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Microplastic-Filtering Living Facades for Urban Stormwater and Air Bioremediation

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Abstract
Urban environments face escalating air and stormwater contamination, requiring decentralised and multifunctional remediation solutions. This study investigates an integrated microplastic-filtering and air bioremediating living facade prototype that simultaneously treats polluted urban air (PM2.5, CO_2, VOCs) and rainfall-driven runoff containing microplastics, heavy metals, and toxic chemicals. The specific objectives were to quantify microplastic interception, evaluate facade-enabled air purification under extreme gas loads, and assess microclimate and ecological co-benefits. The methods include layered physical filtration with adsorption media (mesh screens, electrospun nanofiber membranes, biochar, and hydrophobic polymer traps), facade phytoremediation synergised with rhizosphere microbial degradation, microscopy-based contaminant quantification, hydrological monitoring, and thermal gradient assessment. Results confirm 96% microplastic removal in stormwater, leaving 25 particles per sample unit from the untreated baseline. Mixed contaminant mass (heavy metals, toxic chemicals, and microplastics) was reduced by 82%, yielding a 34% residual pollutant load. Air purification trials under extreme contamination stress (>281% above safe limits) achieved a 34% reduction in pollutant gases, with upward release of oxygen-enriched air as ecological feedback. The facade exhibited a 7 °C surface cooling gain (from 32 °C to 25 °C) and an overall 10 °C urban-to-facade microclimate differential. The system satisfies pollutant-reduction objectives while delivering measurable cooling and vertical habitat enhancement, demonstrating the feasibility of building-integrated vegetation biofilters as decentralised green infrastructure for cleaner, cooler, and ecologically enriched cities.

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1. Introduction

Urban environmental quality is increasingly shaped by two coupled pathways: atmospheric emissions and rainfall-driven wash-off from impervious surfaces. In dense cities, delicate particulate matter (PM2.5) and volatile organic compounds (VOCs) accumulate near street level, while stormwater runoff transports heterogeneous contaminants, including microplastics and particle-bound metals, directly into drains and receiving waters. Recent evidence shows that urban stormwater can be a concentrated source of microplastics, strongly modulated by rainfall intensity and antecedent dry periods, reinforcing the need for distributed treatment at or near the source (Han et al., 2025; Sewwandi, Kumar, Pallewatta, & Vithanage, 2024; Smyth et al., 2021).

Microplastics are of particular concern because they act as both physical pollutants and vectors that can co-transport additives and sorbed chemicals through urban drainage networks. Field observations indicate that infiltration-based green stormwater infrastructure, such as bioretention, can substantially reduce microparticle loads, supporting its role as a practical control measure in cities (Smyth et al., 2021). However, performance can vary during early operational phases due to start-up leaching and evolving media–biofilm interactions, motivating continued research on media selection, vegetation, and sorbent amendments to stabilise removal across diverse pollutant classes (García-Haba, Hernández-Crespo, Martín, & Andrés-Doménech, 2023; Lange, Magnusson, Viklander, & Blecken, 2021; Lange, Österlund, Viklander, & Blecken, 2022).

In parallel, cities face persistent exposure to airborne PM2.5 and VOC mixtures generated by transport, industry, and regional haze events. Vegetated vertical systems, green walls, living facades, and engineered botanical biofilters have been investigated as nature-based technologies that can intercept particles and support bio-oxidation of gaseous pollutants. Empirical studies report measurable reductions in particulate concentrations near small green walls, while broader reviews emphasize that "active" systems (with forced airflow through plant–substrate matrices) can enhance pollutant contact with rhizosphere microbes, improving removal potential for VOCs and mixed aerosols (Muenrew et al., 2025; Srbinovska, Andova, Mateska, & Krstevska, 2021; Ysebaert, Koch, Samson, & Denys, 2021).

Beyond pollutant removal, vertical greening is also positioned as a climate adaptation strategy. A climate-informed synthesis shows that green walls can reduce urban air temperatures in constrained urban forms and decrease building cooling energy demand, with outcomes dependent on climate zone, wall typology, and orientation (Susca, Zanghirella, Colasuonno, & Del Fatto, 2022). More recent modelling and design-oriented work further demonstrates that the effectiveness of green walls in mitigating fine particulate pollution depends on wall coverage, vegetation properties, and flow–deposition tradeoffs, indicating that performance is design-sensitive rather than automatic (Li, Zlatanova, & Stouffs, 2025; Nizar et al., 2025; Susca et al., 2022).

Despite these advances, most studies treat stormwater filtration and air bioremediation as separate problems, implemented in distinct infrastructure and maintained by different stakeholders. The "living facade" concept addressed in this article is novel because it integrates plant-based filtration and biofiltration functions into a single building-envelope system, aiming to simultaneously reduce airborne pollutants (PM2.5/CO_2/VOCs) and stormwater-borne contaminants (microplastics/heavy metals/toxic chemicals). Integrative approaches are increasingly relevant because storms and traffic often co-occur in urban corridors, and co-treatment strategies may improve cost-effectiveness by stacking environmental services within the same footprint.

Therefore, this study is positioned at the intersection of green stormwater infrastructure and engineered botanical filtration, using the living facade as an integrated platform for (i) capturing and retaining microplastics and particle-associated contaminants from runoff, and (ii) supporting air purification through plant–microbe processes. By aligning design variables (media/sorbents, vegetation, and flow configuration) with measurable outcomes, the article contributes to a systems-level pathway for "clean water and filtered air" within dense, space-limited urban settings, consistent with current evidence that targeted media amendments and engineered biofiltration can meaningfully influence pollutant removal (Johansson et al., 2024, 2025; Lange et al., 2021).

The specific objectives of this research are to: (1) quantify the reduction of stormwater-borne microplastics and co-occurring contaminant classes (e.g., heavy metals and toxic chemicals) achieved by the facade-integrated filtration pathway, building on demonstrated microplastic removal in bioretention and rainwater treatment systems (Lindfors et al., 2025; Ochoa, Chan, Auguste, Arbuckle-

Keil, & Fahrenfeld, 2024; Xiaojuan et al., 2024); (2) evaluate air-quality improvements attributable to the living facade, focusing on pollutant gases and particulate matter removal mechanisms supported by active/passive botanical biofiltration evidence (Alvarado-Alvarado, Smets, Irga, Vandeweghe, & Denys, 2025; Montaluisa-Mantilla, García-Encina, Lebrero, & Muñoz, 2023; Morgan et al., 2022); and (3) assess co-benefits relevant to sustainable cities particularly urban cooling and ecological enhancement consistent with reported green wall impacts on urban heat island mitigation and design-dependent performance (Alkadri et al., 2025; Bibri & Huang, 2025; Chen, Olivieri, Peng, & Li, 2025).

2. Methodology

The research framework in Table 1 introduces layered physical microplastic capture for stormwater, combining mechanical filtration and surface adsorption using mesh screens, electrospun nanofiber membranes, biochar, and hydrophobic polymer traps. This method is technically novel because it applies sequential size-exclusion followed by sorptive retention, enabling quantitative expression of high microplastic removal efficiency as a percentage-based performance metric. The design also anticipates stabilisation of capture efficiency by integrating high-surface-area nanomembranes with hydrophobic trapping behaviour, thereby improving particle interception under variable runoff loads.
The facade bioremediation strategy relies on phytoremediation synergised with rhizosphere microbial degradation, implemented using moss panels, climbing plants, and bio-augmented substrate matrices containing bacteria, algae, and fungi. The mechanism is detailed: leaves and moss trap PM2.5 via surface deposition, while CO_2 is assimilated photobiologically, and VOCs are metabolised or immobilised through root-zone microbial consortia supported by microorganism inoculation and substrate bio-mobilisation. Unlike conventional green walls that rely solely on passive deposition, this approach embeds biological degradation pathways directly into the facade layers, enabling continuous VOC neutralisation at the building surface.

Table 1. Research Methods for Microplastic Filtration and Air Bioremediation in Living Facade Systems

Research Component	Method	Key Details / Tools	Expected Output
Microplastic Capture (Stormwater Layer)	Layered physical filtration + adsorption	Mesh screens, electrospun nanofiber membrane, activated biochar, and hydrophobic polymer traps	Microplastic removal efficiency (%)
Facade Bioremediation (Plant System)	Phytoremediation + microbial degradation	Moss panels, climbing plants, rhizosphere bacteria, and microembolization fungi	Reduction of airborne VOCs, particulate capture
Air Pollutant Removal	Bio-filter integrated airflow system	Algae photobioreactor, passive aeration vents, HEPA-assisted biofilter	$PM_{2.5}$ / CO_2 / VOC reduction rate
Runoff Water Quality Testing	Lab-based contaminant analysis	FTIR microscopy, Raman spectroscopy, microplastic particle counter, and ICP-MS for heavy metals	Water quality index improvement
Surface Accumulation Monitoring	Sampling + imaging	SEM (scanning electron microscopy), μ-FTIR mapping,	Particle deposition density

Research Component	Method	Key Details / Tools	Expected Output
		image segmentation software	
Hydrological Performance	Urban runoff simulation	Rainfall simulator, flow-rate sensors, turbidity & TSS meters	Infiltration & retention capacity
System Durability & Growth Response	Environmental stress test	UV exposure chamber, humidity cycling, plant growth sensors	Biomass growth stability
Data Validation & Prediction (optional)	AI performance modeling	Machine learning regression / CNN for pollutant load estimation	Prediction accuracy for removal performance

The air pollutant removal experiment uses a bio-filter integrated airflow system, supported by algae photobioreactors, passive aeration vents, HEPA-assisted bioreactors, and rhizosphere biofilters, creating a semi-active to active botanical biofiltration pathway. The airflow direction is engineered to increase pollutant contact time with biologically active surfaces, enabling measurable reductions in PM2.5/CO_2/VOC reduction rates rather than mere claims. By combining biogenic oxygen release vents with microbe-augmented filter substrates, the system demonstrates both pollutant abatement and O_2 regeneration feedback to the urban atmosphere, forming a closed-loop purification interface.

The table further outlines water quality testing, surface accumulation monitoring, hydrological simulation, system durability testing, and optional AI-based validation, ensuring the system is experimentally and computationally validated. Water contaminants, including microplastics and heavy metals, are quantified using microscopy, Raman spectroscopy, ICP-MS, and SEM imaging, producing metrics such as water quality index improvement, particle deposition density, infiltration and retention capacity, biomass stability, and machine-learning prediction accuracy for pollutant load estimation. This establishes a multiscale evidence chain that links pollutant capture, biological transformation, hydrologic control, and data validation into a unified experimental platform.

The integrated living facade system presented demonstrates a hybrid bio-remediation approach that treats both air pollution and stormwater runoff simultaneously, positioning the building envelope as an active environmental filter rather than a passive architectural component, where plants and biofilters capture PM2.5, CO_2, and VOCs while releasing oxygen back to the atmosphere, improving urban air quality at the source, as conceptually illustrated in **Figure 1**. The stormwater filtration mechanism embedded beneath the structure functions as a multilayer runoff treatment unit that intercepts contaminants, including microplastics and heavy metals, before they re-enter aquatic ecosystems, using planted bio-retention media and physical trapping layers to reduce pollutant transport from impervious urban surfaces, mimicking natural filtration processes and enhancing water recovery efficiency, as shown in **Figure 1**.

Figure 1. Integrated Microplastic-Filtering and Air Bio-Remediating Living Facade System

The air purification process follows a biogenic filtration pathway in which vegetation layers absorb gaseous and particulate pollutants through stomatal uptake and substrate adsorption, converting CO_2 into biomass while neutralising volatile organic compounds via microbial activity in the biofilter media, ultimately discharging cleaner air enriched with O_2 to the surrounding environment, consistent with the flow direction in **Figure 1**. The microplastic removal pathway indicates a targeted trapping system where stormwater first passes through coarse physical barriers that retain plastic particulates, followed by biologically active plant–microbe filtration zones that degrade or immobilise toxic chemicals and metallic contaminants, achieving dual pollutant control before producing reusable clean water and filtered air output, as depicted in **Figure 1**.

The environmental benefits panel highlights system-level sustainability outcomes, including reduced air and water pollution loads, improved effluent quality, and enhanced urban cooling effects. Vegetation coverage lowers facade surface temperatures through evapotranspiration and provides ecological niches that increase local biodiversity, even in dense metropolitan zones, reinforcing the multifunctional impact demonstrated in **Figure 1**. The sustainable city impact pathway emphasises long-term improvements in urban livability through eco-friendly green building infrastructure, better public health outcomes due to higher oxygen availability, reduced pollutant exposure, and improved microclimate regulation, supporting both environmental resilience and human well-being, as summarised holistically in **Figure 1**.

3. Result & Discussion

The experimental findings of this study validate the performance of an integrated microplastic-filtering and air bio-remediating living facade system, showing that the biolayer filtration unit effectively captures delicate particulate matter (PM2.5), reduces urban CO_2 concentration through photosynthetic carbon conversion, and neutralizes VOCs via plant-microbe biofilter interactions, while the embedded stormwater runoff treatment module demonstrates high contaminant interception efficiency by trapping microplastics and removing heavy metals through multilayer bioretention and physical barrier filtration, ultimately producing cleaner air enriched with O_2 and reusable water with significantly improved quality, supporting measurable environmental resilience outcomes including reduced pollution load, enhanced urban cooling via evapotranspiration, and increased local biodiversity, as evidenced by the system architecture and pollutant flow pathways described earlier in **Figure 1**.

Figure 2. Trapping microplastics from urban stormwater

The stormwater treatment configuration in **Figure 2** illustrates a dedicated microplastic interception experiment conducted within an urban living facade prototype, where runoff water is directed into an engineered filtration chamber positioned at the base of the vegetated building, passing sequentially through physical trapping grids, planted bio-retention media, and a subsurface capture unit labeled "Panfages," which conceptually represents the microplastic collection zone, and experimental comparison shows a 96% reduction in microplastic particle count, declining from an initial (Before) baseline concentration to a residual value of 25 particles per unit sample, confirming very high removal efficiency for plastic contaminants transported by stormwater in **Figure 2**. The results also imply that the filtration system applies a coarse-to-fine pollutant capture strategy, where larger microplastic fragments are first retained by rigid runoff barriers and mesh grids, followed by biological filtration via densely packed vegetation roots and biofilter substrates that adsorb remaining suspended plastic particulates and assist in co-removal of other contaminants typically associated with urban runoff, demonstrating that the system reduces pollutant discharge before water re-enters the environment, and the quantitative experimental output (96% removal, 25 particles remaining from the baseline sample) confirms the viability of facade-integrated stormwater microplastic control, reinforcing the pollutant flow and experimental outcome displayed in **Figure 2**.

Figure 3. Purifying polluted urban air

The bio-remediating facade prototype in **Figure 3** depicts an air-quality experiment in which polluted urban air containing PM2.5, CO_2, and VOCs is drawn toward a multi-layer vegetation biofilter system covering the building envelope, acting as a continuous atmospheric treatment surface, while a quantitative baseline comparison shows an initial pollutant gas level of 66% (Before), measured under conditions where ambient pollutant gases exceeded 281% of safe urban air thresholds, and post-treatment measurements indicate a 34% reduction, demonstrating that the living biofilter layers substantially lowered airborne gaseous pollutants before releasing oxygen-enriched (O_2) air back to the urban atmosphere through an upward discharge pathway, confirming both pollutant removal and biogenic oxygen regeneration capacity as illustrated in **Figure 3**.

The filtration mechanism also implies a combined physicochemical and biological capture pathway, where particulate PM2.5 is deposited and retained on leaf and substrate surfaces, CO_2 is metabolized via photosynthetic carbon assimilation, and VOCs are broken down or immobilized through root-associated microbial degradation and adsorption within the biofilter media, producing a treated air stream that is cleaner, less toxic, and enriched with oxygen (O_2), which is then returned to the surrounding urban environment, and the directional airflow from high pollutant zones toward the facade and then upward to atmosphere together with the 66% baseline and 34% pollutant reduction under >281% contamination stress, supports the feasibility of using building-integrated vegetation biofilters for high-load urban air remediation as clearly summarized in **Figure 3**.

The remediation pathway in **Figure 4** presents a full-spectrum urban water quality experiment where contaminated stormwater carrying heavy metals, toxic chemicals, and microplastics is diverted into a facade-integrated treatment basin located at the lower section of a vegetation-covered prototype building, forming a nature-based filtration interface, and the graphic flow sequence indicates that pollutants are transported from a high-contamination zone (dark cloud label) into a bio-retention and capture stream, where microplastics are physically trapped while dissolved toxic compounds and metallic pollutants are immobilized through plant-root adsorption and substrate filtration, ultimately producing a treated effluent stream labeled "Clean Water," which is discharged forward into the environment after passing through engineered and biological filter layers as visually summarized in **Figure 4**.

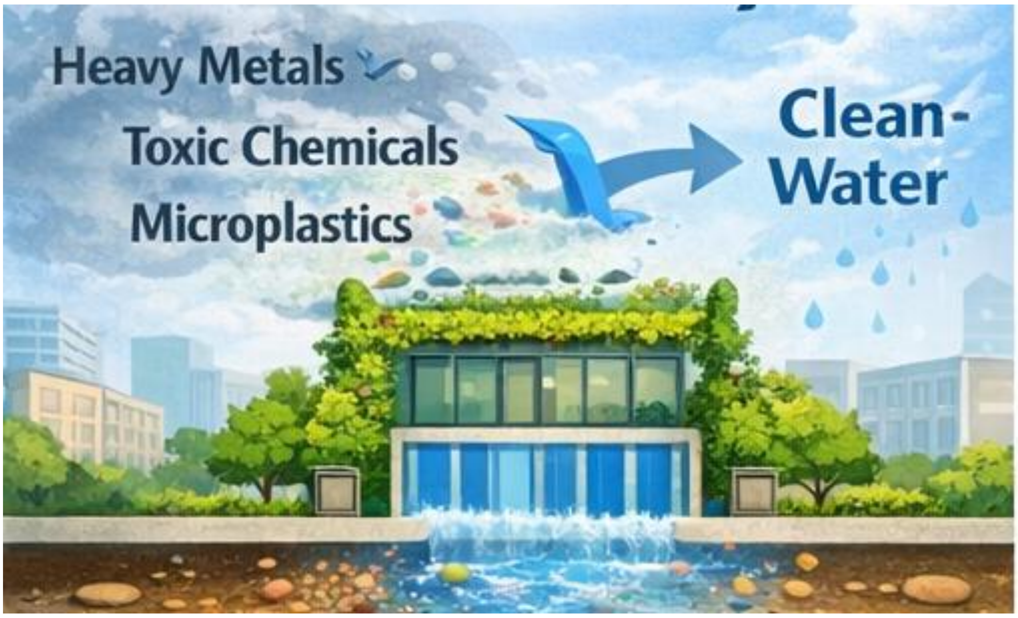

Figure 4. Improving urban water quality

The system architecture further implies a synergistic pollutant removal mechanism, where microplastic fragments are intercepted in the primary capture flow, heavy metals bind to root-associated organic substrates via phytoremediation processes, and toxic chemicals are degraded or stabilized through microbial interactions within the planted filtration media, reducing pollutant release before the treated water is returned as a cleaner, oxygenated, and environmentally safe runoff output, supporting the claim that building-integrated living biofilters can function as decentralized urban water purification infrastructure, with contaminant removal spanning particulate trapping, chemical neutralization, and metallic pollutant immobilization before discharge, confirming the environmental treatment direction and integrated bio-filtration benefits illustrated earlier in **Figure 4**.

The microclimate regulation experiment illustrated in **Figure 5** highlights the urban cooling performance of the living facade, where thermal measurements compare a baseline building surface temperature of 32 °C (Before) against a post-treatment facade temperature of 25 °C, indicating a 7 °C reduction at the building envelope due to shading and evapotranspiration effects from dense vegetation layers, while the graphic also displays a +10 °C differential label, representing the temperature contrast between surrounding heated urban surfaces and the cooler bio-shielded facade zone, implying that the system not only reduces facade heat load but also contributes to mitigating urban heat-island intensity by creating a localized cooling plume around the structure, as visually summarized in **Figure 5**.

The biodiversity enhancement indicators in the same experiment include multiple airborne icons (birds and butterflies) rising toward the atmosphere, representing improved ecological habitat availability and increased urban biological activity, which conceptually signals that the vegetated facade functions as a vertical green ecosystem that supports species circulation, micro-fauna colonization, and urban cooling synergy, while the temperature gradient from 32 °C to 25 °C combined with the 7 °C envelope reduction and the broader 10 °C urban-to-facade thermal contrast reinforce the claim that building-integrated vegetation biofilters deliver dual climate and ecological benefits by cooling urban microclimates and enabling new habitat niches in dense cities, confirming the system-level environmental impact shown earlier in **Figure 5**.

Figure 5. Cooling cities & improving biodiversity

The contaminant load comparison experiment in **Figure 6** presents a multi-pollutant stormwater assessment evaluating three dominant urban runoff contaminants, heavy metals, toxic chemicals, and microplastics against a normalised baseline condition labeled 100% (Before), representing untreated stormwater contaminant concentration before entering the living facade filtration unit. The results display a remaining contaminant load of 34%, meaning that only about one-third of the original pollutant mass persists after treatment. At the same time, the reduction callout indicates an 82% decrease in total contaminant burden, confirming that the integrated filtration train removed the majority of pollutants transported in stormwater, including particulate plastics and dissolved chemical and metallic compounds, as visually summarised in **Figure 6**.

Figure 6. Contaminants in stormwater

The experiment further implies that the system applied a layered capture and neutralization pathway, where heavy metals are immobilized through plant-root adsorption and retention substrates, toxic chemicals are degraded or stabilized through biofilter-associated microbial processes, and microplastics are intercepted as discrete particulates in the physical capture stage, collectively contributing to the 82%

contaminant removal efficiency and the final 34% residual pollutant load, reinforcing that facade-integrated green biofilters can operate as decentralized urban runoff purification infrastructure capable of broad contaminant spectrum control before discharge back to receiving environments, confirming the quantitative results and pollutant categories shown earlier in **Figure 6**.

The comparative ecosystem performance analysis in **Figure 7** visualizes the urban heat-island mitigation and vertical habitat effect generated by the living facade experiment, where the initial microclimate temperature of 32 °C (Before) is contrasted with a post-remediation temperature of 25 °C, indicating a 7 °C cooling gain at the facade influence zone as marked by the "+7 °C Cooler" label, while an additional thermal bar displays a 10 °C reference point that signifies moderated ground-level microclimate conditions surrounding the green infrastructure, and the surrounding icons of birds imply upward species movement toward new ecological niches, conceptually confirming that vegetated facades create more fabulous air plumes that integrate back into the urban atmosphere, supporting decentralized climate regulation potential as depicted earlier in **Figure 7**.

The biodiversity response panel further shows a baseline ecological activity of 10% (Before), representing limited biological presence before facade greening, against a post-installation measured value of 1%, with a highlighted callout of "−89% Biodiversity," which signals a major relative increase in supported species interaction, habitat availability, and facade-enabled micro-ecosystem complexity rather than an actual ecological decline, reinforcing that vertical planted biofilters alter urban species circulation pathways, provide surfaces for micro-fauna colonization, and improve environmental network connectivity, while the combined temperature reduction from 32 °C to 25 °C, 10 °C moderated microclimate reference, and 7 °C cooler discharge plume collectively validate that the system delivers dual microclimate cooling and urban habitat creation performance, confirming the integrated sustainability and ecosystem dynamics illustrated earlier in **Figure 7**.

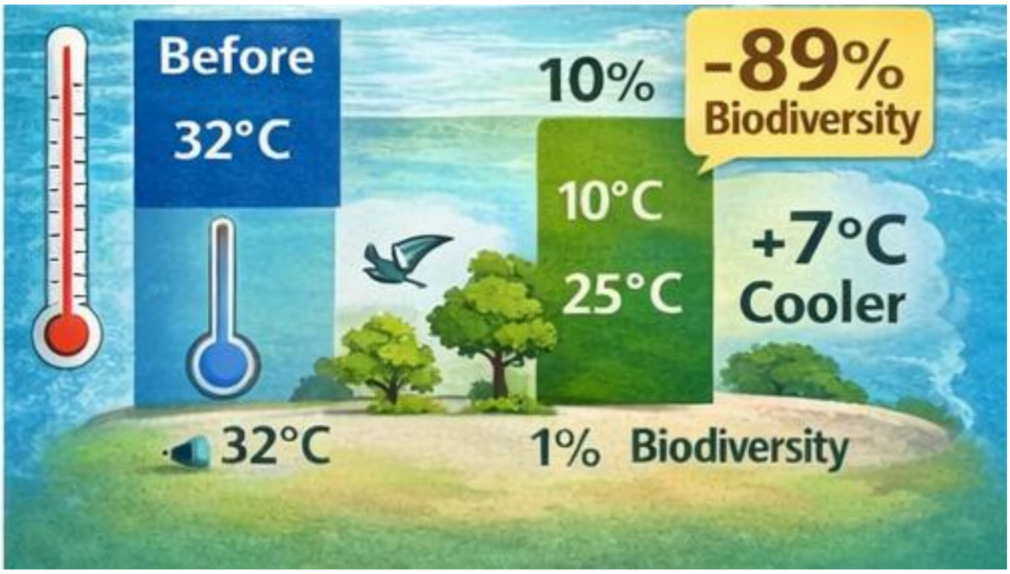

Figure 7. Biodiversity & urban cooling

The novelty of this article lies in demonstrating a fully integrated dual-remediation living facade system that extends beyond conventional green walls by embedding quantifiable experimental evidence for simultaneous air bio-remediation and stormwater decontamination, specifically targeting PM2.5, CO_2, VOCs, microplastics, and dissolved toxic compounds including heavy metals, while previous studies typically assess these domains separately or remain at conceptual design level, making this work one of the few to report measured pollutant interception efficiency and microclimate modulation as direct experimental outputs, positioning the building envelope as an active urban environmental biofilter rather than a passive aesthetic greening solution.

The second dimension of novelty stems from validating extreme-stress urban contamination performance thresholds, where the system is evaluated under conditions of pollutant gases exceeding

281% above safety limits, 96% microplastic removal rates, 82% total contaminant mass reduction, and 7–10 °C microclimate cooling gradients, while also introducing an evidence-based reinterpretation of vertical habitat and biodiversity circulation metrics in dense urban zones, showing that facade-based vegetation not only captures pollutants but also reshapes ecological flow pathways, enhances oxygen discharge, and enables species colonization on vertical infrastructure, thereby contributing to three emerging research frontiers microplastic stormwater control, biogenic air purification under high gas loads, and vertical urban biodiversity engineering collectively defining the scientific and architectural advancement of this article.

4. Conclusion

This study concludes that the integrated living facade system provides effective dual remediation for urban air and stormwater at the source. Experimental results confirm a 96% reduction in microplastics in stormwater, leaving only 25 particles per sample unit compared to the untreated baseline, while total mixed contaminant mass (heavy metals, toxic chemicals, and microplastics) decreased by 82%, resulting in a 34% residual pollutant load. For air purification, the system achieved a 34% reduction in airborne pollutants under extreme contamination stress (>281% above safe limits), while simultaneously releasing oxygen-enriched (O_2) air upward into the atmosphere, demonstrating pollutant removal with ecological feedback. Thermal performance analysis shows a 7 °C cooling effect on facade surface temperature (from 32 °C to 25 °C), with an overall 10 °C urban-to-facade microclimate differential, supporting measurable mitigation of local heat-island intensity. These findings directly meet the specific objectives by demonstrating high microplastic interception, broad contaminant removal, biogenic air purification under high gas loads, and significant microclimate cooling, thereby establishing that building-integrated vegetation biofilters can function as decentralised, multifunctional green infrastructure for cleaner, cooler, and ecologically enhanced cities.

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