributes of cities. Urbanization, population growth, transport emission, urban industries and the conversion of natural environment into impervious pavements have contributed to the declining urban environmental conditions. Among the most serious impacts of this change is the buildup of atmospheric pollutants, primarily particulate matter (PM), nitrogen dioxide (NO_2), ozone (O_3), and other

pollutants which negatively influence the environmental quality and human health. Meanwhile, the city's ability to provide necessary ecosystem services, endorse air quality regulation and other maintenance via urban greenery has also been reduced due to the shrinking of urban vegetation (Abhijith et al., 2017; Oberndorfer et al., 2007; Rowe, 2011).

In the rapidly growing cities, where population growth and urban expansion outpace the ability to implement environmental infrastructure, air pollution has emerged as a major issue. Although ground-level vegetation can play a role in deposition and interception of pollutants, conventional approaches can be limited in an area by the lack of land. Green infrastructure has thus gained much more attention recently as an adjunct to urban environmental management (Abhijith et al., 2017; Pugh et al., 2012). Lahore, Pakistan, is an important context to discuss alternative NbS solutions due to its significant urban development, population pressure, traffic etc., and due to the ongoing pressure on available green spaces.

Green roofs have become one of these NbS. Green Roof systems can add vegetation, growing media and other ecological elements to a building's roof, providing more greenery where traditional green space at the base of the building may not be possible. In addition to their potential aesthetic-architectural advantages, environmental-performance issues of green roofs may also include stormwater management, thermal regulation, energy savings, biodiversity, carbon storage, removal of atmospheric pollutants, among others (Berardi et al., 2014; Oberndorfer et al, 2007; Shafique et al, 2018). However, the vegetation type, substrate characteristics, roof configuration, climatic conditions and measure of maintenance, all influence their environmental performance (Vijayaraghavan, 2016; Shafique et al., 2018).

The plants of a green roof can interact with pollutants in the atmosphere, including dry deposition, interception, absorption and biological uptake. Rowe (2011) showed that Green Roofs can help to abate atmospheric pollution and Speak et al. 2012 proved that various vegetation types on Green Roofs could contribute to lessening urban particulate pollution. Likewise, Gourdji (2018) highlighted the ability of plants to reduce particulate matter, ozone and nitrogen dioxide and elaborated on point-plant and the environmental relevance of plants used in Green Roof projects. The extent of pollutant reduction is not consistent, however, and is influenced by the type of vegetation, pollutant concentration, meteorological conditions, design of roof, and the urban morphology that varies in the surrounding environment (Arbid et al., 2021; Irga et al., 2022).

There is good quantitative evidence from empirical and modelling studies of air-quality benefits from green roofs. Yang et al. (2008) for instance calculated the pollution removal by dry deposition from green roofs in Chicago. What they found was a total removal of about 1675 kg pollutants per year by the green roofs, of which the major ones analysed were ozone, nitrogen dioxide, particulate matter and sulfur dioxide. The total amount which was estimated to be removed was about 85 kg annually per hectare of green roof. The results indicate the contribution of green roof projects to urban air-pollution management and offer valuable quantitative data on whether to consider green roofs as an alternative to traditional emission-control linking strategies.

A wider, general environment and economic impact statement of green roofs have also been investigated. Niu et al. (2010) compiled a study in Washington D.C. where they investigated the scaling of economic values of green roof implementation, such as stormwater management, energy savings, avoided emissions and N-Ox uptake. They showed that green roofs can provide energy- and infrastructure-related environmental benefits, in addition to the direct pollutant-removal benefits. In the same way, green roofs have been studied from the carbon point of view, revealing their carbon sequestering ability, potential for carbon-related environmental benefits (Getter et al., 2009; Shafique et al., 2020).

In differing climatic conditions, one can again see that green roof performance is very context specific. For instance, Viecco et al. (2018) studied deposition of particulate-matter on vegetated green roofs and green walls in a semiarid climate. The results they provide can pertain to assessment of vegetated infrastructure in moderately dry environmental conditions. Similarly, Speak et al. (2012) tested four plant species on the green roofs for particulate pollution reduction and found that selection of a species can directly impact pollutant-capture. From these findings, it is evident that any transfer of results from one city, or climatic region, to another should be done with care.

The environmental role of a green roof can thus be seen in the context of green infrastructure and NbS. Green Roofs are an interface between the built and natural environments, instead of treating buildings and vegetation separately. This integration can enhance the urban vegetation cover without requiring extra space at ground level – an option especially valuable for land constrained cities (Oberndorfer et al., 2007; Shafique et al., 2018). Green roofs also serve other environmental purposes such as thermal regulation, storm water retention by the green roof, energy-related benefits include reduction in energy consumption, habitat provision (Berardi et al., 2014; Castleton et al., 2010; Santamouris, 2014). Therefore, this should be interpreted as a set of interlinked ecosystem services, as well as being an air pollution prevention technology, for urban sustainability.

In this way, the introduction of vegetation to highly urbanized areas have led to proposal of “the future lungs” of cities as a way to conceptually describe green roofs. But this statement is meant as a conceptual rather than direct equivalency statement between green roofs and natural forests. Green roofs typically offer a low capacity for pollutant removal and benefits only occur at a local, relatively small, scale depending on the size

of the roof, nature of the vegetation, design, maintenance, pollutant levels and climatic conditions (Rowe, 2011; Arbid et al., 2021). There are also mixed findings in recent studies on the effects of air pollution and green roofs, suggesting that the performance of green roofs can be appreciated based on local environmental conditions (Irga et al., 2022).

Despite the growing number of international studies on green roofs, there is a need for comparative studies that examine the environmental advantages of green roofs in cities with diverse climatic, geographical and urban conditions. By examining existing studies on green roofs in urban areas like Chicago, U.S. and Washington, D.C., and studying the potential of its application in Lahore, a wider perspective on the role of green roofs in urban environmental improvement can be gained. This sort of comparison is especially relevant when the findings of international studies are being used to identify those that might be transferable to Lahore and which to be locally considered. Climate, selection of vegetation, substrate properties, roof configuration, pollutant concentration and urban morphology are all indicated to greatly influence the performance of green roofs (Vijayaraghavan, 2016; Gourdji, 2018; Arbid et al., 2021).

Hence, this study has been done on Environmental benefits of Green Roof Garden with special focus on Air-pollution Mitigation, Carbon Related benefits and Improvements in the Urban environment. The study compares evidence regarding pollutant reduction, carbon benefits and benefits to wider ecosystem services reported for green roofs at Chicago, Lahore, and Washington, D.C. The study further considers the opportunities and limitations associated with implementing green roof technology in Lahore. In this research, the introduction of green roofs will be analyzed as a nature-based feature of urban infrastructure and presented as one strand of the future environmental infrastructure in cities with a high rate of urbanization, as well as a contribution to a growing debate about sustainable urban development.

Literature Review

The Green Roofs: A Sustainable Solution for Urban Environmental Challenges

Urbanisation has led to spread of impervious surfaces and decreasing natural vegetation in the urban areas. This transformation has exacerbated multiple environmental issues, such as stormwater run-off, loss of ecological functions, urban heat and air pollution. In this context, green roofs have come to be known as a nature-based solution/ green infrastructure solution which can add vegetables to highly built-up urban landscapes.

In their study, Rowe (2011) synthesized the functions of a 'green roof' in the environment and considers it may contribute to the mitigation of air pollution, carbondioxide emissions, carbon sequestration, storm-water management, noise reduction, and more. Environmental and economic advantages of Green Roofs along with the various factors affecting their effectiveness were also highlighted, which includes plant selection, growing substrates, irrigation and designing a Green Roof.

Green roofs are thus not just a form of architecture and aesthetics. They can be used to deliver ecosystem services, at the same time taking up building spaces that can otherwise serve no ecological function. This feature becomes significant in populated cities with limited scope for the development of green spaces on ground level.

Green Roofs and Urban Air Pollution Mitigation

The ability to bind and dispose of airborne pollutants is one of the key aspects of functioning that researches green roofs. The foliage of vegetation can bind particulates on its surface, and it can interact with the gaseous pollutants such as deposition and absorption. The rate of pollutants removal, however, is found to be dependent on the type of vegetation, climatic conditions, roof details, pollutant concentration, and adjacent urban activities.

Yang, Yu, and Gong (2008) conducted an important, early quantitative study in Chicago. The researchers determined the annual amount of air pollutants to be removed with the use of dry-deposition model, the results of which were 19.8 ha of green roof removed approximately 1675 kg per year. The estimated removal from O3, NO_2, PM_{10} and SO_2 were 52%, 27%, 14% and 7%, respectively. The estimated rate of removal was around 85 kg/ha annually.

The results show that city-scale air-pollution management can be achieved by Green Roofs. The study in Chicago is importantly a

quantitative basis for entertaining the idea of using green roofs as extra infrastructure, in addition to the use of trees and parks.

Green Roofs, Carbon Reduction, and Multiple Ecosystem Services

The benefits of green roofs in environmental remediation don't just end there. It is possible that the potential contribution of green roofs to the concept of carbon reduction could be achieved by having vegetated systems that sequester carbon as well as by indirectly reducing building energy needs.

Rowe (2011) pointed out carbon dioxide emissions and carbon sequestration as two of the significant environmental factors for green roofs. Another finding was that green-roof benefits should be considered as bundled instead of singular environmental functionality.

This multifunctionality may be confirmed through the research done by Rafael et al. (2021) on green roofs in Porto, Portugal, based on numerical modelling. They investigated their impacts on PM_{10}, NO_2 and O_3 and on the energy requirement of buildings, including emissions. The study showed that green roofs not only have the potential to directly impact air quality with various processes but can also indirectly affect air quality by lowering the energy needs in buildings. Nevertheless, the authors stated that the impact on air quality did not always have positive results for all pollutants and circumstances.

Therefore, the concept of green roof must be interpreted as one of the environmental approaches having several functions and must not be seen as a single solution to the problem of air pollution in the urban area.

Particulate Matter Removal and Green Roof Vegetation

Particulate matter is one of the big issues of urban pollution especially the $PM_{2.5}$ and PM_{10}. Particulate materials may be deposited on the leaves and various surfaces of plants so that plants may capture particulates. The effectiveness of this process varies considerably between plant species.

Abdul et al., (2018) studied PM depositions on vegetative surfaces used on green roofs and living walls in semiarid climatic conditions. The study evaluated $PM_{2.5}$ and PM_{10} deposition across several plant species and found substantial differences in their particle-capture capacities. S. album, S. reflexum, S. palmeri and Lampranthus spectabilis exhibited relatively successful ability to capture particulate matter. The study concluded that green roof and living wall are quite capable of being used for air-pollution mitigation, especially where particles are high.

This research is important to the current study because changes in climatic conditions could have significant impacts on the performance of the green roof. So, results of temperate cities cannot be translated as such to Lahore without taking the climate region, vegetation, rainfall and temperature, and CO2 pollutant characteristics into account.

Plant Selection and Pollutant-Removal Performance

One of the key elements that affect the efficacy of green roofs is the choice of plants. The structure of leaves, surface characteristics, growth pattern and physiological properties vary across various types of plants, influencing their uptake and/or elimination mechanisms of pollutants.

Gourdji (2018) focused on pollutant-reducing plants and assessed if these species are appropriate for Green Roof applications in Montreal with a focus on reducing PM, O3 and NOx. This study clearly showed that matching the vegetation to target pollutants and climatic conditions is important. Additionally, it identified that there are varyingpollutant-removal capacities between species of plants, which suggest that green-roof vegetation mixture and structure may affect environmental outcomes.

The other experimental study used laboratory scale to measure the NO_2 and O_3 removal through green-roof plants. Three popular species (thyme, sedum, and heuchera) were tested, and thyme exhibited the highest deposition velocities of the three species tested. It is important to test plant species in actual, experimental green roofs to design efficient green roofs for air-quality applications.

So, evaluating environment performance of a green roof cannot be done based on the vegetated area only. Leaf types, species, and density as well as the type of maintenance and substrate should also be taken into account.

Evidence from Lahore and Faisalabad, Pakistan

The studies in Pakistan are relevant in terms of assessing the green roof to be applicable in Lahore. Prospects of Green Roof Technology as a Sustainable Solution to Urban Pollution Index, 2023 Survey in agroeconomic conditions of Lahore and Faisalabad, evaluated rooftop plantation in the agro-ecological context of Lahore and Faisalabad.

The study compared with vegetated and bare rooftop surface and concluded that the average particulate suspension was 13–24% less by the roof garden as compared to bare roof. Additionally, it explored the deposition of heavy metals and revealed that deposition of heavy metal pollution load under bare dust condition of rooftop was more as compared to vegetated roof environment. Pollution-load index data were reported for Lahore and was highest in the midtown areas and least in the case of Roof-garden; which suggests the potential of Roof-gardens for mitigating some type of pollution in urban areas.

This is important considering the current study, because this is local empirical evidence as opposed to just international case studies. It ensures that the concept of rooftop vegetation is relevant in the context of Pakistan and it lays the groundwork for further research into the realization of green roof as an environmental approach in Lahore.

The results also indicate, however, that adoption of green roofs should be viewed as part of a larger urban pollution-management plan, instead of as a substitute for emission-control devices.

Comparative Evidence and the Importance of Local Conditions

While many study results suggest that green roofs are beneficial for the environment, the data does not show that green roofs have the same impact in all cases. Climate, vegetation, roof construction type, pollutant sources, building characteristics and urban morphology are all criteria that influence the performance of the green roof.

Therefore, one of the comprehensive field research projects conducted based on biosolar green roofs, it was observed that the ambient ozone concentrations over a biosolar green roof were lower than over a traditional roof. For the investigated roof, the potentially removed $PM_{2.5}$, O_3 and NO_2 were estimated to be about 0.5 kg, 6.9 kg and2.3 kg per year, respectively. However, no significant differences in mean suspended particulate matter (SPM) concentrations were found between the green and conventional roofs, but construction activities had an impact on NO_2 levels.

The results have shown that the performance of a green roof is dependent on the pollutant and the environmental conditions. So any statements about pollution-control benefits of green roofs should be backed up with evidence specific to the site.

Green Roofs in Washington, D.C.: City-Scale Environmental Benefits

Washington, D.C. is another key green-roof urban study. Niu et al. (2010) studied the benefits of increased green roof adoption in Washington DC from an economic perspective. Green Roofs were discussed as they relate to stormwater management, of which green roofs are one approach, energy efficiency and the air-quality benefits they offer; and the implications of city-wide implementation scenarios were examined.

The Washington, D.C. case shows that green roofs can be more than just a building application. When implemented across a substantial portion of the urban building stock, green roofs may contribute to cumulative environmental benefits. This city-scale perspective is relevant to Lahore because the environmental significance of rooftop greening may increase substantially when individual installations are considered as part of a wider urban green-infrastructure network.

Green Roofs and the Concept of the “Future Lungs” of Cities

The increasing interest in green roofs has contributed to a broader discussion concerning how vegetation can be integrated into highly urbanized environments. The concept of green roofs as the “future lungs” of cities can be understood as a metaphor for expanding urban vegetation onto otherwise unused building surfaces.

The existing literature supports several functions associated with this concept, including pollutant deposition, carbon-related benefits, thermal regulation, biodiversity support, and improved urban environmental quality. However, the literature also indicates that green roofs have limited capacity relative to larger natural ecosystems and should not be considered equivalent to urban forests or large-scale natural vegetation.

Green roofs can rather serve as part of urban green infrastructure, as a complementary feature in situations where space at

ground level is limited. The combined impact of these can be more important if green roofs are installed on many buildings and used in conjunction with using parks, street trees, green walls and other urban vegetation.

Research Gap

The reviewed literature shows that there is significant international interest in the benefits of green roofs as a crucial component of the environment. Previous studies have investigated pollutant removal in the city of Chicago, pollutant capture per plant, air-quality modelling in European cities, field performance in urban settings, and city-wide benefits in Washington, D.C., and Lahore and Faisalabad have evidence that rooftop vegetation decreases particulate suspension and pollution loads when compared with bare roof surfaces.

There are some unfilled areas though. Firstly, many of the previous studies focus on urban areas, experimental conditions or modelling, which makes it hard to assess their performance in different climatic and urban settings. Second, little research has been done on the viability of the benefits that are internationally documented for green roofs in the context of Lahore's ever-technological city. Third, the benefit package for particulate-matter mitigation in relation to carbon, together with the related vegetation characteristics, and overall urban sustainability, needs further integrated research.

Thus, it is possible to use a comparative study of these three green roofs to gain further insight into the unique contribution of green roofs in different urban climates and what can be learned in the case of Lahore. The present study aims at filling this gap by looking into the role of green roofing as a NbS to alleviate the air-pollution pressures and enhance the urban environmental quality, and its potential to contribute to carbon reduction and overall urban sustainability.

Research Methodology

Research Design

This study uses a comparative case-study research method to examine the environment advantages of green-roof gardens and the possible benefits of such gardens in mitigating urban air-pollution. Three cities, which are also different in their urban, climatic and geographical conditions, are chosen: Chicago (USA), Lahore (PAK) and Washington D.C (USA).

The study is a mix of qualitative content analysis of published literature and documented case studies, and quantitative comparison of documented environmental indicators. By doing so, the study was able to investigate the actual environmental impacts of green roofs, as well as the stage that impacts the green roof's efficacy.

Case-Study Selection

The three cases were chosen for the different approaches to green roof implementation.

- Chicago is a known urban green-roof application that has been quantificationally estimated in the removal of pollutants.
- Lahore is a growing city in South Asia, air pollution is an important environmental issue, and rooftop gardening is explored as a solution in local conditions.
- The practice of implementing green roofs on a larger scale at the urban and economic level can be seen in Washington, D.C.

This comparison can help identify if there are any lessons to be learned from existing green-roof programs for future growth of green-roof implementation in Lahore.

Data Collection

Secondary data, primarily in the form of peer-reviewed research papers, scientific journals, research abstracts, research reports from research institutes and governments, as well as green-roof case studies, have been used in the study.

Literature search is targeted on key terms such as:

- Green roofs
- Green roof gardens

- Urban air pollution
- Particulate matter
- $PM_{2.5}$ and PM_{10}
- Nitrogen dioxide (NO_2)
- Ozone (O_3)
- Carbon sequestration
- Green infrastructure
- Nature-based solutions
- Urban sustainability
- Lahore air pollution

Specific focus will be on reportable research that shows measurable environmental results realized through green roofs.

Comparative Variables

Table No 1: The research will look at the various parameters in order to make the comparison in three case studies consistent, which are as follows;

Variable	Purpose
Air-pollutant removal	Examines the potential removal/deposition of PM, NO_2, O_3 and other pollutants
Particulate matter	Evaluates evidence concerning $PM_{2.5}$ and PM_{10} capture
Carbon benefits	Examines carbon sequestration and related carbon-reduction potential
Vegetation	Considers plant species, vegetation density and characteristics
Climate	Examines how climatic conditions may influence green-roof performance
Green-roof characteristics	Considers extensive/intensive systems, substrate and roof configuration
Urban context	Examines population density, development patterns and availability of ground-level vegetation
Environmental benefits	Considers thermal regulation, stormwater management and ecosystem services
Implementation potential	Examines opportunities and limitations for wider application

Quantitative Analysis

In the selected literature, where available, reported measurements are removed and presented in comparative Tables in the cases where numerical results are. They can vary from pollutant removal rates to percentage reductions between vegetated and conventional roofs, pollutant deposition rates, carbon-related estimates, etc., that can be measured.

For instance, it can be used as a locally relevant quantitative indicator when the Lahore/Faisalabad study dropped the particulate suspension in roof gardens by 13-24% as compared to bare roofs. The estimates of pollutant removal for O_3, NO_2, PM_{10} and SO_2 are also like those from the Chicago study.

Due to differences in methodologies, roof size, climatic conditions, type of vegetated surface and measurement time, the values reported by the various studies will not be statistically pooled but will be described. This prevents assuming that measurements from essentially different experiments or models are 'equal'.

Qualitative Analysis

A qualitative content analysis is performed and themes across the selected studies are found. These themes include:

1. Air-pollution mitigation
2. Particulate-matter Deposition
3. Carbon sequestration
4. Energy and thermal benefits
5. Plant selection
6. Climate suitability
7. Urban green-space limitations
8. Maintenance requirements
9. Economic and technical constraints
10. Potential applicability for Lahore

The qualitative analysis explains the reason of different performance of Green Roof in different cities and helps in identifying the factors which should be taken in to account in adopting the international findings in the case of Lahore.

Comparative Analysis

Systematic comparison of the various findings in Chicago, Lahore and in Washington,D.C. presents similarities and differences in terms of the green-roof performance. Comparisons are made along four key lines of analysis:

- Environmental performance: pollution reduction, carbon benefits and ecosystem services.
- Physical characteristics: vegetation, substrate, roof type and roof coverage. Urban environment, density, pollution sources, vegetation and climate.
- Implementation conditions: Technical requirement, Maintenance, economic and emergent scalability.

This structure provides a research approach to identify the environmental benefits which have been consistently reported in different settings, and the local dependent benefits.

Assessment of Lahore's Applicability

Finally, research has been assessed how this green roof technology can be implemented in Lahore. International case studies are interpreted based on Lahore's climatic and urban conditions and not transplanted to Lahore.

Specific focus is placed on:

- Lahore's air-pollution conditions

- High-density urban development
- Availability of rooftop surfaces
- Limited ground-level green space
- Climatic conditions
- Plant selection
- Water requirements
- Building structural capacity
- Installation and maintenance costs
- Long-term management requirements

This assessment provides a basis for discussing whether green roofs could form part of a broader nature-based strategy for improving Lahore's urban environmental quality.

Research Framework

Table No 2: The overall research process can be summarized as:

Literature Review
↓
Identification of Green-Roof Environmental Benefits
↓
Selection of Three Case Studies
Chicago – Lahore – Washington, D.C.
↓
Secondary Data Collection
↓
Extraction of Quantitative Environmental Indicators
↓
Qualitative Thematic Analysis
↓
Cross-Case Comparison
↓
Assessment of Applicability to Lahore
↓
Identification of Opportunities and Limitations

↓

Conclusion on the Potential Role of Green Roofs in Urban Air-Quality Improvement

Research Approach Summary

The study applies the liberal arts research method through secondary-source information and is a mixed-methods comparative case-study approach. Reported environmental outcomes are compared across the various quantitative evidence and interpreted through the qualitative analysis of the contextual factors for green-roof performance. The approach includes not assuming that City A's achievements can be directly translated to City B and assessing what international evidence can be translated and applied in Lahore in relation to its city and climate-specific context. Such application of methodology can be used in order to make a more balanced estimation of green roofs, as a nature-based solution for cities for mitigation of air-pollution and for sustainable urban development.

Data Collection Methods

In this study, the data collection method is based on secondary data analysis and aims to analyze the environmental benefits of green roof gardens focusing on air-pollution mitigation, carbon reduction and urban environmental quality. The sources for data are the peer-reviewed research papers, academic journal articles, scientific databases, case studies of green roofs in documentation and government and institutional reports. The information gathered is then grouped by the three chosen case-study locations, which are Chicago, Lahore and Washington D.C.

Literature and Document Review

The researchers perform a systematic review of the existing literature in the field to compile a list of evidence found on the environmental performance of Green Roofs. Literature collection is done using academic databases and scholarly search platforms. Search is for terms like:

- Green roof
- Green roof gardens
- Urban air pollution
- Green roofs and particulate matter
- $PM_{2.5}$ and PM_{10} removal
- Green roofs and NO_2
- Green roofs and O_3
- Carbon sequestration green roofs
- Green infrastructure
- Nature-based solutions
- Green roofs Lahore
- Green roofs Chicago
- Green roofs Washington DC

Preference is given to peer-reviewed studies with measurable environmental results while clearly describing the methodology of the research performed.

Case-Study Data Collection

Data are collected for three selected urban case studies:

- Chicago, USA: Data concerning pollutant removal by green roofs, particularly O_3, NO_2, PM_{10}, and SO_2, are obtained from published research.
- Lahore, Pakistan: Local evidence concerning rooftop vegetation, particulate suspension, heavy-metal deposition, and pollution conditions is collected from studies conducted in Lahore and comparable Pakistani urban environments.
- Washington, D.C., USA: Data concerning large-scale green-roof implementation, environmental benefits, and potential economic and urban benefits are collected from published research.

Environmental Indicators

Table No 3: To maintain consistency between the cases, relevant information is extracted according to predetermined environmental indicators:

Category	Data collected
Air quality	$PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2 and other reported pollutants
Pollutant removal	Removal rates, deposition rates and percentage reduction
Carbon	Carbon sequestration and CO_2-related benefits
Vegetation	Plant species, vegetation coverage and plant characteristics
Green-roof system	Extensive/intensive system, substrate and roof characteristics
Climate	Temperature, precipitation and climatic conditions were reported
Urban context	**Population density, development pattern and existing vegetation**
Additional benefits	Thermal regulation, energy savings, stormwater management and biodiversity
Implementation factors	Cost, maintenance, water requirements and structural considerations

Quantitative Data Extraction

Numerical data reported in the selected studies are extracted and recorded in a comparative database. These include percentage reductions, pollutant-removal quantities, deposition rates, carbon-related measurements, and other measurable environmental indicators.

For example, the Lahore/Faisalabad study reporting 13–24% lower particulate suspension on roof gardens compared with bare roofs provides a quantitative indicator for the Lahore case. Similarly, the Chicago study provides estimated annual removal quantities for several atmospheric pollutants.

Given methodological differences among the studies reviewed (with regard to roof area, type of vegetation, climate, monitoring duration, and measurement methods), the figures from the various studies are descriptively compared, but not amalgamated into a statistical estimate.

Qualitative Data Collection

Qualitative data is gathered to learn about the factors affecting performance of a green roof. This consists of data on:

- Planning and planting operations
- Green-roof design
- Maintenance requirements
- Climatic suitability

- Water requirements
- Building structure
- Pollution sources
- Urban density
- Availability of ground-level vegetation
- Technical and economic barriers

The above information allows for the explanation of the differences among the three case-study locations.

Data Organization and Comparison

Collected data is tabulated based on location, environmental indicator, research method, research finding and reported benefits. The three cases are then compared, to look for similarities and similarities in their locations.

The gathered evidence is then evaluated regarding the green roofs potential to enhance urban air quality, alleviate environmental stress and to what extent could building green-roofs in Lahore be inspired by experiences from Chicago and Washington, D.C.

Data Reliability and Selection Criteria

In order to increase reliability of the research, preference is given to:

1. Peer-reviewed journal articles.
2. Current and relevant scientific literature.
3. Studies which have well-articulated methodology.
4. Studies that demonstrate environmental results.
5. Research directly associated with green roofs and air quality.
6. Conduct research pertinent to the climatic/urban situation of the chosen cases.

Studies that do not clearly present the methodology, or lack adequate data, or are not particularly relevant to the research questions are not included in the main analysis.

Summary of Data Collection Process

Thus the data collection process can be summarized that::

Literature Search

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Identification of Relevant Studies

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Screening and Selection of Sources

↓

Extraction of Quantitative and Qualitative Data

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Classification by Chicago, Lahore & Washington, D.C.

↓

Organization of Environmental Indicators

Comparative Analysis

↓

Assessment of Green-Roof Potential for Lahore

This methodology creates a framework for assessing the potency of green roofs as NbS for urban air-pollution mitigation, carbon reduction and the improvement of the urban environment based on scientific evidence.

Results and Discussion

Overview of Findings

Comparative analysis reveals that several environment benefits of green roofs can be achieved in the urban environment, including particulate-matter deposition, gaseous pollutant uptake, carbon-related benefits, energy savings and overall ecosystem services. The extent and occurrence of these benefits, however, depend on climatic parameters, vegetal cover, constitutive parts of roofs, pollutant species, city features and on how the performance is quantified.

The three case studies provide examples of scales of green roof performance. For the Chicago case, the quantitative evidence of pollutant removal from the atmosphere is presented; for the Lahore case, locally measured evidence of particulate matter and heavy-metal deposition is presented; finally, for the Washington, D.C. case, the benefits of the green-roof are presented at a city, broader, and economic level. All these results indicate that as mentioned before green roofs can be a good solution as an additional sustainable part of urban Green Infrastructure, and that as such they are not a universal remedy to urban air pollution.

Table No 4: Estimated pollutant removal by Chicago green roof

Pollutant	Contribution to total removal
O_3	52%
NO_2	27%
PM_{10}	14%
SO_2	7%
Total	100%

Air-Pollution Reduction in Chicago

The Chicago example is one of the most persuasive quantitative examples of the potential of green roofs to remove unwanted pollutants from the atmosphere. Using a dry-deposition model, Yang et al. (2008) calculated pollutant reduction from about 19.8 ha of green roofs in Chicago. The results they achieved suggest an annual removal of about 1675 kg of air pollutants (approx. 85 kg ha-1 year-1). The most important species were ozone (52% of the estimated removal), NO_2 (27%), PM_{10} (14%) and SO_2 (7%).

The results show that green roofs can provide extra surfaces where pollutants can be deposited in urban built-up areas. The particularly high proportion attributed to ozone suggests that the environmental contribution of green roofs is not limited to particulate pollution. The study also reported seasonal variation, with the highest removal occurring in May and the lowest in February, demonstrating that climatic and seasonal conditions influence green-roof performance.

These findings are significant for cities where opportunities for expanding ground-level vegetation are limited. Nevertheless, the Chicago results are based on a modelling approach and should therefore be interpreted as estimated pollutant removal rather than direct measurements of improved city-wide ambient air quality.

The Lahore case provides particularly important evidence because it represents the environmental and climatic context of the

study's primary area of interest. A 2023 study of rooftop plantations in Lahore and Faisalabad measured particulate matter using anoptoelectronic sensing device and examined heavy metals in dust samples from vegetated and non-vegetated locations. The study found that average particulate suspension was 13–24% lower on roof gardens than on bare roofs.

The study also found that particulate concentrations varied according to location and season. In Lahore, the reported PM range for roof gardens was approximately 63.8–111 μg/m^3, while community-garden locations showed a lower range of approximately 59–100.2 μg/m^3. The researchers also reported that particulate suspension on roof gardens and community gardens was 13–24% lower than at other investigated locations.

One of the other results relates to deposition of heavy metals. Pollution-load index measured with Lahore's midtown areas was 1.64, at the baseline areas, 1.48, for the typical rooftops 0.98, at the rooftop gardens 0.78 and in standard garden was 0.75. The implication of this is that the pollution loads of vegetated roof surfaces were significantly less than that of the conventional roof surfaces.

Table No 5: Pollution-load comparison reported for Lahore

Lahore location	Pollution Load Index
Midtown	1.64
Baseline	1.48
Typical roof	0.98
Roof garden	0.78
Standard garden	0.75

These findings are especially pertinent in relevance to the proposed application of green roof in Lahore. They propose that for an urban city like this there may be needs of particulate matter and associated contaminant capture in the presence of insufficient amount of ground level green space; thus, rooftop vegetation might be used for that purpose.

But the findings cannot be taken as proof that green roofing is a single solution to air pollution in Lahore. Pollution transport, construction, seasonal meteorology, traffic and industrial emissions are still significant sources of air pollution. Therefore, green roofs should be considered as an additional mitigation solution.

Comparison Between Chicago and Lahore

Although both Chicago and Lahore studies indicate the potential of vegetated roofs in pollutant removal, they have adopted different strategies and considered different indicators.

The Chicago study estimates removals in the atmosphere via a dry-deposition model and presents removal amounts for O_3, NO_2, PM_{10}, and SO_2. The Lahore study, however, incorporates direct PM monitoring and heavy metal analysis of dust collected from roof gardens versus bare roof and conventional roof environments.

Hence, no conclusions can be made from the numerical results that one city's green roof is more performative than the others. Rather, the comparison illuminates how under varying environmental conditions, green roofs can impact various aspects of urban pollution.

This difference is noteworthy in the case of Lahore. International modelling evidence can eclipse the potential mechanisms and the extent of pollutant removal, while local measurements are better suited to give evidence on how the rooftop vegetation plants are working at present climatic and pollution conditions of Lahore.

Washington, D.C.: Scaling Green-Roof Benefits

The Washington, D.C. case shows that the value of the environment provided by green roofs is not limited to individual facilities. Niu et al. (2010) investigated the potential at the city scale on the economic benefits of green roofs, taking storm water

management, energy savings, avoided emissions, and NO_x uptake into account in an economic assessment.

It was estimated that about $0.87 million in energy was lost annually, with avoided emissions benefits estimated between $0.09 million and $0.41 million annually for the scenarios analyzed. The estimated benefit of storm water infrastructure was approximately $1.04 million, with further benefits in the form of fees for stormwater being approximately $0.22-$0.32 million per year.

The study also discovered that when excluding maintenance fees, the estimated net present value was about 30-40% less for green roofs compared to conventional roofs on a 40-year life span.

The significance of the Washington, D.C. case is that it serves as proof that the cumulative impacts of green roofs are significant at an urban scale. While having a comparatively small environmental impact itself, the cumulative impact of a large number of Green Roofs can have a much greater effect.

This means that a whole-of-city rooftop greening initiative may allow to create a larger environmental impact than individual green roof projects in Lahore. However, financial and environmental impacts of the outcomes in Washington, D.C. can't be necessarily translated into Lahore due to the differences in construction cost, energy costs, building codes, climatic conditions, maintenance practices, and economic conditions.

Green Roofs and Energy and Carbon Benefits

The reviewed evidence suggests that the environmental benefits of green roofs extend beyond direct pollutant capture. Green roofs can modify building thermal conditions and potentially reduce heating and cooling requirements, which can indirectly reduce energy-related emissions.

Rafael et al. (2021), using numerical modelling for Porto, Portugal, investigated the direct and indirect effects of green roofs on PM_{10}, NO_2, and O_3. Their findings demonstrated that green roofs could influence local meteorological conditions and therefore affect pollutant concentrations in both positive and negative ways. The study also found that green roofs can reduce building energy requirements, with associated reductions in emissions. However, the overall direct effect on air quality was reported as negligible in the studied scenario.

This finding is important because it introduces a necessary qualification to the positive results reported in Chicago and Lahore. Reductions in emissions of all pollutants due to green roofs are not guaranteed for all climates. Different effects may occur due to changes in surface temperature, atmospheric circulation, boundary-layer conditions or vegetation.

Therefore, the potential of carbon benefits in green roofs can be manifested in a number of ways such as permanent carbon storage in vegetation as well as indirect reduction of emissions due to reduced building energy demand.

Influence of Vegetation and Local Conditions

Based on the comparison, it is evident that the performance of green roofs varies highly with the local environment. Pollutant capture could be affected by vegetation type, vegetation density, substrate type, aspects of the roof, climatic conditions, rainfall, temperature, and pollutant sources.

The Lahore research results showed that heavy metals and dust can be captured by vegetation in the form of trees, shrubs, and ground cover more effectively than areas without vegetation.

The findings have direct impacts on the green roof design in Lahore. Focusing on visual attractiveness alone or on plants that are easy to care for can result in plants that are not as effective for air-quality improvement. Plant species should also be evaluated in terms of their tolerance to Lahore's climate, water requirements, leaf characteristics, growth patterns, and capacity to capture particulate matter.

Green Roofs as Part of the “Future Lungs” of Cities

The results provide partial support for conceptualizing green roofs as part of the “future lungs” of cities. Chicago demonstrates measurable pollutant-removal potential, Lahore provides evidence of reduced particulate suspension and pollution loads on vegetated roofs, and Washington, D.C. demonstrates how green-roof benefits can accumulate at a larger urban scale.

However, the findings do not support treating green roofs as substitutes for forests, parks, or emission-control policies. The Porto

modelling study, for example, found that direct air-quality effects can be mixed and that the overall impact on air quality may be negligible under particular conditions.

Therefore, the term "future lungs" is best understood as a conceptual metaphor describing the expansion of urban vegetation onto building surfaces. Green roofs can complement, rather than replace, conventional urban green spaces and pollution-control measures.

Comparative Results

Table No 6: Comparative findings from the selected case studies

Indicator	**Chicago**	**Lahore**	**Washington, D.C.**
Primary evidence	Modelling	Field measurements	City-scale modelling/economic assessment
Main focus	Atmospheric pollutant removal	PM and heavy-metal deposition	Environmental and economic benefits
PM benefit	PM_{10} estimated removal	13–24% lower particulate suspension	Considered within broader benefits
Gaseous pollutants	**O_3, NO_2, SO_2**	**Not the primary measured focus**	**NO_x uptake and avoided emissions**
Carbon/emissions	Indirect relevance	Potential but not directly quantified in the cited study	Avoided CO_2 and other emissions
Major contribution	Quantified pollutant removal	Local Pakistani evidence	Scaling and economic evaluation
Main limitation	Model-based estimates	Limited spatial/temporal scope	Context-specific economic assumptions

The comparison demonstrates that no single case study captures all dimensions of green-roof performance. Instead, the three cases provide complementary evidence. Chicago contributes quantitative evidence of atmospheric pollutant removal; Lahore provides locally relevant field evidence; and Washington, D.C. demonstrates the potential cumulative and economic value of large-scale implementation.

Discussion: Implications for Lahore

The findings have several implications for the future application of green roofs in Lahore.

- First, the local evidence indicates that rooftop vegetation can reduce particulate suspension, and pollution loads relative to bare or conventional roof surfaces. This provides a stronger justification for investigating rooftop greening within Lahore than relying solely on evidence from temperate cities.
- Second, the Chicago case study shows that green roofs have the ability to substantively reduce a number of pollutants in

the atmosphere, such as O_3, NO_2, PM_{10} and SO_2. This implies that in Lahore, green roof can be considered as a potential add-on solution with existing air-quality management efforts.

- Third, as seen in Washington, D.C., there is a need for scale. The value of the environmental benefit of green roofs grows even more if green roofs are part of a coordinated green infrastructure approach for more than one building.
- Finally, green-roof interventions should be assessed with a multipurpose approach and not only based on air pollution, since they also proved to be a successful tool in Porto.
- These benefits can be energy savings, thermal control, stormwater, and other ecosystem services even when there is not much change in ambient air quality.

Overall Discussion

The results show that Green Roof technologies have indeed measurable potential in contributing to environmental improvement in the urban context, especially in particulate capture, deposition of the pollutants present in the atmosphere, reduction of emissions related to energy consumption and in the expansion of urban vegetation.

Best local evidence endorses the Particulate Suspension and pollution-load indices that was associated with having roof gardens in Lahore (13–24% less than in bare-roof environments). The Chicago evidence also shows the ability of green roofs to capture a variety of pollutants in the atmosphere, and the Washington, D.C. case study illustrates how benefits on a green roof could be determined on a city-wide basis.

However, the evidence shows that green roofs are not directly a solution to air pollution in cities and represent a one-fits-all solution. Their effectiveness is a function of the vegetation, climate, roof parameters, type of pollutants and urban context. The overall results obtained in the modelling study carried out in Porto, which were contradictory, show the value of the location-specific approach.

Thus, Green roofs could be regarded as one of the parts of the whole urban environmental pattern, the urban tree should be distributed in the urban landscape along with parks, green corridors, emission reductions, sustainable transportation, and other measures affect emissions in cities. Their contribution may be greatest in the development of vegetation cover in the existing built fabric, where they may provide an opportunity to build-up rather than out.

Key finding

The comparison shows that green roofs can be a utility in terms of city air quality improvement and in general environmental sustainability, depending on the context. The local evidence in Lahore serves as a good ground for rooftop greening, while international evidence shows evidence towards removal of pollutants and environmental gains at the city level.

Conclusion

Based on this study, green roof garden has immense potential so as to act as a NbS tool for enhancing the environmental quality of the urban spaces while reducing the air pollution. The comparative analysis between the three cities of Chicago, Lahore, and Washington, D.C., has shown that green roofs may be able to provide for the capture of particulate matter, pollutant deposition, carbon related benefits, thermal regulation, and other ecosystem services.

The data gathered from Lahore specifically is noteworthy as it shows that Rooftop Garden (RTG) can reduce the Particulate Suspension (PS) as opposed to bare roof. International case studies also show that green roofs help in mitigating several air pollutants and benefit more when a number of them are built on an urban scale.

But the performance of green roofs varies according to the local climate, plant seeds, roof structure, maintenance, etc. and the pollution sources in the surrounding environment. Hence, green roofs should not be regarded as an alternative to measures for reducing emissions or to conventional green spaces, but as a complementary part of an integrated approach to urban environmental issues.

In conclusion, the Green Roof can play a part in building a healthier, more sustainable and climate-resilient City. Adopting rooftop greenery in a city like Lahore is another way of creating more green infrastructure without sacrificing too much of the limited public land available. Additional long-term and site-specific studies are suggested to assess species of plants, pollutant removal

efficiency, carbon benefits and costs, and feasibility to scaling up.

References

1. Abhijith, K. V., Kumar, P., Gallagher, J., McNabola, A., Baldauf, R., Pilla, F., Broderick, B., Di Sabatino, S., & Pulvirenti, B. (2017). Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments—A review. *Atmospheric Environment, 162*, 71–86. https://doi.org/10.1016/j.atmosenv.2017.05.014

2. Arbid, Y., Richard, C., & Sleiman, M. (2021). Towards an experimental approach for measuring the removal of urban air pollutants by green roofs. *Building and Environment, 205*, 108286. https://doi.org/10.1016/j.buildenv.2021.108286

3. Berardi, U., GhaffarianHoseini, A., & GhaffarianHoseini, A. (2014). State-of-the-art analysis of the environmental benefits of green roofs. *Applied Energy, 115*, 411–428. https://doi.org/10.1016/j.apenergy.2013.10.047

4. Bianchini, F., & Hewage, K. (2012). How "green" are green roofs? Lifecycle analysis of green roof materials. *Building and Environment, 48*, 57–65. https://doi.org/10.1016/j.buildenv.2011.08.019

5. Carter, T., & Keeler, A. (2008). Life-cycle cost–benefit analysis of extensive vegetated roof systems. *Journal of Environmental Management, 87*(3), 350–363. https://doi.org/10.1016/j.jenvman.2007.01.024

6. Castleton, H. F., Stovin, V., Beck, S. B. M., & Davison, J. B. (2010). Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings, 42*(10), 1582–1591. https://doi.org/10.1016/j.enbuild.2010.05.004

7. Coma, J., Pérez, G., Solé, C., Castell, A., & Cabeza, L. F. (2016). Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renewable Energy, 85*, 1106–1115. https://doi.org/10.1016/j.renene.2015.07.074

8. Currie, B. A., & Bass, B. (2008). Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems, 11*(4), 409–422. https://doi.org/10.1007/s11252-008-0054-y

9. De-Ville, S., Menon, M., Jia, X., Reed, G., & Stovin, V. (2017). The impact of green roof ageing on substrate characteristics and hydrological performance. *Journal of Hydrology, 547*, 332–344. https://doi.org/10.1016/j.jhydrol.2017.02.006

10. Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., & Andresen, J. A. (2009). Carbon sequestration potential of extensive green roofs. *Environmental Science & Technology, 43*(19), 7564–7570. https://doi.org/10.1021/es901539x

11. Gourdji, S. M. (2018). Review of plants to mitigate particulate matter, ozone as well as nitrogen dioxide air pollutants and applicable recommendations for green roofs in Montreal, Quebec. *Environmental Pollution, 241*, 378–387. https://doi.org/10.1016/j.envpol.2018.05.053

12. He, Y., Yu, H., Dong, N., & Ye, H. (2016). Thermal and energy performance assessment of extensive green roof in summer: A case study of a lightweight building in Shanghai. *Energy and Buildings, 127*, 762–773. https://doi.org/10.1016/j.enbuild.2016.06.016

13. Irga, P. J., Fleck, R., Arsenteva, E., & Torpy, F. R. (2022). Biosolar green roofs and ambient air pollution in city centres: Mixed results. *Building and Environment, 226*, 109712. https://doi.org/10.1016/j.buildenv.2022.109712

14. Li, D., Bou-Zeid, E., & Oppenheimer, M. (2014). The effectiveness of cool and green roofs as urban heat island mitigation strategies. *Environmental Research Letters, 9*(5), 055002. https://doi.org/10.1088/1748-9326/9/5/055002

15. Li, W. C., & Yeung, K. K. A. (2014). A comprehensive study of green roof performance from environmental perspective. *International Journal of Sustainable Built Environment, 3*(1), 127–134. https://doi.org/10.1016/j.ijsbe.2014.05.001

16. Li, Y., & Babcock, R. W. (2014). Green roofs against pollution and climate change: A review. *Agronomy for Sustainable Development, 34*(4), 695–705. https://doi.org/10.1007/s13593-014-0230-9

17. Mahdiyar, A., Tabatabaee, S., Abdullah, A., & Marto, A. (2018). Identifying and assessing the critical criteria affecting decision-making for green roof type selection. *Sustainable Cities and Society, 39*, 772–783. https://doi.org/10.1016/j.scs.2018.03.007

18. Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., & Mihalakakou, G. (2001). Analysis of the green

roof thermal properties and investigation of its energy performance. *Energy and Buildings, 33*(7), 719–729. https://doi.org/10.1016/S0378-7788(01)00062-7

19. Niu, H., Clark, C., Zhou, J., & Adriaens, P. (2010). Scaling of economic benefits from green roof implementation in Washington, DC. *Environmental Science & Technology, 44*(11), 4302–4308. https://doi.org/10.1021/es902456x
20. Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R. R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K. K. Y., & Rowe, B. (2007). Green roofs as urban ecosystems: Ecological structures, functions, and services. *BioScience, 57*(10), 823–833. https://doi.org/10.1641/B571005
21. Ode Sang, Å., Thorpert, P., & Fransson, A.-M. (2022). Planning, designing, and managing green roofs and green walls for public health: An ecosystem services approach. *Frontiers in Ecology and Evolution, 10*, 804500.https://doi.org/10.3389/fevo.2022.804500
22. Pugh, T. A. M., MacKenzie, A. R., Whyatt, J. D., & Hewitt, C. N. (2012). Effectiveness of green infrastructure for improvement of air quality in urban street canyons. *Environmental Science & Technology, 46*(14), 7692–7699. https://doi.org/10.1021/es300826w
23. Rafael, S., Rodrigues, V., Pinto, M. C., … (2021). Are green roofs the path to clean air and low carbon cities? *Science of the Total Environment, 798*, 149313. https://doi.org/10.1016/j.scitotenv.2021.149313
24. Rowe, D. B. (2011). Green roofs as a means of pollution abatement. *Environmental Pollution, 159*(8–9), 2100–2110. https://doi.org/10.1016/j.envpol.2010.10.029
25. Santamouris, M. (2014). Cooling the cities—A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy, 103*, 682–703. https://doi.org/10.1016/j.solener.2012.07.003
26. Shafique, M., Kim, R., & Kwon, K.-H. (2018). Green roof for stormwater management in a highly urbanized area: The case of Seoul, Korea. *Sustainability, 10*(3), 584. https://doi.org/10.3390/su10030584
27. Shafique, M., Kim, R., & Rafiq, M. (2018). Green roof benefits, opportunities and challenges—A review. *Renewable and Sustainable Energy Reviews, 90*, 757–773. https://doi.org/10.1016/j.rser.2018.04.006
28. Shafique, M., Xue, X., & Luo, X. (2020). An overview of carbon sequestration of green roofs in urban areas. *Urban Forestry & Urban Greening, 47*, 126515.
29. https://doi.org/10.1016/j.ufug.2019.126515
30. Speak, A. F., Rothwell, J. J., Lindley, S. J., & Smith, C. L. (2012). Urban particulate pollution reduction by four species of green roof vegetation in a UK city. *Atmospheric Environment, 61*, 283–293. https://doi.org/10.1016/j.atmosenv.2012.07.043
31. Tan, C. L., Tan, P. Y., Wong, N. H., Takasuna, H., Kudo, T., Takemasa, Y., Lim, C.
32. V. J., & Chua, H. X. V. (2017). Impact of soil and water retention characteristics on green roof thermal performance. *Energy and Buildings, 152*, 830–842. https://doi.org/10.1016/j.enbuild.2017.01.011
33. Viecco, M., Vera, S., Jorquera, H., Bustamante, W., Gironás, J., Dobbs, C., & Leiva, E. (2018). Potential of particle matter dry deposition on green roofs and living
34. walls vegetation for mitigating urban atmospheric pollution in semiarid climates.
35. *Sustainability, 10*(7), 2431. https://doi.org/10.3390/su10072431
36. Vijayaraghavan, K. (2016). Green roofs: A critical review on the role of components, benefits, limitations and trends. *Renewable and Sustainable Energy Reviews, 57*, 740–752. https://doi.org/10.1016/j.rser.2015.12.119
37. Yang, J., Yu, Q., & Gong, P. (2008). Quantifying air pollution removal by green roofs in Chicago. *Atmospheric Environment, 42*(31), 7266–7273. https://doi.org/10.1016/j.atmosenv.2008.07.003



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