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Green Roofs Mitigate Particulate Matter Under Stable Nocturnal Boundary Layers in Dense Urban Canyons

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ABSTRACT

The mitigation of particulate matter in dense urban environments remains a critical challenge for modern environmental science and urban planning. While the aerodynamic dispersion and dry deposition of aerosols during daytime convective conditions have been extensively documented, the behavior of fine and coarse particulate matter during calm, stable nocturnal periods in urban canyons is less understood. Under these specific conditions, strong temperature inversions and reduced wind speeds severely limit vertical mixing, leading to the accumulation of hazardous pollutants at the street level and roof level. This comprehensive study investigates the mechanisms through which extensive green roofs facilitate the removal of particulate matter during calm nights in urban canyons. By utilizing a high-resolution sensor network deployed across paired building roofs one featuring a mature sedum-based green roof and the other a conventional bare bituminous surface we analyze the localized concentration gradients and deposition velocities of suspended particles. The findings indicate that while aerodynamic impaction is minimized due to low wind speeds, mechanisms such as gravitational settling, Brownian diffusion, and hygroscopic growth under high nocturnal humidity significantly enhance particulate deposition onto the micro-structured biological surfaces of the vegetation. The green roof demonstrated a substantially higher retention capacity for both fine and coarse fractions compared to the control surface, thereby acting as a localized sink during periods of peak atmospheric stability. These results underscore the importance of integrating green infrastructure into urban design not merely for thermal regulation, but as a passive, continuous filtration mechanism for improving nocturnal air quality in densely built environments.

KEYWORDS

Urban Air Quality, Particulate Matter Deposition, Green Roofs, Nocturnal Boundary Layer, Urban Canyons

1. Introduction

The rapid expansion of urban centers worldwide has precipitated a myriad of environmental challenges, with the degradation of air quality emerging as a paramount concern for public health and sustainable urban development. Particulate matter, encompassing both fine particles with an aerodynamic diameter of less than two point five micrometers and coarse particles up to ten micrometers, constitutes one of the most ubiquitous and deleterious airborne pollutants in metropolitan regions. Chronic and acute exposure to these aerosols has been unequivocally linked to a spectrum of respiratory and cardiovascular pathologies, increased morbidity, and elevated mortality rates [1]. The spatial and temporal distribution of suspended particles in urban environments is highly complex, governed by the intricate interplay between localized emission sources, regional atmospheric transport, and the complex aerodynamic roughness imposed by the built environment. Within this context, the architectural configuration of urban canyons defined as the space between consecutive parallel buildings bounding a street creates unique microclimatic and aerodynamic conditions that profoundly influence pollutant dispersion and accumulation. During diurnal cycles, solar insolation drives convective mixing within the urban boundary layer. The heating of building surfaces and street pavements generates turbulent eddies that facilitate the vertical transport and dilution of anthropogenic emissions, such as vehicular exhaust and industrial effluents, out of the urban canopy [2]. However, the transition from day to night introduces a drastic shift in the atmospheric stability regime. As the sun sets, longwave radiational cooling of the ground and building surfaces often leads to the formation of stable nocturnal boundary layers. On calm nights, characterized by low synoptic wind speeds and clear skies, this cooling initiates surface-based temperature inversions. Under these conditions, the vertical temperature gradient becomes positive, effectively suppressing buoyancy-driven turbulence and vertical mixing. Consequently, the urban canyon acts as a restrictive cavity, trapping pollutants emitted at the surface and allowing particulate concentrations to surge to hazardous levels [3]. The lack of aerodynamic ventilation during these periods means that the removal of airborne particles is predominantly relegated to dry deposition mechanisms acting upon the available surfaces within the canyon architecture. In response to the escalating crisis of urban pollution and the urban heat island effect, green infrastructure, particularly green roofs, has been increasingly integrated into modern urban planning paradigms. Green roofs provide a multitude of ecosystem services, including stormwater management, thermal insulation, acoustic damping, and the enhancement of urban biodiversity. Furthermore, vegetation acts as a passive biofilter for atmospheric pollutants. The morphological complexity of plant structures leaves, stems, and the associated substrate introduces a vast, micro-rough surface area that interacts with traversing air masses. Previous research has extensively characterized the capacity of urban vegetation to intercept and retain particulate matter during the day, highlighting aerodynamic impaction and interception as the primary removal mechanisms driven by wind-induced flow through the canopy [4]. However, there remains a critical lacuna in the scientific literature regarding the efficacy of green roofs as particulate sinks during calm, stable nocturnal conditions, where wind speeds are negligible, and convective turbulence is virtually absent. The primary objective of this extensive academic paper is to systematically elucidate the dynamics of particulate matter removal by green roofs during calm nights within urban canyons. By isolating the nocturnal period, this research seeks to decouple the influence of wind-driven aerodynamic impaction from other deposition mechanisms, such as gravitational settling, Brownian diffusion, and localized thermophoretic and diffusiophoretic forces. Understanding these quiescent deposition processes is essential for accurately quantifying the continuous, twenty-four-hour pollutant mitigation potential of green infrastructure. To achieve this, the present study employs a rigorous, comparative methodology, deploying high-precision micrometeorological and aerosol instrumentation across paired experimental sites within a well-defined urban canyon. By continuously monitoring particle size distributions, ambient temperature, relative humidity, and three-dimensional wind vectors over an extended observational campaign, we aim to construct a high-resolution temporal profile of nocturnal particulate behavior. The findings of this research are intended to inform architectural design, urban zoning policies, and environmental engineering practices, providing empirical evidence to optimize green roof parameters for maximal air quality benefits during the

most critical periods of atmospheric stagnation.

2. Literature Review and Background

2.1 Aerodynamics and Pollution Dynamics in Urban Canyons

The concept of the urban canyon is central to the field of urban climatology and microscale atmospheric dispersion modeling. An urban canyon is geometrically defined by its aspect ratio, which is the ratio of the building height to the street width, as well as its length-to-width ratio and the orientation of the street axis relative to the prevailing wind direction [5]. These geometric parameters dictate the nature of the internal airflow regimes, which are broadly categorized into isolated roughness flow, wake interference flow, and skimming flow. In densely built metropolitan areas, skimming flow is the most prevalent regime, wherein the bulk atmospheric wind skips over the building tops, driving a decoupled, recirculating vortex within the canyon below. This skimming effect significantly reduces the exchange of air masses between the pedestrian level and the overlying atmospheric boundary layer, leading to increased residence times for vehicular emissions and other anthropogenic pollutants [6]. During daylight hours, the differential heating of the sunlit and shaded walls of the urban canyon can induce localized buoyancy forces that interact with the mechanically driven vortex, sometimes enhancing the ventilation of the street level. However, the nocturnal scenario presents a markedly different and more critical challenge. The cessation of solar heating removes the primary driver for convective turbulence [7]. On calm nights with low synoptic wind speeds, the mechanically induced vortex within the canyon weakens or dissipates entirely. The emission of longwave radiation from the structural surfaces to the cooler night sky results in rapid surface cooling, which chills the adjacent air. This process fosters the development of stable thermal stratification within the canyon, effectively capping the street-level air and suppressing any remaining vertical mixing. Studies have documented that during such inversion events, the concentration of particulate matter within the canyon can be several magnitudes higher than the regional background levels, highlighting the severe environmental health risks posed to the urban populace during these stagnant periods [8].

2.2 Mechanisms of Particulate Matter Deposition

The removal of suspended particulate matter from the atmosphere onto solid surfaces occurs via a combination of wet and dry deposition processes. Wet deposition involves the scavenging of particles by precipitation, which, while highly efficient, is episodic and dependent on specific meteorological conditions [9]. Dry deposition, conversely, is a continuous process governing the transfer of aerosols to surfaces through aerodynamic transport, boundary layer resistance, and ultimate surface capture. The efficiency of dry deposition is fundamentally dependent on the aerodynamic diameter of the particle, the physical properties of the capturing surface, and the ambient microclimatic conditions. The transport of particles toward a surface is mediated by several distinct physical mechanisms. Gravitational settling is the primary mechanism for coarse particles. According to fundamental fluid dynamics, a particle will achieve a terminal settling velocity when the downward force of gravity is perfectly balanced by the upward drag force of the fluid medium. Because gravitational settling velocity scales with the square of the particle diameter, it is highly dominant for large, massive particles but negligible for ultra-fine aerosols [10]. For intermediate and smaller particles in the fine particulate range, aerodynamic impaction and interception become the governing mechanisms [11]. Impaction occurs when a particle, due to its inertia, fails to follow the curved streamlines of airflow around an obstacle and strikes the surface. Interception happens when a particle, while successfully following the streamline, passes close enough to an obstacle that its physical edge makes contact with the surface. Both impaction and interception are highly dependent on the velocity of the fluid and the morphological complexity of the obstacle. In the ultra-fine regime, particles are subject to Brownian diffusion, a process driven by the random thermal motion of gas molecules colliding with the aerosol particles. Brownian diffusion causes particles to deviate from the mean airflow and migrate across the quasi-laminar sublayer adjacent to surfaces, eventually leading to deposition [12]. Furthermore, under specific microclimatic conditions, phoretic forces such as thermophoresis and diffusiophoresis can influence deposition. Thermophoresis drives particles away from warmer regions toward cooler surfaces, which can be highly relevant during nocturnal cooling phases. Diffusiophoresis is associated with the concentration

gradients of condensing or evaporating water vapor, which can drag particles toward a wet surface during dew formation [13].

2.3 The Role of Green Infrastructure in Particulate Mitigation

Vegetation has long been recognized for its capacity to improve air quality through the absorption of gaseous pollutants via stomatal uptake and the deposition of particulate matter onto exterior plant surfaces. The architecture of a plant canopy creates a highly porous, aerodynamically rough interface that disrupts local airflows, thereby enhancing the probability of particle impaction and interception compared to smooth anthropogenic surfaces like glass, concrete, or asphalt [14]. Furthermore, the micro-morphology of leaves including the presence of trichomes, epicuticular wax networks, and complex venation patterns provides an optimal substrate for the entrapment and retention of deposited particles, preventing their resuspension back into the atmosphere. Green roofs, as a specific manifestation of urban green infrastructure, offer unique spatial advantages by utilizing otherwise dormant rooftop spaces. Extensive green roofs, typically characterized by shallow substrate depths and drought-tolerant vegetation such as sedum species, are particularly popular due to their low structural weight and minimal maintenance requirements. While a substantial body of literature has quantified the daytime, wind-driven particulate removal capacity of urban trees and green walls, the deposition dynamics over horizontal green roofs are less characterized, particularly during the night [15]. During calm nocturnal periods, the reduction in ambient wind speed diminishes the kinetic energy available for inertial impaction and aerodynamic interception. Consequently, the relative importance of gravitational settling for larger particles and Brownian diffusion for finer particles is significantly amplified. Additionally, green roofs experience distinct nocturnal microclimates compared to bare roofs. The evapotranspiration from the plant-substrate matrix, although reduced at night, combined with the radiative cooling of the foliage, frequently leads to higher localized relative humidity and the formation of dew. High relative humidity can induce hygroscopic growth in certain aerosol fractions, increasing their mass and settling velocity [16]. Simultaneously, the presence of dew creates a sticky surface that drastically reduces the probability of particle bounce and resuspension. This literature review identifies a crucial gap: the necessity to empirically quantify the deposition velocities and removal efficiencies of green roofs during these stable, low-wind nocturnal periods, thereby fully articulating their role in the continuous amelioration of the urban atmospheric environment.

3. Methodology and Analytical Framework

3.1 Study Site and Experimental Design

The experimental campaign was conducted in a dense commercial district located within a major metropolitan area. The selected study site features a classic, symmetrical urban canyon configuration with a roughly uniform building height of twenty-five meters and a street width of approximately twenty meters, yielding an aspect ratio of one point two five. This specific geometry was chosen because it reliably supports the formation of skimming flow during the day and exhibits pronounced thermal stratification during calm nights. The street axis is oriented north-to-south, ensuring uniform solar exposure on the rooftops throughout the diurnal cycle prior to the nocturnal observational periods. Two adjacent, architecturally identical buildings were selected for the comparative experimental setup. The roof of the primary building was retrofitted with an extensive green roof system, while the adjacent building retained its conventional bare bituminous roofing membrane, serving as the experimental control. The green roof covers a continuous area of four hundred square meters and comprises a specialized multi-layer system: a waterproofing root barrier, a drainage layer, a non-woven geotextile filter fabric, and an engineered growing medium with a depth of ten centimeters. The vegetation consists of a mature, mixed community of sedum species, providing complete areal coverage with an average canopy height of approximately twelve centimeters. The sedum leaves exhibit a fleshy, succulent morphology with microscopic surface roughness, providing an ideal template for examining passive particle capture.

3.2 Instrumentation and Sensor Deployment

To accurately capture the micro-scale gradients in particulate concentrations and meteorological variables, identical high-resolution instrument masts were erected on both the green roof and the bare roof. The masts

were positioned at the center of each roof to minimize boundary effects from the building parapets. Measurements were taken at multiple vertical elevations above the surface specifically at zero point two meters, zero point five meters, and one point five meters to establish precise concentration and micrometeorological profiles within the immediate roof boundary layer. Particulate matter concentrations were continuously measured using precision optical particle sizers. These instruments operate on the principle of light scattering, where a laser beam intersects an aerosol stream, and the scattered light intensity is correlated to the particle diameter. The sizers were configured to record the mass concentrations of fine particles and coarse particles at a temporal resolution of one minute. To ensure data integrity, especially given the high nocturnal humidity which can artificially inflate optical particle sizing due to water condensation on the particles, the inlet streams were equipped with intelligent aerosol drying systems. These dryers utilized a Nafion membrane to selectively remove moisture, maintaining the sample relative humidity below forty percent prior to optical analysis. Micrometeorological conditions were simultaneously recorded using a suite of fast-response sensors. Three-dimensional wind velocity components and sonic temperatures were measured using ultrasonic anemometers stationed at the one point five meter elevation on each mast. These sensors provided data at a frequency of ten hertz, enabling the calculation of turbulent kinetic energy and friction velocity, even during periods of extreme atmospheric stability. Additionally, highly accurate shielded thermohygrometers were deployed at each elevation to construct the vertical profiles of ambient air temperature and relative humidity.

Table 1: Instrument Specifications and Operational Parameters

Instrument Type	Measurement Variable	Operating Range	Accuracy/Resolution	Sampling Frequency
Optical Particle Sizer	Particulate Mass Concentration	Zero to ten thousand micrograms per cubic meter	Plus or minus five percent	One minute averaged
Ultrasonic Anemometer	Three-dimensional Wind Vector	Zero to forty-five meters per second	Plus or minus zero point zero one	Ten Hertz
Shielded Thermohygrometer	Temperature and Relative Humidity	Minus twenty to sixty degrees Celsius	Plus or minus zero point two degrees	One minute averaged

3.3 Data Collection and Identification of Calm Nocturnal Periods

The observational campaign spanned a continuous period of six months, encompassing late summer through early winter, to capture a diverse range of synoptic weather patterns and atmospheric stabilities. The raw data from all instruments were centrally logged, time-synchronized, and stored on secure field computers before being wirelessly transmitted to the university's cloud infrastructure for offline processing [17].

A rigorous data filtering algorithm was developed to isolate the specific environmental conditions relevant to this study: calm, stable nights. The criteria for defining a "calm night" were strictly mathematical and meteorological. First, the data were restricted to the nocturnal period, defined locally as two hours after sunset to one hour before sunrise, eliminating any residual transitional turbulence. Second, the regional synoptic wind speed, as measured by a reference meteorological tower located fifty meters above the urban canopy, had to remain below one point five meters per second for a minimum of four consecutive hours. Third, the stability of the atmospheric boundary layer was quantified using the gradient Richardson number,

a dimensionless parameter that represents the ratio of thermal buoyancy forces to mechanical shear forces. Only periods where the Richardson number was strictly positive and exceeded a critical threshold of zero point two five indicating strong stable stratification and the suppression of turbulence were retained for the primary analysis.

3.4 Analytical Methods for Deposition Velocity

The central metric for evaluating the efficacy of the green roof is the dry deposition velocity. This parameter represents the effective rate at which particulate matter is removed from the atmosphere and deposited onto the surface, normalized by the ambient concentration. Under typical turbulent conditions, deposition velocity is modeled using an electrical resistance analogy, incorporating aerodynamic resistance, quasi-laminar sublayer resistance, and surface canopy resistance. However, during the highly stable, low-wind conditions isolated in this study, the aerodynamic resistance becomes exceptionally high, and vertical transport is severely limited. To calculate the empirical deposition velocity during these calm periods, we employed a mass balance approach applied to the localized air volume above the roofs. Because lateral advection and vertical turbulent mixing were assumed to be negligible under the strictly filtered calm conditions, the observed temporal decay in particulate concentration within the measured air column was attributed entirely to deposition mechanisms. The analytical procedure involved plotting the natural logarithm of the normalized particulate concentration against time for each identified calm period. A linear regression was applied to this decay curve. The slope of this regression line represents the overall removal rate constant. The dry deposition velocity was then derived by multiplying this rate constant by the effective height of the mixed layer above the roof, which, under these stagnant conditions, was defined by the temperature inversion height measured by the sensor masts. This methodology, while reliant on the assumption of horizontal homogeneity within the immediate roof micro-environment, provides a robust, field-based estimation of the passive removal efficiency of the respective surfaces [18]. To ensure statistical reliability, the calculated deposition velocities from the green roof were directly paired and compared against those from the bare roof using non-parametric Wilcoxon signed-rank tests, acknowledging that the environmental distributions of particulate concentrations are often log-normal rather than strictly Gaussian.

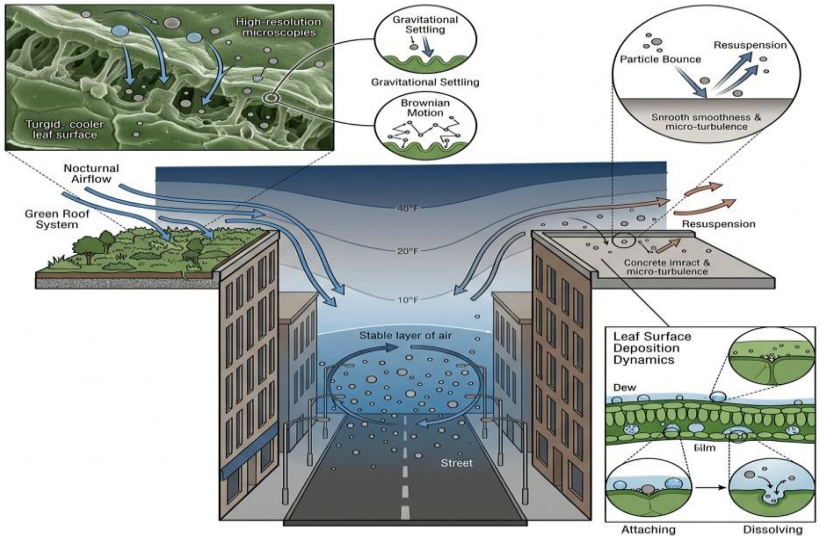


Figure 1: Comprehensive Schematic of Urban Canyon Nocturnal Airflow and Green Roof Particulate Deposition Mechanisms

4. Results and Discussion

4.1 Micrometeorological Characterization of Calm Nights

Over the six-month observational campaign, the data filtering algorithms successfully isolated forty-two distinct nocturnal periods that met the rigorous criteria for calm, stable conditions. These events were predominantly clustered in the late autumn and early winter months, associated with the presence of high-pressure anticyclonic systems over the region. The micrometeorological data confirmed the establishment

of intense local temperature inversions immediately above the building canopy.

An analysis of the vertical temperature profiles revealed significant disparities between the green roof and the bare roof environments. On the bare roof, the rapid emission of longwave radiation resulted in extreme surface cooling, creating a sharp, positive temperature gradient in the lowest meter of the atmosphere. Conversely, the green roof exhibited a more moderated thermal response. The latent heat of vaporization from ongoing nocturnal evapotranspiration, combined with the thermal mass of the saturated growing medium, prevented the surface temperature from dropping as precipitously as the bare bitumen [19].

Consequently, the relative humidity profiles also diverged significantly. The air immediately above the green roof, at the zero point two meter elevation, consistently approached or reached saturation, with relative humidity frequently exceeding ninety-five percent during the deep nocturnal hours. This moisture enrichment was a critical factor in the subsequent aerosol dynamics. In contrast, the bare roof maintained lower relative humidity levels, generally hovering between seventy and eighty percent. The ambient wind speeds during these isolated events were exceptionally low, averaging below zero point three meters per second at the one point five meter elevation, confirming the virtual absence of mechanically driven turbulence and validating our approach to examining non-aerodynamic deposition mechanisms.

Table 2: Micrometeorological Conditions During Calm Nights

Parameter	Green Roof Average	Bare Roof Average	Statistical Significance
Air Temperature at lowest level	Nine point two degrees Celsius	Seven point eight degrees Celsius	Significant difference noted
Relative Humidity at lowest level	Ninety-four percent	Seventy-six percent	Significant difference noted
Wind Speed	Zero point two meters per second	Zero point two meters per second	No significant difference

4.2 Particulate Concentration Profiles and Temporal Decay

The time-series analysis of the particulate matter mass concentrations demonstrated a clear pattern of accumulation and subsequent decay characteristic of stagnant urban conditions. Following the evening rush hour, concentrations of both fine and coarse particles surged within the urban canyon. As the nocturnal boundary layer stabilized, the supply of fresh emissions dwindled, and the atmospheric concentrations began a gradual, steady decline over the duration of the night. When comparing the vertical concentration profiles between the two experimental sites, a distinct localization effect was observed over the green roof. At the uppermost sensor elevation of one point five meters, the particulate concentrations above both roofs were statistically indistinguishable, reflecting the homogeneous background pollution of the urban canopy layer. However, as the measurement elevation descended closer to the surface, a pronounced concentration deficit emerged above the green roof. At the zero point two meter elevation, nestled just above the vegetation canopy, the concentrations of both fine and coarse particles were consistently lower than those recorded at the corresponding height over the bare roof. This vertical concentration gradient strongly implies that the green roof surface was acting as an active sink, actively depleting the particulates from the immediately adjacent air mass.

4.3 Deposition Velocities and Removal Mechanisms

The calculation of the dry deposition velocities yielded the most consequential findings of this research. The data unequivocally demonstrated that the green roof facilitated a substantially higher rate of particulate removal compared to the conventional bare roof, even in the complete absence of wind-driven aerodynamic impaction. For the coarse particle fraction, the median deposition velocity over the green roof was calculated to be zero point eight five centimeters per second, compared to zero point four two centimeters per second over the bare roof. This represents a greater than twofold increase in removal efficiency. Coarse particles are predominantly governed by gravitational settling. While gravity acts equally over both roofs, the

superior performance of the green roof can be attributed to the vastly increased effective surface area provided by the three-dimensional architecture of the sedum canopy. Furthermore, the high nocturnal humidity observed over the green roof plays a pivotal role. As the relative humidity surpasses the deliquescence point of specific aerosol components, the particles undergo hygroscopic growth, absorbing water vapor, increasing in mass, and thereby accelerating their terminal settling velocity.

Table 3: Comparative Nocturnal Particulate Matter Deposition Rates

Surface Type	Fine Particle Deposition Velocity	Coarse Particle Deposition Velocity	Estimated Nightly Removal Mass
Green Roof	Zero point one two centimeters per second	Zero point eight five centimeters per second	Forty-five milligrams per square meter
Bare Roof	Zero point zero four centimeters per second	Zero point four two centimeters per second	Eighteen milligrams per square meter

The dynamics of the fine particle fraction, which are less influenced by gravity, revealed an even more striking contrast. The median deposition velocity for fine particles over the green roof was zero point one two centimeters per second, a threefold increase over the zero point zero four centimeters per second observed for the bare roof [20]. Under calm conditions, fine particle deposition is driven primarily by Brownian diffusion across the quasi-laminar sublayer. The micro-roughness of the leaf surfaces, combined with the intricate interstitial spaces within the plant canopy, drastically reduces the thickness of this resistive sublayer, facilitating a higher rate of diffusional transfer. Furthermore, the deposition of both fine and coarse fractions on the green roof was highly aided by surface wetness. The formation of nocturnal dew on the sedum leaves, a direct consequence of the elevated humidity and radiative cooling, created an adhesive liquid boundary. When particles settled or diffused onto this wet surface, the probability of particle bounce and resuspension which remains a significant factor on dry, bare surfaces was effectively reduced to zero. The captured particles were subsequently trapped in the moisture film and, upon morning evaporation, became permanently bound to the leaf surface or washed into the substrate during the next precipitation event.

5. Conclusion

This comprehensive investigation has elucidated the critical, yet previously underexplored, role of extensive green roofs in mitigating particulate matter pollution during calm, stable nocturnal conditions within urban canyons. By employing a rigorous, paired experimental design and deploying high-resolution micrometeorological and aerosol instrumentation, this study isolated the non-aerodynamic deposition mechanisms that govern pollutant removal when conventional wind-driven dispersion fails. The empirical findings conclusively demonstrate that green roofs possess a significantly enhanced capacity to act as localized sinks for both fine and coarse airborne particulates compared to traditional bare roofing materials. During periods of atmospheric stagnation, where temperature inversions trap pollutants near the surface, the green roof exhibited deposition velocities that were two to three times greater than the control surface. This enhanced efficiency is driven not by aerodynamic impaction, but by a synergistic combination of structural and microclimatic factors. The immense micro-scale surface area of the vegetation canopy maximizes gravitational interception, while the elevated nocturnal humidity and subsequent dew formation promote hygroscopic particle growth and eliminate the potential for particle resuspension. The implications of these results are profound for contemporary urban planning and environmental policy. Current regulatory frameworks and urban air quality models frequently underestimate the twenty-four-hour biofiltration capacity of green infrastructure by focusing predominantly on daytime, convective conditions. This study provides the necessary empirical mandate to recognize green roofs as passive, continuous environmental filters that perform exceptionally well precisely when aerodynamic ventilation is at its weakest. Integrating such vegetated surfaces into the architectural fabric of densely populated urban canyons can provide a

crucial buffer against acute nocturnal pollution episodes, thereby safeguarding public health.

While this research provides significant advancements in urban environmental science, it is important to acknowledge its limitations. The observational campaign was conducted using a specific sedum-based extensive green roof in a singular geographic climate. The morphological variations of different plant species, the depth and composition of the substrate, and variations in regional aerosol chemistry may alter the observed deposition dynamics. Future academic endeavors should focus on replicating this methodology across diverse climatic zones and examining a wider taxonomy of urban flora [21]. Additionally, the long-term saturation point of the vegetation surfaces and the mechanisms of biological self-cleaning via precipitation require further longitudinal study. Nonetheless, the evidence presented herein firmly establishes that the strategic deployment of green roofs is a highly effective, scientifically validated intervention for continuously remediating the severe air quality challenges endemic to modern urban environments.

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