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The Impact of Selected Bio-Facades on Air Pollution Reduction: A Comprehensive Analysis

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Abstract

One of the major global issues affecting both the environment and human health is air pollution. The goal of this research is to decrease the negative impacts of air pollution by applying architectural solutions. In order to reduce air pollution, the study investigates creative designs, building techniques, and regulations. To highlight the critical relationship that exists between architecture and environmental health, the study looks at three different kinds of facades: water, green living, and algae. The main goal is to understand how bio-facades like these support better living environments, less pollution, and improved air quality. This research suggests using specific facade types in conjunction with sustainable design techniques to reduce air pollution in the built environment. By providing relevant information, the goal is to assist government environmental agencies, builders, architects, urban planners, and other stakeholders. The purpose of this material is to guide sustainable means of reducing air pollution, especially in urban areas where planting traditional plants may be challenging due to space limits. In summary, the research aims to address the increasing issues brought about by air pollution by encouraging a harmonious coexistence of architectural innovation and environmental preservation.

Keywords: air pollution, bio-facades, green facades, water facades, sustainability

Introduction

By definition, "air pollution" refers to the presence of one or more pollutants in the open atmosphere that have particular properties and consistency that are dangerous enough to pose a risk to human life, the health of plants and animals, or seriously interfere with essential life processes (Peavy, Rowe, & Tchobanoglous, 1985). The measurement of air pollution allows for the identification of air quality, with urban areas often experiencing elevated levels of pollutants, posing a considerable risk to human health (Brunekreef & Holgate, 2002).

The air quality in North Macedonia for a long time has not been very good. According to the World Health Organization, Skopje, the capital city, ranks third in the World Health Organization European area MKD (37 $\mu g/m^3$), after Bosnia and Herzegovina (42 $\mu g/m^3$) and Tajikistan (41 $\mu g/m^3$) for annual population-weighted modeled urban and rural median PM2.5 concentrations (World Health Organization (WHO), 2016).

Between 2005 and 2013, five air quality monitoring stations in Skopje were operational, and these stations measured PM10. Two of the stations started monitoring PM2.5 in the fall of 2011. PM has been continually monitored by three stations: Rektorat (urban traffic), Lisice (suburban industrial), and Gazi Baba. The data shows that the connection between the five monitoring stations measuring PM10 from 2012 to 2013 was significant. Even though average readings for PM2.5 and PM10 from the monitoring stations were high (Table 1), the availability of data was limited. For the two urban traffic monitoring stations, Centar and Karpos, the observed ratio of PM2.5/PM10 was 0.610 and 0.609, respectively.

The building facade serves as the prominent exterior envelope, acting as a shield against external atmospheric factors to create a comfortable indoor environment. Beyond its protective role, the facade significantly contributes to the overall aesthetic appeal of a building, capturing attention as the first visible element. In addition to these essential functions, a facade can play a pivotal role in enhancing the sustainability of buildings. This paper delves into the analysis of three distinct types of bio-facades—algae facades, green facades, and water facades—specifically examining their impact on air pollution reduction.

Table 1

Data availability and mean values by pollutant and monitoring station in Skopje for three consecutive years (Martinez, et al., 2018)

Average values for PM2.5 and PM10 measured by the monitoring stations					
PM2.5(μg/m3)	Centar (Traffic)	Gazi Baba (Traffic)	Karposh (Traffic)	Lisice (Industr.)	Rektorat (Traffic)
13 December 2011 availability (% per year)	48.3 28 91 85	n.a. n.a.	41.6 29 97 50	n.a. n.a.	n.a. n.a.
13 December 2011 availability (% per year)	48.3 28 91 85	84.4 3 58 58	68.3 29 97 91	108.6 86 92 98	71.7 21 96 99

The paper addresses the pressing issue of air pollution, a global concern impacting human health and the environment. Given the elevated pollutant levels in urban areas, the research aims to improve the broader understanding and resolution of this widespread problem. A proactive and sustainable approach is employed to tackle environmental challenges through the exploration of innovative architectural strategies, specifically bio-facades, for mitigating air pollution. This represents a progressive direction in addressing environmental issues by advancing building design and construction practices.

Focusing on Skopje, North Macedonia, where poor air quality is a prevalent issue, the research tailors its findings to address regional challenges effectively. This targeted approach makes the research particularly relevant for local policymakers, urban planners, and environmental agencies. The paper advocates for the integration of sustainable design systems to combat air pollution, especially in urban areas where conventional vegetation may face constraints. This emphasis on sustainability aligns with global initiatives aimed at fostering environmentally friendly solutions within the built environment.

The overarching goal of the research is to offer valuable insights to a diverse range of stakeholders, including government environmental agencies, architects, urban planners, and builders. These insights can play a pivotal role in shaping decision-making processes, influencing policy development, and inspiring the widespread adoption of sustainable practices. By promoting bio-facades as a solution, the paper underscores the vital connection between architectural innovation and environmental preservation, contributing to a harmonious balance between advancing architectural practices and safeguarding the environment.

Literature Review

Algae Facade System

In recent years, a more environmentally friendly alternative to traditional glass façades—a novel algae façade system—was developed. This system incorporates an algae bioreactor into a glazed facade, offering sufficient thermal and structural performance, good light transmission, and shading capacity. By producing oxygen and removing CO2 through photosynthesis, algae façades improve air quality in the surrounding environment (Gosztonyi et al., 2013).

The algae facade system consists of two glazing sheets with an algae bioreactor positioned between them (Figure 1). Inside the bioreactor, which is enclosed by two acrylic sheets, algae thrive in a nutrient-rich liquid. The configuration includes a "vision zone" and an "algae-growing zone," which provides both energy and structural performance. The vision zone permits unobstructed viewing, daylighting, and ventilation. The algae-growing zone contains a water cavity where algal cultures reside. Mechanical systems, including air, water, and algae filtration pumps, as well as distribution pipes, support the algae growth. Table 2 summarizes the strengths and weaknesses of algae facades.

Figure 1

An Illustration of the Experimental Research Design (Griffee, 2012)

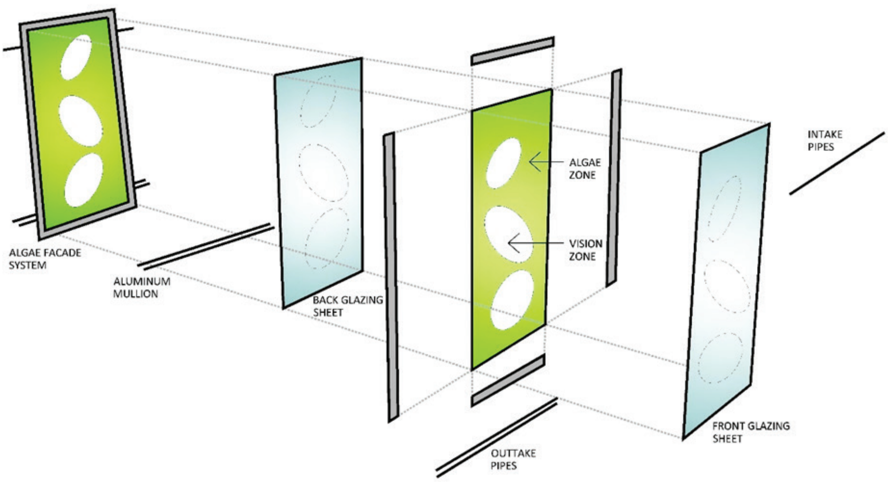

Table 2

Strengths and weaknesses of Algae Facades

	Strengths	Weaknesses
Climate aspects	Creating sub-climates	Inadequate performance in all climates
Financial aspects	Increasing value in the market	Higher production cost (lack of technology) Experts are needed for maintenance and repairs
Architecture and structural aspects	It could be used as a loading wall Beautifying the wall Creating penumbra effect due to reflection	Increasing the weight of the building Obstructing the visual structure
Environmental aspects	Removing pollutants Absorption of CO_2 Improving the quality of air	/ / / /
Stability aspects	Reduced energy consumption Rapid biomass production Increasing the quality of life Sound insulation Encouraging governmental and non-governmental organizations to invest more in algal research	Lack of knowledge about algae facades facades Lack of technology availability

Green Facade System

Forests absorb approximately one-third of the yearly global emissions. Therefore, the most practical instruments for humans to control air pollution are vegetation and plants, which impact localized air pollutant depositions with the added benefit of removing particle pollutants from the nearby atmosphere (Gallagher et al., 2015). Vertical greenery uses plants that are grown in tiny pots, planter boxes, or on surfaces with specific design elements hung vertically on walls (Ghazalli et al., 2018). In addition to reducing air pollution (Sternberg et al., 2010), surface temperature (Karim, 2012), and noise (Azkorra et al., 2015), green walls are expected to have various positive effects on the urban environment. They also serve as a valuable tool for implementing biophilic design principles.

Most research on green walls has primarily been conducted in Europe and Asia, resulting in a lack of comprehensive testing for different green wall systems across diverse climatic and pollution conditions (Ghazalli et al., 2018; Pérez et al., 2014). Table 3 shows the benefits and challenges of green walls.

Table 3

Benefits and challenges of green walls

Benefits	Challenges
Improving the weather quality	Installation and maintenance fee
Minimizing the thermal island effect	Creating an ecosystem for insect
Aesthetic appeal	Increasing the weight of the building
Lowering of noise pollution	Increasing moisture in the space
Ecological impact	
Decrease of greenhouse gases	

Figure 2 shows four different typologies of green walls. The green facade – indirect green façade combined with planter boxes (Figure 2 – number 3) is the most common type of green wall solution for outdoor settings. The plants either climb directly up the building's exterior walls or indirectly on ropes, which is a distinguishing aspect of this sort of solution. The soil substrate is placed in a single location—the foot of the wall, where the plants are planted or in special planter boxes. This method was created with ivy-like vines plants. Table 4 shows the strengths and weaknesses of the green façades.

Figure 2

Typology of green walls: 1. Direct green façade; 2. Indirect green façade; 3. Indirect green façade combined with planter boxes; 4. Living wall systems (Wesołowska & Laska, 2019)

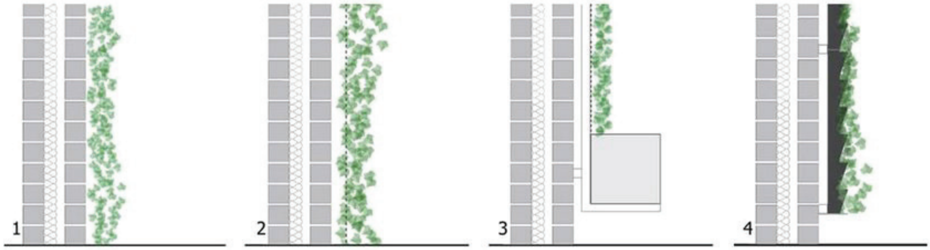

Table 4

Strengths and weaknesses of Green Facades

	Strengths	Weaknesses
Climate aspects	Creating sub-climates Reducing the heat island effect	Impossibility of applying it in all climates Inconsistency and not functioning in a similar manner in all seasons Limitations in terms of plant selection in different climates
Financial aspects	Reducing the cost of energy for cooling Reducing the costs resulting from air pollution Easy repair and maintenance	Lack of knowledge about the financial benefits Higher costs of building Higher water consumption

Architecture and structural aspects	Increasing plant coverage in private areas Efficient use of façade Ameliorating scenery of the city Increasing the design of green spaces in the city	Requiring suitable structural metrics Requiring structural strengthening to apply the green wall Creating visual distraction due to changing of the colors of plants in different seasons
Environmental aspects	Reviving the green space of the city Absorption and filtering of the pollutants Creating wildlife in the city Cleaning the air Improving atmospheric conditions Purifying the weather and creating sub-climates Managing rainwater	Possibility of making bad smell Possibility of making allergy for some people Absorbing insects
Stability aspects	Noise reduction Reducing energy consumption Reducing façade temperature Cooperation of citizens in making green spaces Increasing living area	Lack of knowledge on the benefits of green walls Possibility of being damaged by people

Water-based Facade System

Rain has served as an inspiration for the water layers on the building's façade. During rainfall, air contaminants are captured by raindrops in this natural process. Polluting gases are simultaneously absorbed into the rain, which eventually descends as droplets that have been cleaned. This demonstrates how rainfall acts as a natural air purifier and lowers air pollution. This natural phenomenon is utilized in water-based facades. An artificial or secondary wall is formed by a layer of water in front of the primary building exterior (Figure 3). This method's advantage is that the water is recycled and used once more, starting a never-ending cycle while the water collects pollutants as it moves. The strengths and the weaknesses of the water-based facades are summarised in Table 5.

Figure 3

A representation of a watery wall details (Bastanfard, Controlling Air Pollution with the Use of Bio Facades (A solution to Control Air Pollution in Tehran), 2018)

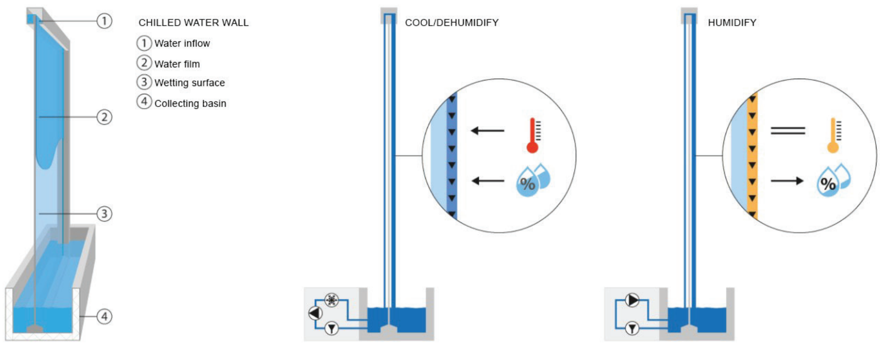

Table 5

Strengths and Weaknesses of Water-Facades

	Strengths	Weaknesses
Climate aspects	Creating sub-climates Reducing the effect of heat islands Cooling the weather Increasing humidity	Impossibility of applying it in all climates Inconsistency and not functioning in a similar manner in all seasons Limitations in terms of plant selection in different climates

Financial aspects	Reducing the costs resulting from air pollution Increasing the value in the market The duration of usage Easy repair and maintenance	Lack of knowledge about the financial benefits Higher costs of building Higher water consumption
Architecture and structural aspects	Ameliorating the beauty of the city Creating lighting effect due to reflection Not cutting the visual connection of inside and outside Not applying heavy load on the façade	Requiring suitable structural metrics Requiring structural strengthening to apply the green wall Creating visual distraction due to changing of the colors of plants in different seasons
Environmental aspects	Absorption and filtering of polluters Ameliorating the air Improving atmospheric conditions and creating sub climates Managing rainwater	Possibility of making bad smell Possibility of making allergy for some people Absorbing insects
Stability aspects	Less energy consumption Reducing façade temperature Increasing living space Increasing life quality	Lack of knowledge on the benefits of green walls Possibility of being damaged by people

Research Methodology

The research methodology initiated with an extensive review of literature to establish a comprehensive understanding of air pollution, its ramifications, and existing mitigation measures. Scientific databases, journals, and reputable publications were meticulously examined to gather pertinent information on air quality, pollutants, and their implications for human health. In parallel, annual air quality data for Skopje, focusing on PM2.5 and PM10 concentrations, was sourced from credible outlets, including the World Health Organization and local air quality assessment reports.

Subsequently, a thorough analysis of three bio-facade systems—algae facade, green facade, and water facade—was undertaken. Each system's strengths, weaknesses, and potential for reducing air pollution were systematically reviewed. This analysis encompassed factors such as climate compatibility, financial considerations, architectural and structural nuances, environmental benefits, and overall stability. A comparative analysis ensued to evaluate the climatic, economic, architectural, environmental, and sustainability aspects of the three bio-facades. This process involved synthesizing insights from the literature review and facade system analysis to cultivate a holistic understanding of each system's adaptability to diverse climates and contexts.

To simulate real-world application, bio-facade systems were scrutinized through a case study centered on a public building in Skopje, North Macedonia—a school facility. The analysis informed the selection of algae and green facades as a hybrid system tailored to address air pollution concerns specific to the location. The design process unfolded by conceptualizing the bio-facade elements, focusing on structural stability, cost-effectiveness, and visual aesthetics. The chosen orthogonal shape for the facade was a deliberate choice to streamline construction, ensure stability, and minimize costs. Furthermore, 3D representations of the selected facade concepts—algae and green facades—were created to offer a tangible preview of their integration into the chosen building. These visualizations played a pivotal role in evaluating the aesthetic impact and practical feasibility of the proposed designs.

Research Design: Comparison of Bio-based Facades

Three bio-facades were introduced, and their specific characteristics were discussed:

- **Water-based Facade**: By lowering the temperature of the surroundings, this facade generates a sub-climate for the nearby area. On the other hand, it cannot be utilized in all climates and uses a lot of water and energy, particularly in areas with little rainfall.
- **Algae Facade**: It can control the inside room's temperature, making the interior space comfortable. Reduced energy use is a major factor affecting this particular system, but ignorance about algae facades and a lack of technology are also major factors.
- **Green Facade**: Increases plant coverage in urban areas while minimizing heat islands and the cost of energy needed to cool the structure. On the other hand, due to high water consumption and construction costs, it cannot be used in all climates. It is also difficult to maintain.

It is crucial to highlight that the general advantages of various facade types are not neglected, but what matters is a detailed examination of their characteristics to determine the degree to which these design methods can be used in our structures. This analysis was completed considering the local environment's architecture, structures, economic importance, and weather patterns. It should be emphasized that this area of architecture is currently lacking significant expertise, particularly in relation to the algae facade. However, the terms "water facade" and "green facade" can be used interchangeably, especially in areas with a reasonably ample supply of water and weather suitable for the development of plants on specific surfaces. Table 6 shows the comparison of the facades based on climate, economy, architecture and structure, environment, and sustainability.

Table 6

Comparison of bio-based facades

Climatic Comparison			
	Watery Shell	**Algae Facade**	**Green Living Wall**
Usable climate	-Hot and dry	-Hot	-Hot and dry
Location of the facade	-All facade's	-Sunshiny	-Sunshiny
Economic Comparison			
	Watery Shell	**Algae Facade**	**Green Living Wall**
Façade lifetime	-Unlimited	-	-15-25 years
Building cost	-Relatively low	-High (due to lack of technology in the country)	-High
Utilization period	-Low	-Moderate	-Moderate (dependent on plant type)
Repair and maintenance	-Easy – Requiring periodic control	-Requiring experts	-Requiring periodic control
Increasing market value	-High	-High (Due to innovation in the facade)	-High
Architectural and Structural Comparison			
	Watery Shell	**Algae Facade**	**Green Living Wall**
Aesthetics	-Positive	-Relatively positive	-Positive
Façade operation (Internal and external obstruction)	-Not a physical obstruction per se	-Yes	-Yes
Light passage	-Yes	-A little	-No
Visual connection of the inside and outside	-Yes	-A little	-No
Increasing building weight	-A little	-Yes	-Yes

Environmental comparison			
	Watery Shell	**Algae Facade**	**Green Living Wall**
Improving air quality inside	-Yes	-Yes	--Yes, in some
Improving air quality outside	-Yes	-Yes	-Yes
Moisture control	-Increasing moisture level (desirable)	-Increasing moisture level (undesirable)	-Increasing moisture level (undesirable)
Rainwater management	-Possible	-Unpredicted	-Possible
Improving public health	-Yes	-Yes	-Yes
Sustainability comparison			
	Watery Shell	**Algae Facade**	**Green Living Wall**
Heat control	-Yes – cooling effect of air	-Yes	-Yes
Requiring insulation of the facade	-If it is in front of main facade, insulation is required	-No	-Yes
Noise insulation	-Very low	-Yes	-Yes
Resistance to wind	-No	-Yes	-Yes
Urban climate balance	-Yes	-Yes	-Yes

Result: Application of a Bio-Based Facade in a Project

Based on the analysis, bio-facades were applied to a project for a public building, specifically a school, to mitigate the surrounding area's pollution and assist in eliminating pollutants. Having a specific case study in mind during the design process was critical for selecting or rejecting various concepts.

The building plot covers an area of 11,700 m². The newly designed facility is situated in the municipality of Karposh, Skopje, North Macedonia. After analyzing the bio-facades, a concept incorporating both an algae façade and a green wall façade was selected. This hybrid system aims to reduce the area's air pollution throughout the year.

Several designs for the façade elements were proposed and discussed. The orthogonal shape was chosen for its structural stability, particularly concerning the weight of the water modules and its flexibility during assembly due to the pipe system running along the façade. Additionally, cost considerations were significant; the mechanism required numerous mechanical components, making a straightforward design preferable.

Figure 4

Form genesis. From idea to development.

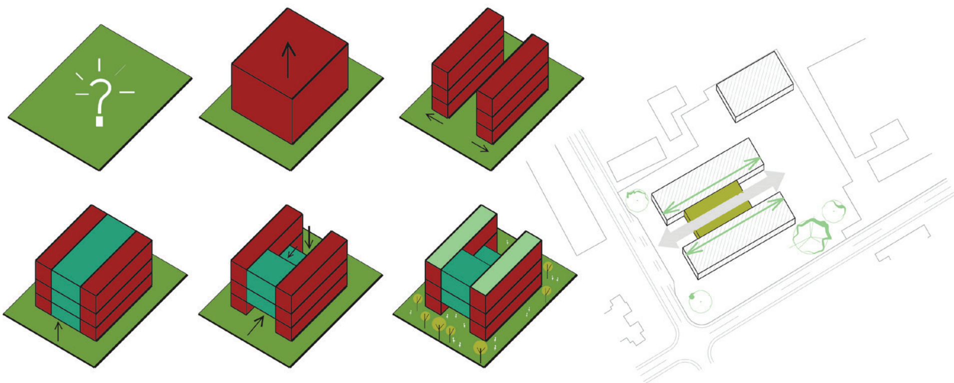

Figure 5

3D Representation of the Green Facade

Conclusions

The purpose of this study was to draw attention to the potential of architectural interventions with a particular focus on their application in Skopje in reducing pollutants and air pollution through creative design strategies and regulated construction processes. Through a thorough examination of appropriate research, the study improved our understanding of how bio-façade walls mitigate air pollution and impact different aspects of human life. These findings show that there is an insufficient amount of empirical or quantitative data on these systems' efficiency, which raised some serious concerns and underscored the need for more study in this field.

The literature review underscored the significant role of the built environment in contributing to environmental pollutants, emphasizing that construction activities release pollutants into the atmosphere. Health issues are becoming more common among people living in urban areas, and this is due to pollutants increase caused by the building and development projects and the lack of efficient pollution control measures.

The implications of these findings for building design, construction, and city development are substantial. It is recommended that urban construction projects mandate a designated amount of green space, allowing for traditional tree planting or integrating building walls as green surfaces. Educational initiatives and interactive forums should be established within the construction industry to promote awareness and understanding of bio-responsive designs, facilitating the incorporation of these approaches into architectural practices. Cost-effective solutions such as water fountains, green roofs, and balcony gardens can significantly enhance indoor environmental quality.

These findings show that using bio-façades in construction could be a sustainable way to reduce energy use in the built environment. As observed, these structures could help regulate ambient temperatures, enhance indoor thermal comfort with minimal energy usage, and aid in the overall process of reducing air pollution. Bio-façades could offer a chance to turn building walls into micropower plants, considering N. Macedonia's irregular power supply. These findings show that integrating bio-façades into architectural projects not only provides a sustainable energy source for housing units but may also directly contribute to a clean, healthy, and sustainable environment, thereby raising societal values.

On a final note, bio-façades present a practical solution to the problem of air pollution, especially when it comes to metropolitan areas. By improving environmental conditions and aesthetics at the same time, these bio-inspired designs offer sustainable and effective ways to lower building energy consumption and expenses. Regrettably, Macedonian city developers have not yet fully utilized bio-facades, even though stakeholders in the built environment around the world are beginning to embrace them. It is imperative that more research be done to investigate the potential of bio-facades in promoting sustainable design and improving architectural quality while protecting the environment.

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