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The Potential of Using Moss Walls as a Nature-Based Solution for Improving Air Quality in Urban Buildings: A Comprehensive Literature Study

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A B S T R A C T

The rapid increase in urbanization has exacerbated air pollution and intensified the urban heat island effect, posing serious health risks. Nature-based green infrastructure, particularly moss walls, offers potential as an innovative solution for air pollution mitigation and improvement of the built environment. This study aims to conduct a comprehensive literature review on the mechanism of pollutant absorption by moss, compare its efficiency with vascular plants, and examine its impact on air quality, microclimate, and building comfort. The results of the study show that moss has a high capacity to absorb heavy metals, particulate matter (PM), and pollutant gases, with higher efficiency than vascular plants in certain contexts. In addition, moss walls have been shown to contribute to humidity control, noise reduction, and mitigation of the urban heat island effect. However, their implementation still faces technical challenges, including species selection, substrate and irrigation requirements, and limitations on viability in indoor environments. This study highlights research gaps, particularly regarding long-term monitoring methodologies in tropical climates, integration with building systems, and economic analysis and public acceptance. Thus, moss walls have great potential as an effective and sustainable air pollution mitigation strategy, while also providing important implications for ecological architecture and sustainable urban design.

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1. INTRODUCTION

The rapid increase in global urbanization has exacerbated the problem of ambient air pollution and the urban heat island effect , making it a significant risk factor for human health. In this context, the development of innovative nature-based solutions, particularly green infrastructure such as green roofs and green walls, offers great potential to improve air quality, mitigate the urban heat island effect, and contribute to the sustainability of urban environments (Donateo et al., 2021; Marsaglia et al., 2023). Indoor air quality (IQ) is a crucial issue in the context of human health, given that a large portion of modern individuals' activities are spent inside buildings. Concentrations of pollutants such as carbon dioxide (CO_2) and hazardous particles, even at low levels, can significantly impact the health of occupants (Quijada et al., 2022). The use of nature-based green infrastructure in buildings emphasizes that vegetative elements, including green walls and moss walls, can function as effective biofiltration systems in reducing air pollutants. This aligns with the theory of ecological architecture, which emphasizes the integration of biological systems into buildings to achieve a healthier and more sustainable built environment (Perini et al., 2020). One approach being explored is the use of moss walls.

Figure 1. Example of Moss Wall Art installation in a commercial building in an urban area
(Source: warungtanaman.com, 2025)

Moss walls , as a form of vertical green infrastructure, although not yet fully recognized, offer a variety of environmental benefits in urban areas, including humidity control, noise reduction, and air filtration. They have the potential to be an innovative tool for air quality monitoring, extending their utility beyond traditional green infrastructure (Gecheva et al., 2025a). Despite these significant benefits, the cost of installing and maintaining traditional greening systems is often prohibitive. Moss walls are particularly advantageous because their non-vascular morphology allows them to directly absorb pollutants from the atmosphere, thereby increasing filtration efficiency compared to vascular plants (Chaudhuri & Roy, 2024). Unlike vascular plants commonly used in green wall systems, moss offers advantages in terms of ease of application, low maintenance requirements, and high desiccation tolerance, making them an attractive option for large-scale applications in existing and new urban buildings (Perini et al., 2020).

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Figure 2. Moss species that are effective in absorbing urban air pollution
(Source: Kariklina, 2025)

Figure 2 shows the moss species selected for the experiment, namely (a) *Dicranum scoparium* , (b) *Plagiomnium affine* , and (c) *Hypnum cupressiforme.* These three species are the most effective in absorbing urban air pollution, are cosmopolitan, able to adapt to various environmental conditions, and have a high capacity in absorbing air (Karklina, 2025). By exploring the characteristics of moss and the potential ecosystem services they can provide as a new green building typology, it is hoped that it can contribute to improving air quality, mitigating the urban heat island effect. (Veeger et al., 2023).

This study aims to conduct a comprehensive literature review on the potential of moss walls as a nature-based solution to improve air quality in urban buildings. The study focuses on the pollutant absorption mechanism through the morphological and physiological characteristics of moss, a comparison of its efficiency with vascular plants, and an evaluation of its performance in reducing pollutant concentrations that impact the microclimate and thermal comfort. Furthermore, this study highlights implementation challenges, including species selection, maintenance, sustainability, and aesthetics. By identifying research gaps such as limited comparative studies between species, the absence of a standard methodology for long-term monitoring in tropical climates, integration with building systems, and the lack of economic analysis and public perception, this study is expected to provide practical recommendations for architects, urban planners, and researchers in optimizing moss walls as an effective and sustainable air pollution mitigation strategy in urban areas.

1.1 Literature Review

The use of moss walls is gaining increasing attention as an innovation in technological greenery systems. Moss is considered a multifunctional material that not only provides aesthetic value but also has the technical capabilities to be integrated into modern building facades to create a more sustainable environment (Marsaglia et al., 2023). The unique characteristics of moss allow it to persist on a variety of vertical surfaces, making it a key component in green infrastructure development in dense urban areas.

The effectiveness of moss in improving air quality is based on its ability to efficiently absorb pollutants compared to other higher plants. Studies show that moss is superior to the leaves of vascular plants in monitoring and absorbing heavy metal pollution in the urban atmosphere due to its large surface area and lack of a cuticle (Jiang et al., 2018). This mechanism allows moss to act as a natural filter, capturing harmful particles dispersed in urban air.

In addition to heavy metals, moss walls have also been shown to be effective in absorbing particulate matter (PM), a major air quality problem on city streets. Laboratory testing has shown that various types of moss (bryophytes) are highly efficient at absorbing particulate matter from the atmosphere, reinforcing their potential as passive air purifiers (Karklina et

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al., 2025). Field implementations, such as in a street canyon in Italy, demonstrate that moss-based green panels can significantly improve air quality in microclimates confined by high-rise buildings (Donateo et al., 2021).

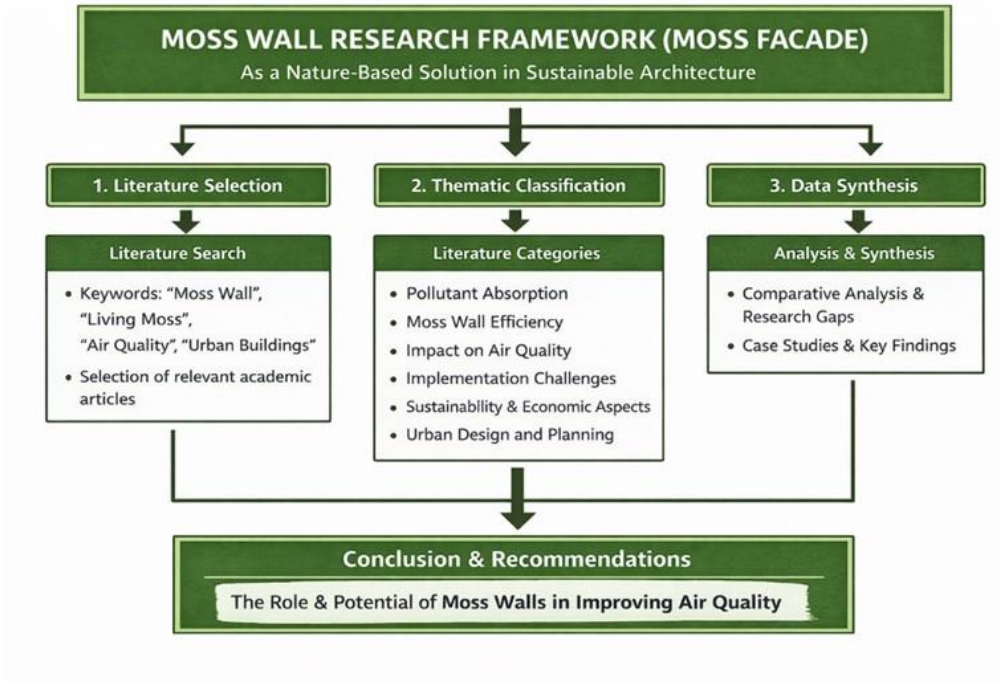
Substrate development is also crucial for the success of moss walls as a lightweight and functional building system. Research into moss-based biocomposites is underway as a sustainable substrate alternative to ensure optimal moss growth on building walls (Alvarez Gutiérrez et al., 2023). Furthermore, innovations like MosSkin offer lightweight building systems that allow moss to be applied to exterior structures without adding excessive weight to the underlying structure (Perini et al., 2022).

The sustainability of moss walls depends heavily on water and humidity management to maintain their vitality. Moss has complex moisture interactions with its supporting substrate, particularly stone or concrete, which impacts its long-term survival (Jang & Viles, 2022). To ensure moss survives and functions as a pollutant filter in indoor environments, proper temperature, humidity, and irrigation are crucial parameters (Zechmeister et al., 2023).

In addition to air quality benefits, moss walls also provide solutions to other urban issues such as stormwater management. Moss has significant potential value in managing runoff in urban environments due to its high water retention capacity (Anderson et al., 2010). Thus, the integration of moss walls not only directly improves air quality but also helps create more resilient cities to climate change by improving water regulation in building facades (van Briemen, 2024).

Finally, the use of moss walls can be expanded to include active air quality monitoring tools. Using biomonitoring techniques, moss installed on the exterior walls of buildings can be used to periodically detect aerosol and heavy metal pollution levels (Świsłowski et al., 2022). This demonstrates that moss walls are not simply decorative elements, but rather smart green infrastructure capable of providing environmental data while improving air quality for urban building occupants (Gecheva et al., 2025b).

2. RESEARCH METHOD



This study uses a descriptive qualitative method to describe the phenomenon systematically, factually, and accurately based on secondary data. This method was chosen because the study did not conduct direct experiments, but rather analyzed various literature

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to understand the potential of moss facades (engineered moss walls) as a nature-based facade solution. According to the view (Sandelowski, 2000), this approach is effective in explaining the phenomenon based on secondary sources, so that the study is able to provide a comprehensive picture of the role, benefits, limitations, and opportunities for developing moss facades in sustainable architecture.

The research stages are carried out through three main steps, namely;

1. Literature was selected based on relevance to the air quality theme using keywords such as "Moss Wall," "Living Moss," "Air Quality," and "Urban Buildings." Only articles discussing the potential of moss in improving urban air quality were selected.
2. Thematic classification, namely grouping literature into several categories, namely :
   a. Pollutant Absorption Mechanism by Moss Wall
   b. Moss Wall Efficiency with Vascular Plants
   c. Impact of Moss Walls on Air Quality and Microclimate
   d. Technical Challenges of Moss Wall Implementation in Urban Buildings
   e. Sustainability, Economic, and Aesthetic Aspects
   f. Implications for Urban Design
3. Data synthesis, comparing research results to find similarities, differences, and research gaps, and analyzing case studies that demonstrate the potential of moss walls in improving air quality.

3 RESULTS AND DISCUSSION

3.1 Pollutant Absorption Mechanism by Moss Wall

Moss walls have gained significant attention as an innovative green infrastructure solution for mitigating environmental pollution, particularly in urban areas. The ability of moss to absorb pollutants from the atmosphere and soil is central to their effectiveness. This absorption mechanism is multifaceted, involving both passive bioaccumulation and active physiological responses at the cellular level. A thorough understanding of these mechanisms is crucial for optimizing the design and application of moss walls in air quality monitoring and remediation strategies (Gecheva et al., 2025b; Kłos et al., 2012).

One of the main mechanisms is passive bioaccumulation, the process by which moss absorbs pollutants directly from its environment. Because it is a non-vascular plant without complex roots and a thick cuticle, moss is more easily exposed to pollutants in the air and from wet and dry deposition. Its large surface area and open cell structure allow for efficient absorption of elements, including toxic ones. Several studies have shown that moss walls are capable of accumulating heavy metals such as zinc (Zn) and cadmium (Cd) from the atmosphere, which generally originate from vehicle emissions and industrial activities (Gecheva et al., 2025b).

Based on research by Jiang et al. (2018), it was shown that the concentration of heavy metals in the moss Haplocladium angustifolium had significantly higher values than the leaves of the vascular plants Cinnamomum bodinieri and Osmanthus fragrans ($p < 0.05$). The average metal concentrations in moss followed the order Mo > Mn > Zn > Pb > Cu, with Mo, Mn, and Zn exceeding 100 µg/g, while Cd and Ag were less than 1 µg/g. In contrast, in vascular plants, most metals had levels below 1 µg/g. This significant difference indicates that the non-vascular structure of moss, which allows direct absorption from the atmosphere without going through the roots, makes moss much more efficient in accumulating heavy metals than vascular plants.

In addition to absorption from the air, epigeal mosses also translocate pollutants from the soil. According to (Kłos et al., 2012)there are two main pathways: (1) lifting dust containing

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pollutants from the soil and then re-depositing it on the moss surface, and (2) diffusion of metal ions from the soil through the air that wets the moss to the gametophyte tissue. The effectiveness of these two processes is greatly influenced by soil moisture and climatic conditions, which determine how much metal diffusion occurs and how little dust is lifted.

Furthermore, mosses also exhibit adaptive physiological responses to pollutant exposure. They experience biochemical changes, such as a decrease in total lipids and an increase in tocopherol levels, an antioxidant that functions to protect cells from heavy metal-induced oxidative stress. This increase in tocopherols indicates the activation of the moss's natural defense mechanisms to minimize the negative impacts of pollution (Gecheva et al., 2025b).

Figure 3. Moss Hypnum cupressiforme
(Source: Wikipedia.org, 2025)

Furthermore, genetic expression in mosses can be used as biomarkers to assess the impact of pollution. Studies in the moss species Hypnum cupressiforme have shown that expression of the rbcL gene, which encodes the largest subunit of the Rubisco enzyme (essential for carbon fixation in photosynthesis), can be significantly reduced in highly polluted environments. This decreased gene expression indicates disruptions in photosynthesis and overall plant health, making rbcL a potential indicator for air quality biomonitoring programs. Thus, moss walls function not only as physical filters but also as complex bioindicator systems (Gecheva et al., 2025b).

3.2 Comparison of Moss Wall Efficiency with Vascular Plants

Figure 4. Vascular vs. Non-Vascular Plants
(Source: microbenotes.com, 2023)

Moss walls are often compared in efficiency to traditional vascular plants. Mosses possess morphological advantages that make them highly effective bioindicators and bioaccumulators of air pollutants. Unlike vascular plants, which have cuticles and true roots,

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mosses are able to absorb air, nutrients, and pollutants directly from the air through their exposed surfaces (Jiang et al., 2018).

Moss has a much higher ability to accumulate heavy metals than vascular plants. Jiang et al. (2018) reported that moss can accumulate 4–51x more metals than C. bodinieri leaves and 3–18x more than O. fragrans leaves. This advantage is due to the non-vascular structure of moss and its large surface area, allowing metal particles and ions to be absorbed directly from the air. In addition to heavy metals, moss is also efficient in absorbing particulate matter. (Karklina et al., 2025)found that three moss species, Dicranum scoparium, Plagiomnium affine , and Hypnum cupressiforme, were able to absorb an average of 41% of PM2.5 and 47% of PM10. Moss can even remove up to 3.8 times more PM than tree leaves with the same dry weight (Haynes et al., 2019 in Karklina et al., 2025).

The practical application of moss efficiency is evident in the concept of moss walls as an air quality monitoring tool. (Gecheva et al., 2025b)studied living moss walls in Plovdiv, Bulgaria, using the Hypnum cupressiforme species as a biomonitor. After one and five months of exposure, there was a significant increase in 12 toxic elements, particularly zinc (Zn) and cadmium (Cd), which increased by 17- and 3-fold, respectively. This study demonstrates that moss walls not only beautify the city but are also effective as air quality monitoring tools.

Vascular plants like trees help absorb CO_2, produce oxygen, and filter particles, but their bioaccumulation efficiency is lower than that of mosses. Nevertheless, they remain important for regulating temperature, providing habitat, and managing rainfall. Moss walls are more efficient at absorbing heavy metals and particles, making them suitable for biomonitoring and vertical greening in confined spaces. The combination of mosses and vascular plants provides maximum benefits for air quality and urban biodiversity.

3.3 Impact of Moss Walls on Air Quality and Microclimate

Moss wall systems utilize moss's natural ability to absorb air pollutants and regulate ambient temperature and humidity. Moss acts as an effective biological filter due to its dense foliage and large surface area, which traps airborne particles such as PM10 and PM2.5. Some systems include ventilation fans that draw polluted air through the moss and substrate, releasing clean air back out. Filtration efficiencies have been reported to reach 43.1% for PM10 and 22.8% for PM2.5. (Alvarez Gutiérrez et al., 2023; Zechmeister et al., 2023).

In addition to particles, moss also absorbs pollutant gases such as CO2, NO2, and SO2 (Marsaglia et al., 2023). However, its effectiveness is greatly influenced by humidity. Moss performance will be optimal if there is an irrigation system that maintains humidity, because wet deposition helps particles adhere firmly to moss cells (Zechmeister et al., 2023). This aspect is an important consideration in the design and maintenance of moss walls, especially in indoor environments or areas with low rainfall.

In addition to improving air quality, moss walls also play a role in regulating the microclimate. One of their primary benefits is their ability to mitigate the urban heat island effect. Moss vegetation helps reduce heat flux into indoor spaces, thereby reducing the need for air conditioning and energy consumption. The evapotranspiration process from the moss also helps cool the air and surrounding surfaces.(Anderson et al., 2010; Marsaglia et al., 2023)

Moss also maintains humidity, especially in dry spaces, helping to reduce problems such as respiratory irritation and dry skin (Zechmeister et al., 2023). Furthermore, moss on stone substrates can increase water absorption and retention, while protecting the surface from light rainfall (Jang & Viles, 2022). With its air filtration and microclimate modification capabilities, this system not only contributes to cleaner air and more comfortable temperatures but also provides psychological benefits through its green aesthetics and the creation of a biophilic environment.

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3.4 Technical Challenges of Moss Wall Implementation in Urban Buildings

The implementation of moss walls in urban areas offers ecological benefits such as improved air quality and reduced heat island effects. However, their implementation faces technical challenges, including species selection, substrate selection, irrigation systems, and interactions with building materials and microclimate conditions. Species selection is a major challenge due to the extreme temperatures, low humidity, and high pollution levels in urban environments. Species such as Hypnum cupressiforme are more tolerant, but understanding the drought and nutritional requirements of each species remains crucial (Zechmeister et al., 2023; Perini et al., 2020).

Optimal substrate requirements are also crucial because they affect water retention, nutrient retention, and structural stability. Several studies have explored the use of moss-based biocomposites as alternative substrates to replace petroleum-based materials, with the goal of improving the circularity and sustainability of the system (Alvarez Gutiérrez et al., 2023). However, developing lightweight, durable substrates that can consistently support moss growth over the long term requires further innovation.

The irrigation system is a key factor in the success of a moss wall . Moss relies heavily on moisture, so designing an automatic irrigation system that can provide water evenly and efficiently, without causing ponding or wastage, is crucial (van Briemen, 2024). This system must be adaptable to climate variations and minimize maintenance requirements, which is one of the main attractions of moss as a low-cost green building material (Perini et al., 2020).

The interaction between moss and building materials also poses challenges. Moss can grow on a variety of surfaces, including bioreceptive concrete (Mustafa et al., 2021; Veeger et al., 2023). However, the potential moisture interaction between moss and the underlying stone substrate needs to be understood to prevent damage to building materials (Jang & Viles, 2022). Furthermore, the integration of moss walls into building facade designs must consider structural, drainage, and aesthetic aspects to ensure long-term sustainability and performance.

Finally, long-term monitoring and maintenance of moss walls in urban environments still require standardized protocols. Although moss is known as a low-maintenance plant, factors such as pollutant accumulation, weed growth, and potential pathogen infestation can impact its viability. Further research on moss-pathogen interactions and effective management strategies will help ensure optimal performance of moss walls as functional and sustainable green solutions in the future (Zhang et al., 2025).

3.5 Sustainability, Economic, and Aesthetic Aspects

From a sustainability perspective, mosses are effective in mitigating air pollution. Research by (Karklina et al., 2025) shows that moss species such as Dicranum scoparium, Plagiomnium affine, and Hypnum cupressiforme have significant particulate matter (PM2.5 and PM10) absorption efficiency in laboratory settings. This ability highlights the role of mosses as a vital component of urban green infrastructure, helping to clean the air and improve environmental quality. Furthermore, (Gecheva et al., 2025b)found that moss walls can function as air quality biomonitors, accu

mulating toxic elements such as zinc and cadmium, demonstrating the potential of mosses in monitoring and mitigating the impact of industrial pollution.

Economically, moss is cost-effective and requires less maintenance than conventional vertical greening systems. (Perini et al., 2020)Moss requires minimal substrate, requires little water and nutrients, and is drought-tolerant. making it suitable for urban buildings with limited space. However, studies (Zechmeister et al., 2023)indicate that the survival of living

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moss indoors is limited to six months, so further research is needed to confirm its long-term viability.

Aesthetically, moss provides a calming, natural green appearance. (Zechmeister et al., 2023)Studies have shown that moss has a positive perception among urban populations and contributes to the creation of biophilic indoor environments. The attractive green appearance of moss can improve psychological well-being, concentration, and productivity. However, the challenges of maintaining live moss indoors often lead to the use of stabilized moss, which, while aesthetically pleasing, does not provide ecological benefits such as photosynthesis or oxygen production.

3.6 Implications for Urban Design

These findings have important implications for urban design, particularly in densely populated areas with air quality issues. Integrating moss into green walls or roofs can reduce pollutants in confined areas. Furthermore, moss as a biomonitor provides more affordable and high-resolution air monitoring data, complementing conventional systems. This helps urban planners identify pollution hotspots and design evidence-based interventions. From a building design perspective, moss also presents innovative solutions as a biomaterial.

MosSkin is a lightweight, moss-based modular panel system developed as a low-cost and versatile urban greening solution. The panels are lightweight (up to 7 kg/m² when saturated) and feature an internal irrigation system. In terms of cost, MosSkin is highly economical, with total production (panels, irrigation, and moss paste) costing around €18–27.5/m², significantly lower than conventional greening systems, which cost €130–590/m² (Perini et al., 2022).

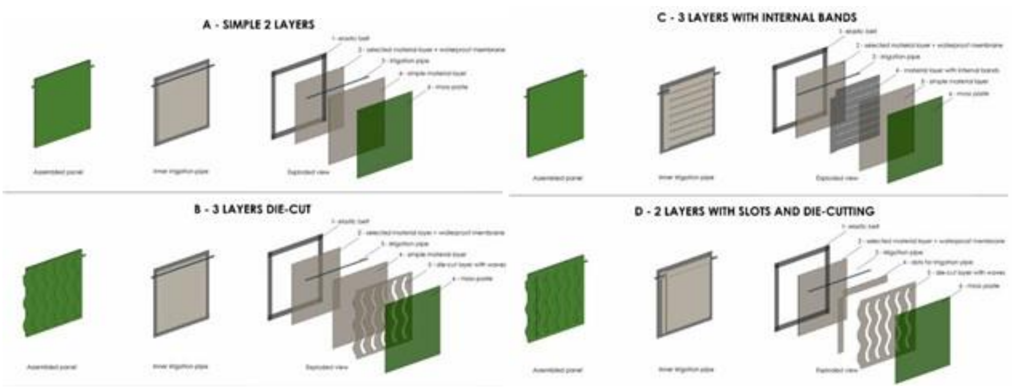

Figure 5. MosSkin Design
(Source: Perini et al., 2022)

Based on Figure 5, a study by Perini et al. (2022) in urban Genoa, MosSkin was designed in four modular panel configurations consisting of elastic belts, layers of selected materials (such as RecyclePav Plus as the best substrate), airtight membranes, and hidden irrigation pipes. Specifically, Configuration C (3 layers with internal bands) showed optimal performance in homogeneous air distribution and retention so that it can be an urban greening solution, especially from the perspective of urban design, sustainability, and economy.

Moss can grow on a variety of building materials with low maintenance and water requirements, making it an attractive alternative to often expensive and maintenance-intensive vertical greening systems and green roofs (Perini et al., 2020). This ability allows urban designers to create building "skins" that are not only aesthetically pleasing but also functional in absorbing pollutants and reducing the urban heat island effect. Moss's flexibility

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in adapting to a variety of surfaces and environmental conditions also supports the diversification of green architectural designs.

However, large-scale implementation of mosses in urban design requires careful consideration of local environmental factors. Although mosses demonstrate resilience to a wide range of conditions, factors such as wind speed, humidity, and sunlight exposure can affect their absorption efficiency and vitality (Karklina et al., 2025). Urban planners should collaborate with botanists and environmental scientists to select moss species best suited to the site's specific microclimate and conditions. Comparative studies of moss exposure techniques also highlight the importance of appropriate methods to ensure effective biomonitoring.(Świsłowski et al., 2022).

4. CONCLUSION

This literature review confirms that moss walls have a significant role as a nature-based solution to address air quality issues in urban environments. The unique pollutant absorption mechanisms of mosses enable the efficient accumulation of heavy metals, particulates, and pollutant gases, even surpassing the capabilities of vascular plants in some aspects. In addition to their biofiltration function, moss walls also provide additional benefits such as increased thermal comfort, humidity control, and aesthetic value, supporting the concept of biophilic architecture. However, widespread implementation is still hampered by technical challenges, limited long-term data, and the need for more in-depth economic and social studies. Therefore, further research is needed to develop standardized methodologies, explore the viability of mosses in tropical climates, and integrate moss walls with modern building systems. With appropriate research and policy support, moss walls have the potential to become an integral part of sustainable urban design strategies and air pollution mitigation efforts in urban areas.

Moss walls have proven to be a highly effective, nature -based solution to address air quality challenges in urban environments. As vertical green infrastructure, moss has advantages over vascular plants in terms of pollutant absorption efficiency, particularly heavy metals and particulate matter (PM), due to its unique biological structure and large surface area. In addition to environmental benefits, this system offers construction flexibility through the development of biocomposites and lightweight panels that can be integrated into new buildings and renovations. While requiring precise moisture management and irrigation, the use of moss walls offers multi-functional benefits that include improved air quality, stormwater management, and potential as a tool for active urban pollution monitoring.

Key Research Findings

Based on the literature analyzed, the following are the key findings:

- High Absorption Efficiency: Mosses are much more effective in accumulating heavy metals and particulate matter than the leaves of higher plants because they do not have a cuticle, so pollutants are directly absorbed through the entire surface of their bodies.
- Material Innovation: The development of systems such as MosSkin and bio-receptive concrete panels allows the integration of moss into building facades with minimal structural loads and better resistance to external conditions.
- Biomonitoring Function: In addition to filtering air, moss walls can function as environmental sensors that provide accurate data on the level of aerosol pollution in a particular area.
- Hydrological Benefits: Beyond air quality, moss has a remarkable water retention capacity, thus contributing to the mitigation of stormwater runoff in dense urban areas.

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- Dependence on Microclimate: The sustainability of moss walls is heavily influenced by temperature and humidity variables; consistent irrigation is crucial, especially in interior applications, to maintain plant vitality.

Recommendation

1. Early Design Integration: A key recommendation is to integrate the moss wall system early in the architectural design phase to ensure optimal irrigation and lighting infrastructure support.
2. Appropriate Species Selection: The type of moss used should be tailored to the specific pollution conditions at the site (e.g., selecting the species with the highest PM absorption capacity for roadside areas).
3. Sustainable Substrate Development: It is recommended to use environmentally friendly biocomposite substrates to support long-term moss growth while reducing the building's carbon footprint.
4. Technology-Based Maintenance: Given the sensitivity of moss to drought, the use of an automatic irrigation system equipped with a humidity sensor is highly recommended to maintain the effectiveness of continuous pollutant absorption.
5. Application as a Monitoring Tool: City governments or building managers can utilize moss walls as part of a low-cost and aesthetically pleasing city air quality monitoring network.

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