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REVIEW

The Economic and Environmental Payoff of Green Roofs and Vertical Forests in Urban Air Pollution Mitigation

Abdulaziz Aljehani [1] **,** ***Rima J. Isaifan*** [1,2*]

[1] Georgetown University, Doha P.O. Box 23689, Qatar

[2] Department of Environmental Sciences, Cambridge Corporate University, Lucerne 6006, Switzerland

ABSTRACT

This study critically reviews the economic, environmental, and health impacts of integrating green infrastructure, specifically vertical forests and green roofs, into urban environments as a strategy for air pollution mitigation. A systematic review of recent studies, selected through PRISMA guidelines from Google Scholar, ScienceDirect, Springer Nature, and Cambridge University Press, was conducted. Evidence shows that green infrastructure reduces concentrations of pollutants such as $PM_{2.5}$, NO_x, SO_2, and O_3 through natural deposition, airflow modification, and vegetation filtering. These reductions translate into measurable health benefits, including lower rates of respiratory and cardiovascular diseases, decreased healthcare costs, and enhanced well-being. Economically, while installation costs vary by region, from $15–540 per m², long-term returns include reduced energy use from improved insulation, higher property values, and healthcare savings. However, valuation models often underestimate long-term benefits by excluding indirect savings. Policy gaps, inconsistent urban planning support, and limited economic justification remain barriers to adoption. The review highlights the need for interdisciplinary evaluation frameworks, integration

*CORRESPONDING AUTHOR:
Rima J. Isaifan, Georgetown University, Doha P.O. Box 23689, Qatar; Department of Environmental Sciences, Cambridge Corporate University, Lucerne 6006, Switzerland; Email: rji7@georgetown.edu , risaifan@cambridgecu.ch

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of health-based urban indicators, and targeted incentives to advance implementation. Future research should prioritize region-specific, longitudinal studies to provide stronger evidence for planning decisions. Overall, green infrastructure represents a cost-effective pathway toward sustainable urban development with co-benefits for public health and the economy.

Keywords: Green Infrastructure; Vertical Forests; Green Roofs; Urban Air Pollution; Environmental Health; Sustainable Cities; Return on Investment; Urban Planning

1. Introduction

As the human population grows, cities and urban areas continue to expand. Some cities have become so large that they are now being referred to as megacities [1]. Typically, the larger the city, the more polluted the air is, as it usually means higher population density, increased vehicular emissions, greater industrial activity, and little to no green spaces. The integration of sustainable infrastructure into urban areas is key to air pollution mitigation, which negatively impacts our health and development. Environmental urbanism is an approach to urban planning that emphasizes the integration of natural ecosystems and environmental principles into urban areas. The main goal is to create cities that are sustainable with clean air and a less polluted atmosphere. Green roofs (GRs) and vertical forests (VFs) are a recent innovation that allows us to implement environmental urbanism in urban areas. Gas and VFs contribute to air purification as the leaves trap dust and airborne particles, and the plants and soil also absorb nitrogen oxides (NO_x), sulfur dioxide (SO_2), Ozone (O_3), and Particulate matter (PM_{10}, $PM_{2.5}$). Air pollution is a significant issue as it contributes to a variety of health issues, which are costly [2–5]. The World Bank estimates that early deaths, increased medical expenditures, lower worker productivity, and lower agricultural output result from air pollution, costing the global economy more than $8.1 trillion a year, or roughly 6.1% of the Gross Domestic Product (GDP) [6]. The return on investment (ROI) for air pollution mitigation in urban planning has been largely unexplored, as investing in the development of green urban areas will have numerous positive outcomes on human health, the sustainability of urban areas, and help mitigate the effects of global warming.

1.1. Impacts of Air Pollution

Vehicle emissions, which release a variety of gaseous and particulate pollutants, construction and demolition activities, which also release dust and other airborne particles, and industrial activities such as factories and power plants, which release sulfur dioxide, are the main causes of air pollution in urban areas. Vehicle emissions are responsible for over half of the PM in urban air, according to studies [7]. The negative health impacts of air pollution are made worse by a lack of green spaces. Over the last ten to twenty years, a large number of epidemiologic studies have demonstrated that exposure to air pollution increases both mortality and morbidity [8]. Among the contaminants that lead to cardiac issues, respiratory ailments, and early mortality are PM, NO_2, SO_2, and O_3. The World Health Organization (WHO) estimates that air pollution results in around 7 million preventable deaths annually, with a disproportionate number of these fatalities occurring in low- and middle-income countries [4]. The effects of air pollution are linked to several financial losses; as mentioned before, air pollution damages the global economy $8.1 trillion annually. The majority of that amount is due to health care-related expenses because of air pollution, and the other part is due to reduced productivity of a workforce in highly polluted areas and high mortality rates. Air pollution in urban environments creates negative externalities such as health care costs and environmental damage that are not reflected in the price of fossil fuel-based activities, which justifies the need to invest and integrate green infrastructure in urban areas [9,10]. The lower price of some non-renewable resources does not represent the health care costs that arise from an overreliance on non-renewable resources. There is a large disconnect between public health costs and urban investment decisions. Often, when urban investment decisions are made, the health impact of those decisions is overlooked, especially in urban planning, as there is a constant lack of green spaces in urban areas. Proper investment and decision-making with sustainability in mind are important, as the long-term effects of green infrastructure are beneficial to human health. There is a return on investment for green infrastructure (GI) as integrating GRs and VFs in urban areas will reduce the amount of money spent on healthcare and will cut labor costs in the long term. The World Bank, in 2013, estimated that premature deaths from air pollution resulted in an estimated **$225 billion** loss in labor income globally due to decreased productivity as a result of air pollution [11].

1.2. Green Infrastructure

There are numerous ways to incorporate greenery into buildings, including both indoor and outdoor, vertical and horizontal areas. All natural, semi-natural, and man-made networks of multifunctional ecological systems that exist within, around, and between metropolitan areas at all geographical scales are included in GI [12]. GRs and VFs are two types of green infrastructure that can be installed horizontally or vertically. The design specifications for each form of green roof affect the choice of plants according to the roof's depth or amount of sunlight; thus, they also affect the possibility of reducing different air pollutants. The growing media in intensive green roofs is between 15 and 120 cm deep. Two forms of green infrastructure that can be erected either vertically or horizontally are GRs and VFs. Each type of green roof design parameter influences the selection of plants based on the depth of the roof or the quantity of sunlight it receives, which in turn influences the potential for lowering various air pollutants. The depth of the growing media in intense green roofs ranges from 15 to 120 cm [13]. Vertical forests can be referred to as the skin of a building, which is a model for sustainable residential buildings (**Figure 1**) [14]. The main aim of green infrastructure is to cover the building with plants. VFs have several structural functions; they contribute to temperature regulation as the shading provided by the plants helps cool buildings, reducing the heat island effect typical in urban areas. VFs also act as natural insulation, reducing the need for air conditioning as the plants absorb sunlight. VFs help purify the air, filtering pollutants such as PM and NO_x. VFs and GRs reduce pollutants through dry deposition and uptake through leaf stomata and are considered an effective mitigation strategy to improve urban air quality [15]. Although different species captured different quantities of PMs, the use of vertical greenery systems (VGS) with smaller-leaved species and leaf needles can potentially be more efficient in removing PMs; other variables, such as traffic volume and the place and design of the walls, also affect the plant's performance and capability in removing PM [16]. There is an emerging scientific interest in the benefits of GRs and VFs, and the need to study the economic benefits of GI and understand the disconnect between public health costs and urban investment decisions.

Figure 1. Bosco Verticale (Vertical Forest) in Milan, Italy [14].

1.3. Purpose and Aim of This Review

This review paper aims to explore the underexploited economic value of investing in GI and the benefits it will have on human health. This paper will also compare the health benefits with the mitigation costs of investing in air pollution. The aim is to determine whether or not the health benefits outweigh the costs of air pollution mitigation in hopes of encouraging sustainable urban investment decisions and to understand what alternative frameworks or interdisciplinary approaches can be proposed to more effectively integrate air quality-related ROI into urban planning, environmental economics, and policy development. Using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to conduct a review of sources and evaluate the benefits of investing in air quality mitigation through green infrastructure.

To enhance reproducibility, each study was independently screened by both authors, with disagreements resolved through consensus. Cost and benefit data were normalized into USD equivalents where possible, and health benefits were extracted from epidemiological or economic models. This strengthened the technical rigor of the review.

2. Materials and Methods

This review paper is committed to a systematic selection procedure following the PRISMA criteria for the sake of transparency, repeatability, and accountability. The primary database that was used to search for records was Google Scholar, ScienceDirect, Springer Nature link, and Cambridge University Press. The initial search yielded 94 records, with 5 additional records identified through other sources or manual searches of reports. A total of 17 Old non-comprehensive records were removed, which left the total number of records at 82. The number of records was then screened based on the title and abstract. Of these, 34 were disqualified for failing to satisfy quality or relevance standards. After being evaluated for eligibility, the final 48 full-text articles were added to the qualitative synthesis. These sources, which include a wide spectrum of research on GI focusing on GRs and VFs, include the economic benefit of installing green infrastructure, the effect that they have on air pollution mitigation, and the human health benefits of sustainable urban investment decisions.

2.1. Search Strategy

The searches were conducted using databases such as Google Scholar, ScienceDirect, Springer Nature Link, and Cambridge University Press. The search included published English peer-reviewed articles using the following keywords: "Vertical forests; Green Roofs; Green Infrastructure; Air Pollution; Air Pollution mitigation; Cost-Benefit analysis; Return on investment of green infrastructure; Economic sustainability of GRs and VFs; Health risks of air pollution; Integrating Green infrastructure in urban areas, Economic costs of Air pollution; Impact of Green infrastructure; Urban investment; Air quality economics; Pollution mitigation in urban planning;"

2.2. Inclusion and Exclusion Criteria

Our inclusion criteria included peer-reviewed journal articles, policy reports, and systematic reviews from English-language publications that focused on the economic assessment of air pollution or control methods and had been published within the last ten to fifteen years. However, an exclusion criterion was implemented to remove non-peer-reviewed blog posts or opinion articles, similar but older or less comprehensive papers, and full-text resources that are not accessible. After removing duplicates and out-of-date sources, abstracts and titles were examined for relevancy. The entire texts of possibly relevant studies were separately evaluated by both writers. Discussions were used to settle disagreements. The selection process is summarized in a PRISMA flow diagram that is supplied in **Figure 2**.

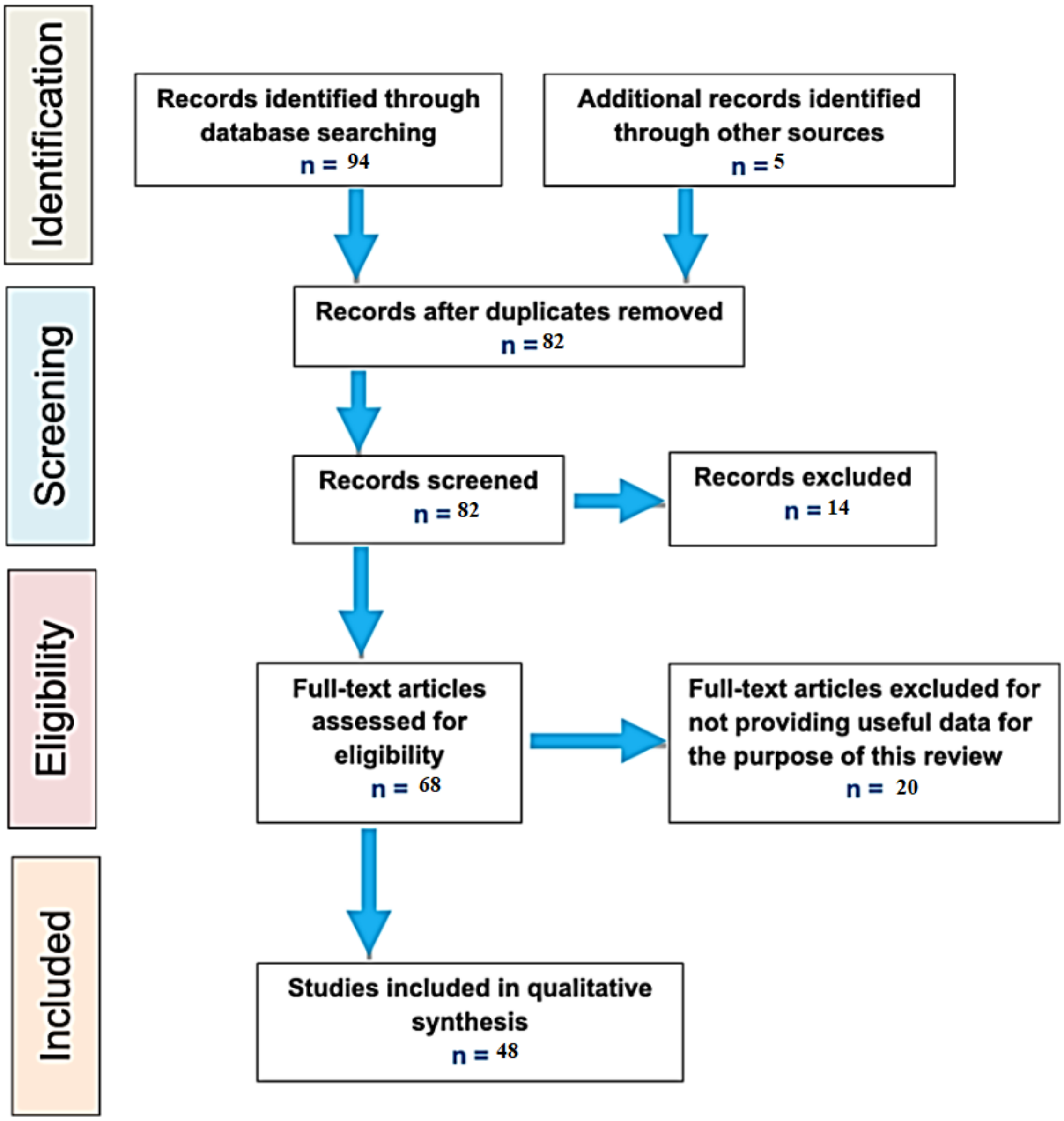

Figure 2. PRISMA Diagram of the Literature Selection Process.

2.3. Data Extraction and Synthesis

Data extraction was conducted manually to maintain uniformity across the selected studies. Each article was examined for key themes, such as the type of green infrastructure discussed, the urban context of the study, the research methods used, and the economic outcomes assessed, such as installation and maintenance costs, long-term savings, and the financial valuation of improved health and air quality. The synthesis process was qualitative, designed to identify recurring patterns, existing knowledge gaps, and redundant or outdated information. Studies were grouped according to their relevance to the central themes of the review: the role of green roofs and vertical forests in reducing air pollution, the resulting health benefits for urban populations, and the broader economic justification for adopting sustainable urban infrastructure.

3. Discussions

3.1. Impact of Green Infrastructure

Using empirical data, this section focuses on how green infrastructure affects air quality. At the local and regional levels, green areas can effectively lower exposure to ambient, airborne PM. At the regional and local levels, GI can effectively lower exposure to ambient, airborne PM. In general, GI can alter PM trajectories, speed, and other characteristics, and can also reduce PM levels in the atmosphere permanently [17]. Because it increases the rates at which particulate matter is deposited and/or gaseous pollutants are absorbed, vegetation—especially trees—plays a significant role in enhancing the quality of the air in metropolitan settings. The U-shaped parabolic curve of deposition velocity indicates that deposition varies among particles of different sizes, with minimum values between 0.1 and 1.0 μm. This suggests that both ultrafine and coarse particles are readily susceptible to deposition onto vegetation surfaces, which is also influenced by the size of the plant leaf [18]. When airborne particles and gas molecules approach the surface, they may deposit. Compared to the smooth, artificial surfaces found in cities, the majority of plants have a significant surface area per unit volume, which increases the likelihood of deposition [19]. When vegetation is added to urban areas, most studies found that the concentrations of different pollutants decreased by 15% to 60% when tree or shrub barriers were placed along open roads. It is anticipated that it will also have the same impact on lowering pollution there [20]. With a linear relationship to increasing filtering efficiency, a vegetation barrier's thickness can directly lower pollution concentrations [21]. Empirical studies have consistently demonstrated that GI can significantly reduce concentrations of key air pollutants such as $PM_{2.5}$, NO_x, and O_3. As stated, vegetation barriers along open roads have been reported to decrease pollutant concentrations by 15% to 60%, depending on specific configurations and environmental conditions. A comprehensive review of GI revealed average reductions of 1% for $PM_{2.5}$, 7% for PM_{10}, and gaseous pollutants like CO, O_3, and NO_x showed average reductions of 10%, 7%, and 12%, respectively [22]. A long-term research study in Shenyang, China, estimated the yearly $PM_{2.5}$ removal capability of urban GI from 2000 to 2019. The findings indicated a large increase in $PM_{2.5}$ removal capacity throughout the research study, with removal amounts rising by 20.64 Mg/a, removal flux by 0.0258 g/m²/a, and removal rate by 0.377%/a[23]. The effectiveness of GI in pollutant removal is influenced by plant species, structural design, and urban morphology. Species with larger leaf surface areas and complex structures, such as coniferous trees, usually have higher deposition rates for PM. The physical characteristics of vegetation barriers, including height, thickness, and porosity, play an important role. Thicker and taller barriers are more effective in reducing pollutant concentrations in urban environments [24]. Urban morphology, particularly in street canyons, affects the dispersion and accumulation of pollutants. High urban canopy resistance, indicative of poor ventilation, correlates with higher $PM_{2.5}$ concentrations. Conversely, increased vegetation cover can enhance air flow and promote pollutant diffusion and deposition, thereby improving air quality [25,26]. While several studies showcase the potential of GI in improving air quality, there are a variety of methodologies employed, leading to challenges in generalizing findings. Many studies rely on modelling approaches that may not capture the complexities of real-world environments. For example, the effectiveness of GI in street canyons can differ significantly from open-road scenarios due to variations in air flow and pollutant dispersion, as well as climate zone and plant species [27]. Recent studies have highlighted the critical role of specific plant species and structural configurations in enhancing the pollutant removal efficiency of green infrastructure. For instance, studies have demonstrated that "removing $PM_{2.5}$ from urban roads and effectively contributing to air quality improvement requires configuring red, green, and blue spectra with suitable tree species and structures." This emphasizes how crucial it is to choose the right vegetation kinds and create VFs and GRs that maximize air purification [28]. Moreover, the structural design of GI significantly influences its effectiveness. According to a study that looked at how building layout and vegetation affect road air quality, "a road greenbelt with even vertical distribution of biomass and diversified vegetation species works better to reduce $PM_{2.5}$ concentration." This implies that vegetation's spatial layout, in addition to its presence, is crucial for the spread and deposition of pollutants [29]. Urban morphology further affects the performance of green infrastructure.

Research shows that "urban air quality is influenced by vegetation through alterations in airflow and pollutant deposition processes". This implies that the integration of green spaces within the urban fabric should consider existing airflow patterns and building layouts to maximize air quality benefits [30]. Additionally, the selection of plant species is crucial for their pollutant absorption capabilities and their emission profiles. Some species emit biogenic volatile organic compounds (BVOCs), which can react with NO_x to form ozone, potentially offsetting the benefits of pollutant removal. Therefore, selecting species with low BVOC emissions is recommended to maximize air quality benefits. The findings collectively emphasize that the effectiveness of green infrastructure in mitigating air pollution is contingent upon the selection of plant species and the strategic structural design based on the climate zone as well. **Figure 3** presents a visual process of how GI helps reduce pollutants in the atmosphere.

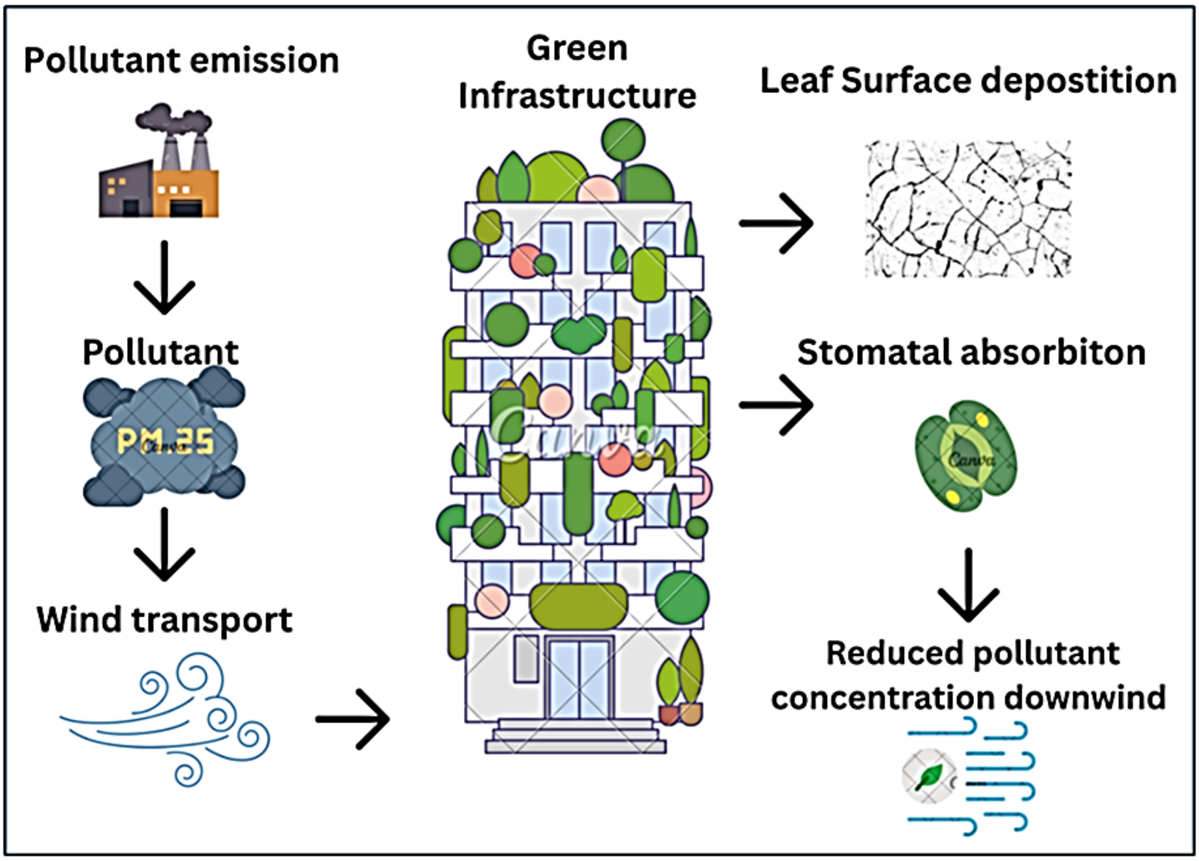

Figure 3. Physical Process Through Which Green Infrastructure Helps Mitigate Air Pollution.

3.2. Economic Costs of Implementing Green Infrastructure

The cost of installing GRs varies significantly based on several factors, such as size, location, and region (**Table 1**). In British Columbia, Canada, a standard intensive GR starts at \$540 m^2, whereas a standard extended GR costs between \$130 and \$165 m^2. The cost of labor and equipment is just two of the many variables that influence the installation cost. Depending on the type of GR and foundation construction, a GR in Singapore might cost anywhere between \$40 and \$65 m2. Three provinces in China were examined, and the average cost of a GR was found to be between \$48 and \$76 m^2. The typical cost of a green roof in a developed market like Germany is between \$15 and \$45 m^2. Two decades of market penetration and continuous research and development have led to decreased green roof prices in Germany. There is little rivalry and no economies of scale in more recent markets. Due to inexperience and the propensity to use custom design systems, labor costs are significantly higher [31]. These prices discourage governments and city planners from implementing GI in urban areas; however, there is a large ROI for green urban investment, as integrating GI reduces health care-related expenses as well as heating and cooling costs, and GRs and VFs also act as natural insulation for buildings.

Table 1. Comparative Costs of Green Roofs Across Regions.

Region	Cost Range (per m²)	Remarks
Germany	$15–45	Mature market; economies of scale
Singapore	$40–65	Higher labor & design costs
China (3 provinces)	$48–76	Emerging market
Canada (BC)	$130–540	Intensive vs. extensive GR designs
Portugal	$120–165	Mediterranean climate

3.3. Return on Investment of Green Infrastructure

This section aims to analyse the ROI of GI and the economic value of GI, filling the research gap in the economic evaluations of air pollution mitigation. While the initial costs of implementing VFs can be high, several long-term economic benefits should be used to justify GI investments. As a study states [32], "Vertical forests can provide natural insulation, reducing heating and cooling costs for buildings," and "Green buildings with vertical forests often command higher property values and rental rates." Additionally, "Some vertical forestry designs incorporate food-producing plants, contributing to local food security and reducing food transportation costs." These are the most frequently cited factors in ROI assessments, emphasizing the direct savings and revenue generation from GI. However, these assessments exclude one of the most significant contributions of GI, which is air quality improvement and its associated health benefits. Vegetation in vertical forests acts as a natural air filter, absorbing pollutants and particulate matter. A study found that urban trees removed 711,000 metric tons of air pollutants in the United States in 2006. This pollutant removal directly correlates with lower public health burdens, especially for respiratory and cardiovascular illnesses. Despite that fact, such benefits are rarely translated into economic terms in ROI models. Moreover, the study highlights overlooked social benefits, as exposure to green spaces has been linked to improved mental health and reduced stress levels in people living in urban areas, further highlighting the mismatch between measurable value and what is considered in planning decisions. There are clear gaps in incorporating air pollution mitigation into these economic evaluations, as often the cost of heating and cooling or the health costs are not considered in the benefits of air pollution mitigation.

3.4. Health Benefits of Green Infrastructure

GI offers substantial health benefits that translate into significant economic value (**Table 2**). A study in China demonstrated that a 10 µg/m³ reduction in $PM_{2.5}$ levels led to an average decrease of CNY 1,699 (USD 263.6) in medical costs per patient and a reduction of 1.24 days in lost work or daily activities. Achieving the national PM2.5 standard could result in over CNY 1.28 billion (USD 198 million) in annual health benefits, accounting for 18% of the city's annual environmental protection investment [33]. In the UK, the implementation of Bradford's Clean Air Zone resulted in NHS savings of approximately £30,700 per month within its first year. This initiative led to a 25% reduction in GP visits for respiratory illnesses and a 24% decrease in heart-related GP visits, equating to 732 fewer monthly visits compared to pre-COVID levels [34]. Similarly, a study in Belgium found that low-emission zones (LEZs) in cities like Brussels significantly reduced air pollution and improved public health. Researchers observed that air pollution levels of PM and NO_x declined more rapidly within LEZs than in other areas. Notably, the use of antidiabetic medication rose more slowly in Brussels' LEZ, suggesting a possible link between reduced nitrogen dioxide exposure and lower diabetes incidence [35]. In Canada, the development of a small urban park in Peterborough was projected to yield annual health benefits of CAD 133,000, including CAD 109,877 from reduced physical inactivity, CAD 23,084 from improved mental health, and CAD 127 from better air quality. When considering the economic value of higher life satisfaction, the total benefit exceeds CAD 4 million annually [36].

Table 2. Health Cost Savings from Pollution Reduction.

Country/City	Intervention	Health Benefit
China	10 μg/m³ $PM_{2.5}$ reduction	USD 263 per patient; $198M annual savings
UK (Bradford)	Clean Air Zone	NHS savings ≈ £30,700/month; 25% fewer GP visits
Belgium	Low-emission zones	Lower NO_2, slower diabetes medication growth
Canada	Urban park	CAD 133,000 annual health benefits; CAD 4M life satisfaction value

3.5. Correlation Between Temperature Reduction and Energy Savings Due to Green Infrastructure

Table 3 compares data from two sources to show the correlation between rooftop air temperature reductions and associated energy savings from GRs and VFs [37,38]. Results indicate that greater reductions in air temperatures are usually accompanied by significant energy savings, especially in cooling loads during summer months. Note that variations depend on climate, plant type, insulation, and GR configuration.

Table 3. Energy Savings and Temperature Reduction Impact of Green Rooftops [37,38].

Location	Climate Type	Surface Temp Reduction (°C)	Energy Savings (%)
China	Humid Subtropical Climate	Summer: Up to 14.8–15.8°C Winter: Up to 7.3–9.4°C	Cooling ↓ 79–86%, Heating ↑ 58–92%
Portugal	Mediterranean Climate	Up to 37°C	Cooling energy ↓ up to 32% Heating - NA
Greece	Mediterranean Climate	Up to 21.9°C	Cooling ↓ 60.5–62.5%, Heating ↓ 21.1–28.4%
Italy	Mediterranean Climate	Up to 42–46°C	Cooling ↓ 23.53%, Heating ↓ 8.41%
Japan	Humid Subtropical Climate	Up to 10°C	Cooling ↓ 2%

3.6. Green Infrastructure in Urban Planning

GI plays an important role in enhancing air quality and public health. However, as mentioned, traditional cost-benefit analyses often overlook these health-related benefits. To accurately assess the economic value of GI, it is essential to internalize air quality improvements into financial evaluations. Conventional economic assessments frequently neglect the health advantages derived from improved air quality due to GI. For instance, A study estimated that trees and forests in the contiguous United States removed 17.4 million tonnes of air pollution in 2010 [39], leading to health benefits valued at $6.8 billion. Similarly, a study in Wuhan, China [40], found that reducing $PM_{2.5}$ and PM_{10} concentrations to 10 and 20 μg/m³, respectively, could prevent hospitalizations for respiratory diseases and avoid economic losses amounting to 152.4 million CNY. These findings underscore the necessity of incorporating air quality improvements into economic evaluations of GI projects. Integrating interdisciplinary approaches enhances the valuation of GI. Environmental economics provides tools to estimate non-market benefits, while public health valuation quantifies health outcomes in monetary terms. Shadow pricing assigns economic value to intangible benefits like reduced morbidity and mortality. For example, a study demonstrated that short-term exposure to $PM_{2.5}$ significantly increased hospital admissions for respiratory diseases in Shanghai [41], highlighting the economic burden of air pollution. By applying these interdisciplinary strategies, policymakers can develop comprehensive evaluations that reflect the true value of GI. City planners and urban economists should adopt policies that recognize and promote the health benefits of GI. Implementing health-based urban indicators can guide development and ensure that projects contribute positively to public health. For instance, integrating metrics that assess vegetation cover and air quality can inform planning decisions. Moreover, policies should incentivize the incorporation of GI in urban development, recognizing its role in enhancing air quality and reducing healthcare costs. Long-term valuation of GI necessitates the use of health-based urban indicators. These indicators, such as the prevalence of respiratory illnesses or levels of air pollutants, provide measurable outcomes that reflect the impact of GI on public health. By monitoring these indicators, cities can assess the effectiveness of GI initiatives and make data-driven decisions to enhance urban health outcomes.

It is worth noting that each climate zone has to have different plants that are equally effective at air pollution mitigation (**Table 4**) [42].

Table 4. The Best Types of Plants to Include in Green Infrastructure, Based on Climate Zone [42].

Climate Zone	Recommended Plants	Key Characteristics
Tropical	Philodendron, Monstera, Ficus	Heat and humidity-tolerant, large leaves
Mediterranean	Lavender, Rosemary, Olive	Drought-resistant, aromatic
Temperate	Heuchera, Ferns, Hostas	Shade-tolerant, diverse foliage
Arid	Succulents, Sedums, Yucca	Water-efficient, heat-tolerant

3.7. Integrating Nanomaterials and Renewable Energy with Green Infrastructure for Enhanced Urban Air Pollution Mitigation

While green roofs and vertical forests have demonstrated quantifiable benefits in reducing urban air pollution, further enhancement of these interventions can be achieved by integrating nanomaterials and renewable energy systems within green infrastructure frameworks. These technologies not only amplify pollutant removal efficiencies but also align with broader sustainable development goals by addressing air quality, energy efficiency, and climate resilience simultaneously.

3.7.1. Role of Nanomaterials in Enhancing Pollutant Removal

Nanomaterials, owing to their large surface area and reactivity, provide innovative solutions for air pollution mitigation in urban settings. Engineered nanostructures such as noble metals, TiO_2, ZnO, and graphene-based composites exhibit photocatalytic properties that enable the decomposition of nitrogen oxides, sulfur dioxide, volatile organic compounds, and particulate matter under solar irradiation [43–46]. For example, nanostructured TiO_2 coatings applied on urban surfaces [47], solar panels [48], and building facades can degrade NO_x into less harmful nitrates, reducing the pollutant load in dense city environments.

Integrating nanomaterials within GRs and VFs can further enhance their pollutant capture capabilities by facilitating faster and more efficient deposition and degradation of airborne pollutants. Nanomaterial-based dust suppressants can be applied on GR substrates to accelerate particle agglomeration and reduce re-suspension, which is especially beneficial in arid climates with frequent dust storms, such as those experienced in the MENA region. Additionally, incorporating nanomaterials into the growing media of green roofs can improve their heavy metal adsorption capacities, mitigating secondary pollution in stormwater runoff.

However, to sustainably implement nanotechnology within green infrastructure, it is essential to consider life-cycle assessments and establish environmental safety standards to prevent nanoparticles from leaching into ecosystems while ensuring consistent performance over time.

3.7.2. Synergies with Renewable Energy Systems

Renewable energy integration within green infrastructure projects presents another layer of environmental and economic benefits. Solar photovoltaic (PV) systems can be seamlessly combined with GRs and VFs to generate clean energy while providing additional shading, reducing rooftop temperatures, and enhancing building insulation. This dual-function approach aligns with the findings of previous research that emphasize the role of integrated renewable energy systems in achieving urban sustainability while lowering operational emissions [47,48].

For example, solar PV panels installed above green roofs can reduce panel temperatures, improving PV efficiency while enabling rainwater capture and plant growth beneath them. The shading provided by PV structures reduces evapotranspiration rates, conserving water in irrigation while enhancing plant vitality, particularly in regions prone to water scarcity.

In the context of vertical forests, renewable energy systems can power irrigation pumps and smart environmental monitoring sensors, ensuring the optimal health of vegetation while minimizing operational costs and emissions. Additionally, integrating small-scale vertical wind turbines on high-rise green buildings can complement solar energy generation, diversifying the renewable energy mix in urban areas.

From an economic perspective, the incorporation of renewable energy within green infrastructure can enhance the return on investment (ROI) by reducing building energy consumption, generating clean energy credits, and lowering carbon tax liabilities for developers and municipalities.

3.7.3. Combined Benefits and Urban Sustainability

The synergistic integration of nanomaterials and renewable energy systems within green infrastructure can significantly amplify the pollutant removal efficiency and energy performance of GRs and VFs while addressing climate adaptation needs in urban planning. Nanomaterial-enhanced surfaces can actively decompose air pollutants, reducing the health burden associated with poor air quality, while renewable energy systems reduce dependence on fossil fuels, cutting greenhouse gas emissions and operational costs.

This integration aligns with a holistic sustainability model, offering a multi-layered mitigation approach:

- Pollutant Decomposition: Nanomaterials degrade NO_x, SO_2, VOCs, and PM directly on surfaces, reducing ambient concentrations.
- Passive Filtration: GRs and VFs capture PM and gaseous pollutants while enhancing urban biodiversity.
- Energy Efficiency: GRs and VFs reduce building heat gain, while renewable energy reduces reliance on grid electricity.
- Climate Resilience: Combined systems contribute to heat island mitigation and stormwater management.
- Economic Co-benefits: Reduced healthcare costs, lower energy bills, and enhanced property values contribute to an attractive ROI for municipalities and private investors.

3.7.4. Future Directions and Policy Recommendations

To maximize the potential of these integrated approaches, urban planners and policymakers should:

1. Incentivize nanotechnology and renewable energy integration within green infrastructure projects through green financing mechanisms, subsidies, and tax incentives.
2. Update building codes and urban planning guidelines to encourage the deployment of multi-functional roofs and facades incorporating nanomaterials and renewable energy systems.
3. Mandate lifecycle assessments and environmental safety standards for nanomaterial deployment to mitigate environmental and health risks.
4. Support interdisciplinary research to optimize nanomaterial formulations and renewable energy configurations suitable for different climatic zones.
5. Implement monitoring frameworks to evaluate the long-term effectiveness of these integrated systems on air quality and energy savings, ensuring adaptive management for urban sustainability goals.

The integration of nanomaterials and renewable energy with green infrastructure offers a transformative pathway for enhancing urban air quality, energy resilience, and public health while delivering robust economic returns. By incorporating advanced technologies into GRs and VFs, cities can accelerate progress toward sustainable development targets, aligning environmental, social, and economic objectives within urban planning frameworks. This integrated approach addresses the persistent valuation gap in green infrastructure by internalizing pollution mitigation, energy efficiency, and climate adaptation benefits, ensuring that cities are better equipped to respond to the escalating challenges of urbanization and environmental degradation.

4. Conclusions

4.1. General Findings

Based on this review, GI specifically VFs and GRs are essential for improving public health and reducing air quality while still having long-term economic gains (**Table**

5). Through deposition, filtration, and changed airflow dynamics, vegetation can dramatically lower concentrations of important air pollutants like $PM_{2.5}$, PM_{10}, NO_x, CO, and O_3, according to empirical evidence. Reduced rates of cardiovascular and respiratory illnesses, and lower medical expenses are a few of the quantifiable health benefits that result from these environmental advantages. By reducing surface temperatures and the need for heating and cooling buildings, GI also increases energy efficiency. However, initial installation expenses differ by location. The ROI is still evident through savings on energy, healthcare, and infrastructure resilience.

Table 5. Comparative Summary of GI Impacts.

Impact	Green Roofs (GRs)	Vertical Forests (VFs)	Overall Evidence
Environmental	Reduces $PM_{2.5}$, NO_x, SO_2 by 10–60%; mitigates UHI	Filters $PM_{2.5}$, NO_x; insulation & shading	Strong pollutant reduction
Health	Fewer respiratory & cardiovascular illnesses; reduced healthcare costs	Improved well-being, mental health	Quantifiable savings
Economic	Property values ↑; energy savings 20–80%	High upfront costs, long-term premiums	ROI positive over lifecycle

4.2. Recommendations

Policy frameworks must give GI incorporation into urban planning top priority if they are able to fully reap the benefits of GI on human health and the environment. Financial incentives like tax credits or subsidies should be put in place by governments to lessen the initial financial burden of installing GI. In addition to enforcing minimum standards for vegetation coverage in new developments, urban planning guidelines should incorporate health-based indicators. To create polices that take into account the many benefits of GI, cooperation between public health specialists, environmental economists, and urban planners is vital. Additionally, metropolitan areas with limited resources should hold public awareness campaigns so that they can foster community-level support and the implementation of localised green solutions.

4.3. Limitations and Future Directions

While this review presents a comprehensive overview, there are several limitations that persist. The study mostly used peer-reviewed, English sources, which would have left out important regional perspectives, particularly from the Global South. Direct comparisons are difficult due to the diverse approaches taken in the examined literature, which emphasises the necessity of standardised measures in GI research. Furthermore, few studies incorporate the economic and environmental benefits into coherent long-term cost-benefit evaluations that incorporate public health indicators, despite the fact that many studies quantify these benefits. Future investigations should concentrate on long-term, practical studies that look at the performance and maintenance costs of vertical forests and green roofs over a range of climate zones. To provide comprehensive frameworks for assessing and putting green infrastructure into practice, more interdisciplinary approaches that combine environmental science, health economics, and urban politics are also required.

Author Contributions

Conceptualization, A.A. and R.J.I.; methodology, A.A.; formal analysis, A.A.; investigation, A.A.; resources, A.A. and R.J.I.; data curation, A.A.; writing—original draft preparation, A.A.; writing—review and editing, R.J.I.; supervision, R.J.I.; project administration, R.J.I. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

Abbreviations

GRs	Green Roofs
VFS	Vertical Forests
NO_x	Nitrogen dioxide
SO2	Sulfur Dioxide
O3	Ozone
PM	Particulate Matter
ROI	Return on investment
GDP	Gross domestic product
CO	Carbon Monoxide
WHO	World Health Organization
GI	Green Infrastructure
VGS	Vertical Greenery Systems
BVOCs	Biogenic volatile organic compounds
LEZ	Low emission zone

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