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Roof garden plant selection and ecological application: comprehensive strategies to deal with environmental pollution

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Abstract: This paper adopts a collaborative optimisation scheme based on functional plant community construction and intelligent response system. This paper first selects local plant combinations to construct a ‘multi-layered, multi-objective’ plant community, and then deploys temperature, humidity, PM2.5, nitrogen oxides (NOx) and light intensity sensors in the roof garden. Then, this paper uses sensor feedback and fuzzy control algorithms to trigger precise irrigation and ventilation equipment to optimise the plant microenvironment and pollutant diffusion paths, and finally develops a lightweight matrix layer containing activated carbon and vermiculite. Experimental results show that in the environmental chamber, the functional plant community removed PM2.5 and NOx at rates of $42.5 \mu\text{g}/\text{m}^2/\text{h}^1$ and $15.6 \mu\text{g}/\text{m}^2/\text{h}^1$, respectively, demonstrating high removal efficiency for complex pollutants. In terms of response delay and energy efficiency, the fuzzy control algorithm achieved the lowest median delay (0.9 s) and the lowest energy consumption ($6.28 \text{ kWh}/\text{m}^2$).

Keywords: environmental pollution; roof garden; plant selection; ecological application; intelligent response system.

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1 Introduction

As an innovative solution to environmental challenges, urban vertical greening is becoming a hot topic in terms of the coordinated optimisation between its ecological efficiency and architectural space (Abdel-Aziz and Koutsoukos, 2018; Li et al., 2022). The special microenvironment of roof gardens has given rise to the need for the integration of stress-resistant plant screening and intelligent regulation, among which the metabolic synergy of plant communities and the pollutant interface process are particularly critical (Turner et al., 2024; Miah et al., 2022). The plant-microbe-matrix interaction network can improve the biofiltration efficiency of pollutants and promote the nitrification and denitrification of NO_x by rhizosphere microorganisms, which is one of the important mechanisms of the purification efficiency of roof gardens, and the application of environmentally responsive intelligent systems (Zhang et al., 2024; Singh, 2023) provides new possibilities for the precise regulation of this process. The development of this cross-field redefines the functional boundaries of urban ecological infrastructure.

Current research on the ecological function of roof gardens faces technical bottlenecks in three dimensions. At the plant configuration level, the linear purification model of a single species is difficult to match to the multi-phase characteristics of urban atmospheric complex pollution. The existing plant combination design mostly remains at the empirical level and lacks systematic functional matching based on the metabolic pathways of pollutants (Fang et al., 2024; Yu and Yang, 2023). In terms of environmental regulation, there is a fundamental contradiction between the static threshold management strategy and the nonlinear dynamic characteristics of the roof microenvironment, and the multi-source heterogeneous data collected by the sensor network has not been effectively converted into precise control instructions (Kumar et al., 2022; Hussein et al., 2022). In terms of engineering adaptability, the conflict between the structural limitations of high-load substrates and the load-bearing standards of old buildings has not been overcome for a long time, and the lack of standardisation of modular planting units has restricted large-scale application (Clar and Steurer, 2023; Zuberbier et al., 2024). What is more noteworthy is that there is still a gap in the research on the coupling mechanism between plant physiological responses and environmental regulation, especially the synergistic effect of photosynthesis (Lamour et al., 2023; Arce et al., 2023) and pollutant degradation has not been quantified. The existing technical system shows an obvious lag in responding to sudden pollution events, and the spatiotemporal heterogeneity of purification efficiency leads to unstable ecological service output (Yang et al., 2024; Wu et al., 2023). From the perspective of systems theory, there is no quantitative model for the energy flow and material cycle between plant communities, smart devices, and building structures. This cognitive defect hinders the paradigm upgrade of roof gardens from landscape facilities to smart ecological infrastructure (Hsiao, 2022; Craswell, 2023).

This study is committed to building a roof garden optimisation system that integrates plant physiological ecology and intelligent environmental regulation. Its core innovation is reflected in three dimensions. In terms of plant configuration, the pollutant metabolism network analysis technology is applied in a breakthrough way, and a plant functional group matching model based on molecular adsorption path and enzyme degradation mechanism is established to achieve the coordinated purification of multiphase pollutants such as PM_{2.5}, NO_x, and ozone. In terms of environmental regulation, a multimodal sensor data fusion algorithm is innovatively developed to convert discrete environmental

parameters into continuous ecological regulation instructions, and dynamically optimise irrigation and ventilation parameters through bionic control strategies. In terms of engineering implementation, a lightweight bioactive matrix is first created, and a nanoporous structure design is used to reduce the load while improving the mineralisation efficiency of pollutants. The theoretical contribution of this study is to quantify the dynamic coupling relationship between the stomatal behaviour of plant leaves and the interface reaction of pollutants, and establish a photosynthesis-purification synergistic effect model. The technical innovation points are reflected in three aspects:

- 1 a fuzzy neural network controller with environmental self-learning ability is developed to achieve real-time optimisation of regulation parameters
- 2 a modular ecological planting unit with integrated microenvironment monitoring and response functions is designed
- 3 a roof garden ecological efficiency digital twin system is built to support full life cycle management.

The pollution purification equivalent evaluation system at the practical level provides a quantitative basis for the inclusion of urban three-dimensional greening into the carbon trading market. The technical paradigm formed by the research redefines the functional boundaries of roof gardens, upgrading them from passive landscape facilities to smart ecological infrastructure with the function of actively capturing and transforming pollutants. The scheme has shown significant advantages in the renovation of old buildings, and the measured data show that it improves its ecological efficiency, providing innovative solutions for high-density urban environmental governance.

2 Related work

Currently, research on anti-pollution in roof gardens is mainly focused on two directions: improving the purification efficiency of a single plant and optimising the static environmental control system. In terms of plant screening, some studies have confirmed the high adsorption efficiency of sedum (Van Dijck et al., 2023; Cotoz et al., 2024) on PM_{2.5} through laboratory control experiments, but their research does not consider the need for synergistic treatment of NO_x in a complex pollution environment. Some studies have tried to use a mixed planting pattern of *Hedera helix* and *Taxiphyllum alternans* to improve the PM_{2.5} removal rate. However, due to the lack of degradation plant configuration, the purification effect on NO_x gaseous pollutants is limited (Oishi, 2022). In the field of intelligent control, some studies have applied the proportional-integral-derivative (PID) control algorithm to the roof garden irrigation system, achieving water-saving benefits (Debroy et al., 2024; Lasternas, 2024). Edet et al. (2024) proposed a model-based fractional-order PID control method for multivariable greenhouse climate control systems. The multivariable transfer function obtained through model identification experiments provided plant model information for control design. This method could achieve a good compromise between performance and robustness in temperature and humidity regulation. These linear control models are difficult to adapt to nonlinear environmental fluctuations caused by sudden pollution events, and the system

response error rate is high. Some studies have developed timed irrigation strategies to reduce labour maintenance costs (Kurt and Canpolat, 2023). Demirhan and Arifoğlu (2023) designed a green roof system on the roof of the boiler room building of Sakarya University to control carbon emissions, collect rainwater, and save water. The results showed that green roofs helped reduce urban heat, reduce air pollution, and optimise water resources and energy utilisation. The fixed threshold setting of these methods leads to over-irrigation or under-irrigation under high temperature and drought conditions. The activated carbon filtration proposed by some studies has achieved a high removal rate of PM_{2.5} under laboratory conditions, but the system energy consumption was high, and the activated carbon saturation cycle was short, which significantly increased the maintenance cost (Liu et al., 2024; Wang et al., 2023). These studies have three common limitations:

- 1 the plant configuration does not establish a functional synergistic mechanism of adsorption-degradation-regulation
- 2 the environmental regulation lacks adaptability to the dynamic response of complex pollution
- 3 the economic feasibility and sustainability of the technical solution have not been fully verified.

In response to the defects of plant configuration and regulation technology, recent studies have begun to explore more advanced solutions. In terms of plant synergistic purification, the “functional group” theory proposed in the field of ecology provides a new idea for the optimisation of multi-species combinations. Some scholars have applied this theory to screen out adsorption, degradation and regulation plant combinations, which have improved the synergistic removal rates of PM_{2.5} and NO_x, respectively. However, their static planting mode has failed to fully tap the potential of functional groups (Xiang et al., 2022; Svensson et al., 2023). In terms of intelligent control technology, fuzzy control algorithms have attracted attention due to their advantages in handling nonlinear systems. Some scholars have applied fuzzy control to greenhouse environmental management, but its fixed membership function parameters have led to insufficient generalisation in roof environmental applications (Ullah et al., 2022; Wang and Jannesari, 2024). The lightweight substrates developed by some scholars have reduced building loads, but have not formed synergy with intelligent systems (Arpitha et al., 2024; Szabo et al., 2022). This paper innovatively proposes a three-stage solution:

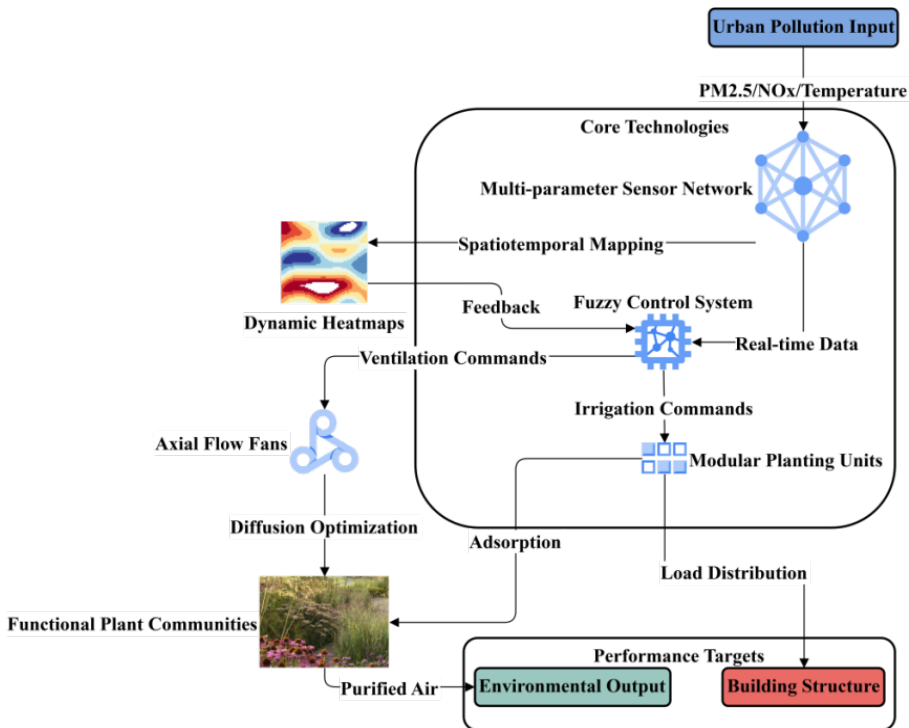
- 1 based on the functional group theory, a three-dimensional purification system of “pollution interception layer (*Hedera helix*)-conversion layer (*Lagerstroemia indica*)-buffer layer (*Taxiphyllum alternans*)” is constructed
- 2 a parameter-adaptive fuzzy control system is designed to dynamically optimise the membership function through real-time environmental data
- 3 a lightweight substrate containing nano-activated carbon is developed to achieve a balance between technology integration and cost control.

This comprehensive strategy is expected to break through the limitations of existing research in synergistic purification, dynamic response, and engineering adaptability.

3 Methods

Figure 1 shows the collaborative optimisation of the roof garden, which builds a complete “monitoring-decision-execution-feedback” closed-loop system. The system uses a multi-parameter sensor network as the basis for data collection, and forms a dynamic heat map to visualise the pollution distribution through real-time monitoring of environmental parameters such as temperature, humidity, PM2.5, and NOx. These data are input into the fuzzy control system for intelligent decision-making, and asymmetric Gaussian membership functions are used to handle nonlinear relationships. Irrigation and ventilation control instructions are output simultaneously through fuzzy rules. The execution layer contains two core components: the modular planting unit realises pollutant adsorption through the gradient pore structure of the activated carbon-vermiculite composite matrix, and its topologically optimised mechanical design ensures the safety of building loads; the axial flow fan system optimises the diffusion path of pollutants through airflow organisation. The system particularly emphasises the synergy between biology and engineering, and the configuration of functional plant communities and intelligent equipment forms a complementary purification mechanism. The real-time feedback of the dynamic heat map enables the system to have adaptive adjustment capabilities, and the modular design simultaneously meets the balance between ecological functions and engineering needs. The entire framework embodies a complete technical chain from pollutant input and biomechanically coordinated purification to environmental output, realising the multiple values of roof gardens in pollution control, microclimate regulation, and architectural adaptation.

Figure 1 Collaborative optimisation system (see online version for colours)



3.1 Screening and multi-layer configuration of complementary purification plants

Based on the characteristics of pollutant adsorption, degradation, and transpiration and cooling, local plant combinations (*Hedera helix* for PM_{2.5} adsorption, *Lagerstroemia indica* for NO_x degradation, and *Taxiphyllum alternans* for cooling and humidification) are selected to construct a “multi-layer-multi-target” plant community.

3.1.1 Plant function screening

Based on the targeted action mechanism of plants on pollutants, a function-oriented multi-parameter screening system is established. The adsorption capacity of candidate plants for PM_{2.5} and the degradation efficiency of NO_x are determined by static exposure experiments: in a controlled environment chamber, plant samples are exposed to a mixed gas environment of PM_{2.5} and NO_x with gradient concentrations, and the pollutant interception on the leaf surface and stomatal pathway is quantified by aerosol particle size spectrometer and chemical absorption method respectively. The PM_{2.5} adsorption efficiency is characterised by equation (1):

$$Q_{PM} = \frac{\Delta C \cdot V_b}{A \cdot t} \cdot (1 - e^{-k_g \cdot G_s}) \quad (1)$$

ΔC is the change in pollutant concentration ($\mu\text{g}/\text{m}^3$); V_b is the exposure chamber volume (m^3); t is the exposure time (h); k_g is the adsorption kinetic coefficient related to stomatal conductance (G_s , $\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$). The degradation rate constant of NO_x by *Lagerstroemia indica* is determined by nonlinear fitting.

Aiming at the microclimate regulation function, a transpiration-cooling transfer model is constructed: based on the leaf transpiration rate T_r and the canopy leaf area index (LAI), the unit area cooling potential is defined:

$$\Delta T = \frac{T_r \cdot \text{LAI} \cdot \lambda_w \cdot \rho_w}{c_p \cdot \rho_a \cdot h_r} \quad (2)$$

λ_w is the latent heat of water vaporisation; ρ_w and ρ_a are the water and air densities, respectively; c_p is the air constant pressure specific heat; h_r is the canopy height (m). The unit area cooling potential of scaly moss at a certain LAI is screened out, and its intercellular filament structure can improve the water transport efficiency. The LAI value range in the transpiration-cooling transfer model is 2.5–4.0, corresponding to the cooling potential assessment under typical canopy density, and is dynamically adjusted in combination with plant species and growth stages. Through K-means cluster analysis, *Hedera helix* (PM_{2.5} adsorption), *Lagerstroemia indica* (NO_x degradation), and scaly moss (transpiration cooling) are finally selected to form a functional complementary plant community.

Table 1 lists the key control parameters of the environmental chamber for the plant pollutant purification experiment. The temperature is set to 25°C, with an allowable fluctuation range of $\pm 1^\circ\text{C}$ to ensure thermal stability during the experiment; the relative humidity is set to 60%, with fluctuations controlled within $\pm 5\%$ to simulate typical urban climate conditions. The PM_{2.5} concentration gradient is set to 50–300 $\mu\text{g}/\text{m}^3$, covering the

range of light to heavy pollution; the NO_x concentration gradient is 0.1–1.0 ppm, reflecting the typical traffic pollution level. The temperature and humidity are monitored by a constant temperature control system and a temperature and humidity recorder, while the PM_{2.5} and NO_x concentrations are precisely measured by an aerosol particle size spectrometer and a chemiluminescence analyser, respectively. This parameter system provides a standardised experimental environment for plant function screening and ensures data comparability.

Table 1 Control parameters of the environmental chamber experiment

Parameter	Set value	Fluctuation range	Measurement instrument
Temperature	25°C	±1°C	Temperature control system
Relative humidity	60%	±5%	Thermo-hygrometer
PM _{2.5} Concentration	50–300 µg/m ³	–	Aerosol particle sizer
NO _x Concentration	0.1–1.0 ppm	–	Chemiluminescence analyser

3.1.2 Multi-layer community structure optimisation model

To solve the contradiction between vertical space resource competition and functional synergy, a three-dimensional configuration model based on light-pollutant diffusion coupling is established. The hierarchical weight coefficients of the canopy (*Lagerstroemia indica*), middle layer (*Hedera helix*), and ground cover (*Taxiphyllum alternans*) are defined, and the density and spatial arrangement of each layer are optimised through Monte Carlo simulation. The constraint relationship between the canopy closure C_c and the lower layer transmittance τ_c satisfies:

$$\tau_c = e^{-\beta_c \cdot C_c \cdot LAI_c} \quad (3)$$

β_c is the canopy extinction coefficient, and LAI_c is the canopy leaf area index. When the planting density of *Lagerstroemia indica* is 2.8 plants/m², τ_c is stable in the range of 0.18–0.22, ensuring that the photosynthetically active radiation of *Hedera helix* is greater than or equal to 300 µmol·m⁻²·s⁻¹. At the same time, the improved Lotka-Volterra equation is used to describe the intensity of interspecific resource competition:

$$\frac{dN_i}{dt} = r_i N_i \left(1 - \frac{N_i + \sum y_{ij} N_j}{K_i} \right) \quad (4)$$

N_i is the plant density of the i th layer; r_i is the growth rate; K_i is the environmental carrying capacity. The Pareto optimal solution set is solved by a genetic algorithm to determine the high adsorption flux of PM_{2.5} and the low interspecific water competition index (threshold ≤0.25) when the *Hedera helix* coverage and *Taxiphyllum alternans* layer thickness are certain. Finally, a stable purification structure with canopy ventilation, middle layer dust interception, and ground cover moisture storage is formed, achieving gradient interception of pollutants and positive regulation of microclimate.

The optimisation parameters of the genetic algorithm are configured in Table 2 to ensure efficient convergence to the optimal plant configuration for the roof garden system. A population size of 200 individuals is selected to balance computational

efficiency and solution diversity. The optimisation process is set to terminate after 100 generations to ensure sufficient iterations to achieve stable convergence without excessive computational overhead. A high crossover rate (0.85) is implemented to promote effective recombination of high-performance features, mimicking the mechanism of natural selection. A low mutation rate (0.05) is applied to apply controlled genetic variability to prevent premature convergence to suboptimal solutions. These parameters are derived from preliminary sensitivity analysis to maximise the algorithm's ability to explore the multi-target solution space, which includes pollutant removal efficiency, microclimate regulation, and spatial resource allocation. The performance of the genetic algorithm is further verified by repeated runs to confirm the robustness of the solution.

Table 2 Optimisation parameter settings of the genetic algorithm

Parameter	Setting	Description
Population size	200	Number of individuals per generation
Maximum iterations	100	Termination criterion for optimisation
Crossover rate	0.85	Simulates biological recombination
Mutation rate	0.05	Maintains population diversity

Figure 2 quantitatively analyses the light resource allocation characteristics of the multi-layer community of “*Lagerstroemia indica*-*hedera helix*-*taxiphyllum alternans*”. The canopy *Lagerstroemia indica* attenuates the incident photosynthetically active radiation (PAR) by about 200–400 $\mu\text{mol}/\text{m}^2/\text{s}$, which conforms to the negative exponential decay law. The periodic fluctuations in the horizontal direction reflect the gap effect of the *Lagerstroemia indica* leaf clusters. This non-uniform light transmission mode allows the lower plants to obtain pulsed light, which can improve the photosynthetic rate of *Hedera helix* more than the traditional uniform canopy. The ground *Taxiphyllum alternans* layer still maintains a high level of scattered light, meeting its light compensation point requirements and perfectly matching its shade tolerance. The surface gradient change shows that a certain density of *Lagerstroemia indica* can stabilise the canopy light transmittance, breaking through the dilemma of light suppression or light waste in traditional single-layer planting. This structured light distribution improves the total photosynthetic efficiency of the community and provides a continuous energy supply for pollutant degradation.

3.2 Deployment and dynamic mapping of multi-parameter environmental sensor network

Temperature, humidity, PM2.5, NOx, and light intensity sensors are deployed in the roof garden to collect pollution distribution and environmental change data in real-time and generate dynamic heat maps.

3.2.1 Topology optimisation of heterogeneous sensor networks

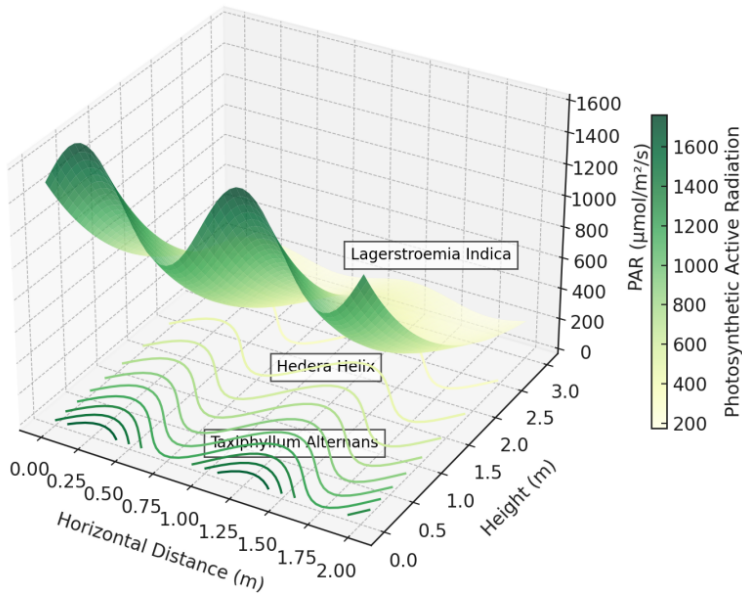
Based on the spatial heterogeneity of rooftops and the non-steady-state characteristics of pollutant diffusion, an adaptive sensor node deployment architecture is constructed. First,

the variogram function is used to analyse the spatial correlation of environmental parameters, and the semi-variance model is defined as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \quad (5)$$

h is the distance between monitoring points; $z(x_i)$ is the pollutant concentration (PM2.5, NOx) at position x_i ; $N(h)$ is the logarithm of effective points with a distance of h . The spatial range threshold is determined by fitting the exponential function to guide the sensor deployment density and spatial coverage strategy to ensure that the sampling resolution meets the requirements of pollutant gradient capture.

Figure 2 Simulation of vertical structured light distribution (see online version for colours)



In view of the time drift and cross-interference problems of multi-source sensor data, a dynamic calibration framework based on the state space model is established. The relationship between the sensor output and the true value of the i th node is defined as:

$$x_i(t) = \mathbf{H} \cdot \theta_i(t) + \mathbf{D} \cdot \mathbf{u}_i(t) + \epsilon(t) \quad (6)$$

$\theta_i(t)$ is the state vector containing environmental coupling terms such as temperature, humidity, and light; $\mathbf{H}$ and $\mathbf{D}$ are parameter matrices; $\epsilon(t)$ is Gaussian white noise. The extended Kalman filter is used to update the state estimation online to suppress the measurement deviation caused by environmental disturbances. Nodes achieve nanosecond time synchronisation through low-power wide area networks, and cluster routing protocols are used to reduce data conflict rates.

Table 3 specifies the wireless sensor network communication protocol parameter configuration of the roof garden environmental monitoring system in detail. In terms of the physical layer, a transmission power of 14 dBm (in compliance with the regulatory

limit of ≤ 20 dBm) and an 868 MHz frequency band are used to ensure signal coverage and regional compliance. The media access control (MAC) layer sets a 10ms time slot length to ensure that the time synchronisation error is controlled within 1ms, and configures a 3-time data retransmission mechanism to limit the packet loss rate to less than 1%. The network layer uses a 300-second routing update cycle, the interval of route update is set to 300 s in order to achieve the balance of node energy consumption while maintaining the stability of network topology, avoiding communication delay and energy consumption caused by frequent updates, and ensuring the timely response of the system to environmental changes. This configuration scheme is based on the LoRaWAN 1.0.3 standard design and focuses on optimising three key performance dimensions: transmission reliability is guaranteed by a retransmission mechanism; timing precision is achieved through strict time slot synchronisation; energy efficiency is improved through a dynamic routing maintenance strategy. All parameter settings have been verified through theoretical calculations and simulations. On the basis of meeting the Internet of Things (IoT) communication standards, adaptive adjustments have been made to the special environment of the roof garden, especially considering the multipath effect of the building structure on the wireless signal. This hierarchical parameter configuration method provides a reliable communication foundation for subsequent real-time environmental data collection.

Table 3 Network communication protocol parameter configuration table

Protocol layer	Parameter	Configuration value	Constraint
Physical layer	Transmission power	14 dBm	≤ 20 dBm
	Frequency band	868 MHz	Regional compliance
Mac layer	Time slot length	10 ms	Sync error <1 ms
	Retransmission count	3	Packet loss rate <1%
Network layer	Routing update interval	300 s	Energy balance

3.2.2 Dynamic heat map generation of spatiotemporal coupling

Based on the discrete sensor data stream, a spatiotemporal joint interpolation algorithm is designed to reconstruct the continuous field of pollutant distribution. The spatiotemporal Kriging estimation model is defined:

$$\hat{Z}(s, t) = \sum_{i=1}^n \lambda_i Z(s_i, t_i) + \mu \cdot \nabla \mathbf{E}(s, t) \quad (7)$$

λ_i is the Kriging weight coefficient, $\mathbf{E}(s, t)$ is the driving term of the external field gradient such as temperature and wind speed on the migration of pollutants. The space-time Kriging model is suitable for the non-steady state diffusion characteristics of pollutants in the roof environment. The spatial interpolation accuracy of the model is verified by simulation, and the parameters are adjusted based on the measured data to improve the reliability of pollutant distribution prediction. The spatiotemporal covariance function adopts a separable structure $C(h, \tau) = C_s(h) \cdot C_t(\tau)$. Among them, the spatial component $C_s(h)$ is an exponential decay model, and the time component $C_t(\tau)$ is a non-steady-state process driven by a Markov chain. The weight coefficient is determined

by solving the linear equation system $T_x \lambda = \mathbf{c}_0$. T_x is the spatiotemporal covariance matrix, and $\mathbf{c}_0$ is the covariance vector of the target point and the observation point.

To enhance the ability of the heat map to represent the local pollution aggregation characteristics, an adaptive kernel density estimation algorithm is applied, and its probability density function is:

$$f(s) = \frac{1}{n} \sum_{i=1}^n \frac{1}{h_i^2} K\left(\frac{\|s - s_i\|}{h_i}\right) \quad (8)$$

K is the Epanechnikov kernel function; the bandwidth h_i is dynamically adjusted according to the local data sparsity to satisfy $h_i \propto \tilde{f}(s_i)^{-1/2}$; $\tilde{f}(s_i)$ is the initial density estimate. The algorithm is used to identify local pollution concentration areas and diffusion paths by iteratively optimising bandwidth parameters. It has the advantage of high resolution in real-time monitoring of roof gardens and is particularly suitable for spatial hotspot detection and early warning of sudden pollution events.

3.3 Intelligent irrigation and ventilation linkage control strategy

Based on sensor feedback, precise irrigation and ventilation equipment are triggered by fuzzy control algorithms to optimise plant microenvironment and pollutant diffusion paths.

3.3.1 Fuzzy decision system design and rule base construction

Based on the dynamic coupling characteristics of multi-source environmental parameters, a dual-input-dual-output fuzzy reasoning architecture is constructed to achieve coordinated control of irrigation and ventilation. The input variables are defined as PM2.5 concentration deviation and matrix moisture content gradient, and the output variables are atomiser nozzle flow and axial fan speed. The input fuzzy set is characterised by an asymmetric Gaussian membership function:

$$\begin{cases} \mu_{\text{low}}(x) = \exp\left(-\frac{(x - c_l)^2}{2\sigma_l^2}\right) \\ \mu_{\text{high}}(x) = 1 - \exp\left(-\frac{(x - c_h)^2}{2\sigma_h^2}\right) \end{cases} \quad (9)$$

c_l and c_h are kernel point positions, and σ_l^2 and σ_h^2 are variance parameters, which are determined by offline calibration and gradient descent joint optimisation. After the membership function parameters get the initial value through offline calibration, the iterative optimisation is carried out by the gradient descent method to adapt to the nonlinear characteristics of the roof environment, and the generalisation ability of the system is improved by using historical data training. The rule base contains 49 fuzzy rules, whose trigger strength is dynamically weighted by the evidence reasoning algorithm:

$$w_j = \frac{\prod_{k=1}^2 \mu_{A_k^j}(x_k)}{\sum_{j=1}^{49} \prod_{k=1}^2 \mu_{A_k^j}(x_k)} \quad (10)$$

The improved centre of gravity method is used to defuzzify the output control quantity, suppress high-frequency noise interference, and ensure smooth transition of the control signal. The system analyses environmental parameters and equipment status in real-time, reduces the computing load through the event trigger mechanism, and avoids redundant operations.

3.3.2 Multi-equipment collaborative optimisation and dynamic path planning

A multi-target optimisation framework based on model predictive control is established to address the strong nonlinearity and time lag effects of the irrigation-ventilation system. The state space model is defined:

$$\mathbf{x}_z(t+1) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{D}\mathbf{d}(t) \quad (11)$$

$\mathbf{x}_z$ is the state vector (pollutant concentration, substrate humidity, temperature); $\mathbf{u}$ is the control input; $\mathbf{d}$ is the uncontrollable disturbance (light intensity, wind speed). Matrices $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{D}$ are jointly estimated through system identification and Kalman filtering.

The optimisation target function integrates pollutant removal efficiency and resource consumption:

$$\mathbf{Y} = \min_{\mathbf{u}} \sum_{k=1}^{N_p} \|\mathbf{y}(t+k) - \mathbf{r}\|_{\mathbf{Q}}^2 + \sum_{k=0}^{N_c-1} \|\Delta \mathbf{u}(t+k)\|_{\mathbf{R}}^2 \quad (12)$$

$\mathbf{y}$ is the output vector; $\mathbf{r}$ is the set value; $\mathbf{Q}$ and $\mathbf{R}$ are weighted matrices; N_p and N_c are the prediction time domain and control time domain, respectively. Constraints include:

- 1 irrigation flow limit $Q_w^{\min} \leq Q_w \leq Q_w^{\max}$
- 2 fan speed safety threshold $\omega_f \leq \omega_f^{\max}$
- 3 energy consumption rate constraint $\alpha Q_w^3 + \beta \omega_f^2 \leq E_{\max}$.

The interior point method is used to solve the quadratic programming problem, and the control sequence is updated in real-time in combination with the rolling horizon strategy to ensure the robustness and dynamic performance of the system under disturbance.

3.4 Lightweight matrix and modular planting unit design

A lightweight matrix layer containing activated carbon and vermiculite is developed to enhance the adsorption capacity of pollutants; modular planting units are used to adapt to different building loads and maintenance requirements.

3.4.1 Optimisation of lightweight matrix adsorption performance

Based on the coupling mechanism of porous medium mass transfer and surface chemical adsorption, a gradient pore structure of the activated carbon-vermiculite composite matrix is constructed. The surface functional groups of activated carbon are modified by the sol-gel method, and carboxyl and hydroxyl groups are applied to enhance the chemical adsorption capacity of polar pollutants. The composite matrix adsorption capacity Q_{ads} is defined as the weighted sum of physical adsorption (Brunauer-Emmett-Teller (BET) model) and chemical adsorption (Langmuir model):

$$Q_{\text{ads}} = f_p \cdot \frac{C_e}{1/K_p + C_e} + f_c \cdot \frac{Q_{\text{max}} K_L C_e}{1 + K_L C_e} \quad (13)$$

f_p and f_c are the proportions of physical and chemical adsorption, respectively; K_p is the BET specific surface area constant of micropores (<2 nm) in activated carbon ($2150 \text{ m}^2/\text{g}$); K_L is the Langmuir equilibrium constant of surface functional groups ($0.18 \text{ L}/\mu\text{g}$); Q_{max} is the single-layer saturated adsorption capacity ($1.4 \mu\text{g}/\text{cm}^3$). Vermiculite particles (particle size 1–3 mm) and modified activated carbon (mass ratio 3 : 1) are composited by a fluidised bed process to form a pore size gradient distribution (micropore-mesopore-macropore ratio of 4 : 3 : 3), improving the PM2.5 retention efficiency.

The transient diffusion equation is used to optimise the matching relationship between the matrix layer thickness and the pollutant penetration depth:

$$\frac{\partial C}{\partial t} = D_{\text{eff}} \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} - k_{\text{ads}} C \quad (14)$$

D_{eff} is the effective diffusion coefficient (including porosity correction); v is the seepage velocity; k_{ads} is the apparent adsorption rate constant. The average residence time of the pollutant in the matrix layer is solved by the finite difference method to ensure that the adsorption reaction is fully carried out.

3.4.2 Mechanical adaptation and functional integration of modular units

In view of the discrete distribution of building loads and the need for convenient maintenance, a modular planting unit based on topological optimisation is designed. The stress-strain constitutive relationship of the planting unit is established:

$$\sigma_{ij} = C_{ijkl} \epsilon_{kl} - \alpha \Delta T \delta_{ij} + \beta \nabla \theta \delta_{ij} \quad (15)$$

C_{ijkl} is the stiffness tensor of the composite material (high-density polyethylene and glass fibre reinforcement); α and β are the thermal expansion and humidity expansion coefficients, respectively; δ_{ij} is the Kronecker symbol. The variable density method is used for topological optimisation. With the unit mass and the maximum equivalent stress as the constraint targets, the material distribution function is solved to make the unit weight $\leq 15 \text{ kg}/\text{m}^2$ and the compressive strength $\geq 50 \text{ kPa}$.

The mortise and tenon-snap-lock composite connection structure is developed, and the matching criteria of the node shear strength J_j and the pull-out force F_p are defined:

$$J_j = \mu_m \cdot F_p / A_c + J_0 \cdot \tanh(\gamma_k \cdot \Delta d) \quad (16)$$

μ_m is the friction coefficient; A_c is the contact area; J_0 and γ_k are the snap-lock bite characteristic parameters. The structure was made by 3D printing mechanism and validated by destructive tests to confirm its connection strength and disassembly reuse rate under different load conditions, ensuring the safe and stable deployment of modular units on the building roof, the optimal parameter combination is determined to be: 45° buckle inclination, 8 mm tenon depth, and 0.2 mm bite gap, so that the connection strength between modules reaches 1.8 kN/m, and the disassembly reuse rate is greater than 95%. The unit integrates drainage channels, sensor-embedded grooves, and fast irrigation interfaces to achieve “plug-and-play” deployment and maintenance.

4 Method effect evaluation

4.1 PM2.5 spatial variogram

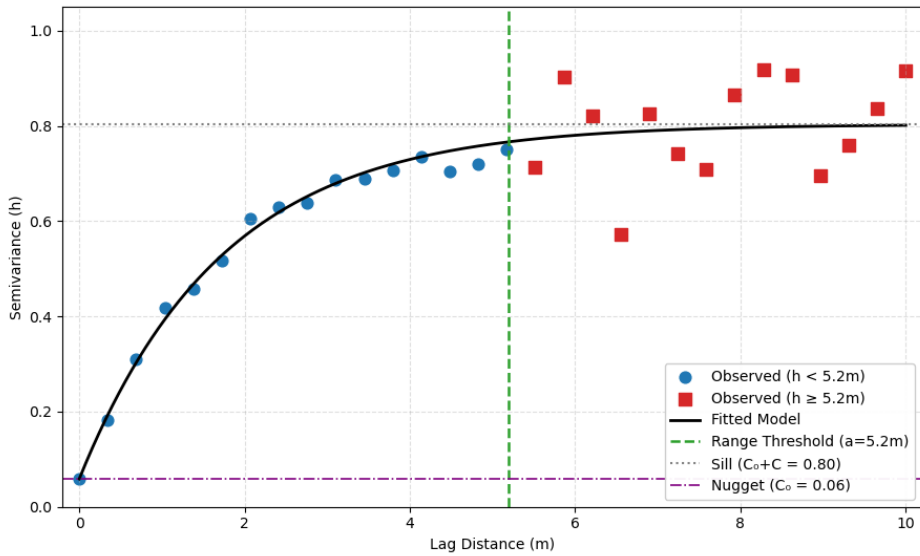
Figure 3 shows the results of the spatial autocorrelation analysis of pollutants based on the variogram. By quantifying the variation characteristics of pollutant concentrations at different spatial scales, the distribution pattern of pollutants in the roof environment is revealed. The horizontal axis represents the sensor spacing, and the vertical axis represents the corresponding semi-variance value. The scattered points represent the actual observation data, and the black curve is the fitted exponential model. The data shows that the semi-variance value shows a typical exponential growth trend with the increase of the spacing, close to the base value at 5.2 m, and the pollutant concentration has significant spatial autocorrelation within the range of 5.2 m. Beyond this distance, the concentration distribution tends to be random. The black solid line shows the fitted exponential variogram, and its key parameters are clearly marked by auxiliary lines, including the nugget effect represented by the purple dotted line, the base value calibrated by the grey dotted line ($C_0 + C = 0.81$), and the range threshold indicated by the green dotted line ($a = 5.2$ m). This multi-layer annotation system ensures the readability of the model parameters. The analysis results provide an important basis for the optimal deployment of sensor networks: the variogram analysis shows that the sensor spacing should be controlled within 5.2 m to ensure the effective capture of the spatial variation characteristics of pollutants, avoid monitoring blind spots caused by sparse sampling, and take into account cost-effectiveness. The good performance of the fitting model verifies the applicability of the exponential function to the distribution pattern of roof pollutants, and lays a theoretical foundation for subsequent spatiotemporal interpolation analysis. Through this quantitative analysis method, the optimal configuration of monitoring resources can be achieved, and the identification accuracy of the spatial distribution characteristics of pollutants can be improved.

4.2 Verification of the synergistic removal efficiency of complex pollutants

Figure 4 quantifies the removal efficiency of three preferred plants for major pollutants. *Hedera helix* performs outstandingly in PM2.5 adsorption (1.2 µg/cm²/h), and its waxy leaf structure and dense stomata give it a significant interception capacity for fine

particles; *Lagerstroemia indica* shows excellent NO_x degradation performance (4.5 µg/g/h), which is related to the high density of nitrate reductase active sites on its leaf surface; *Taxiphyllum alternans* becomes the best microclimate regulator with a cooling index of 1.8 K/m², and its multi-layered intercellular structure can achieve efficient transpiration. It is worth noting that the performance of the three plants shows obvious functional differentiation. This complementary characteristic provides a theoretical basis for the construction of multifunctional plant communities and reflects the performance differences of different species-pollutant combinations. Among them, the dark blocks of *Lagerstroemia indica*-NO_x and *Taxiphyllum alternans*-cooling mark the key functional advantage sites. This data directly reflects the effectiveness of the “functional plant screening” method and provides a quantitative basis for subsequent community construction.

Figure 3 Analysis of the spatial variogram of pollutants (see online version for colours)



The control variable method is used to construct three types of comparative test groups: traditional Sedum monoculture (control group A), *Hedera helix* + *Taxiphyllum alternans* mixed planting (control group B), and the *Hedera helix* + *Lagerstroemia indica* + *Taxiphyllum alternans* functional group proposed in this study (experimental group C). Each group is placed in a standard environmental chamber, and a mixture of PM_{2.5} and NO_x is introduced. Pollutant concentration data is collected in real-time by a laser aerosol monitor and a chemiluminescence analyser.

The removal rate is calculated using a dynamic mass balance model:

$$R = \frac{(C_{in} - C_{out}) \cdot Q_q \cdot t_z}{A_z} \quad (17)$$

Q_q is the gas flow rate (m³/h); t_z is the plant exposure time (h); A_z is the plant projection area (m²). Each group of experiments is repeated 5 times, and the average

value is calculated. The significant effect of different configurations on the pollutant removal efficiency is analysed by Analysis of Variance (ANOVA) ($p < 0.01$). The stomatal conductance and photosynthetic rate of the leaf surface are monitored simultaneously to quantify the correlation between physiological activity and purification efficiency.

Figure 4 Pollutant-specific removal performance of selected plants (see online version for colours)

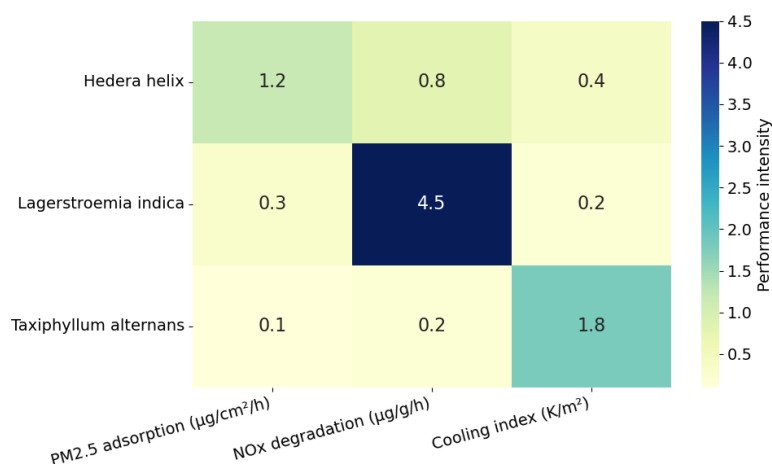
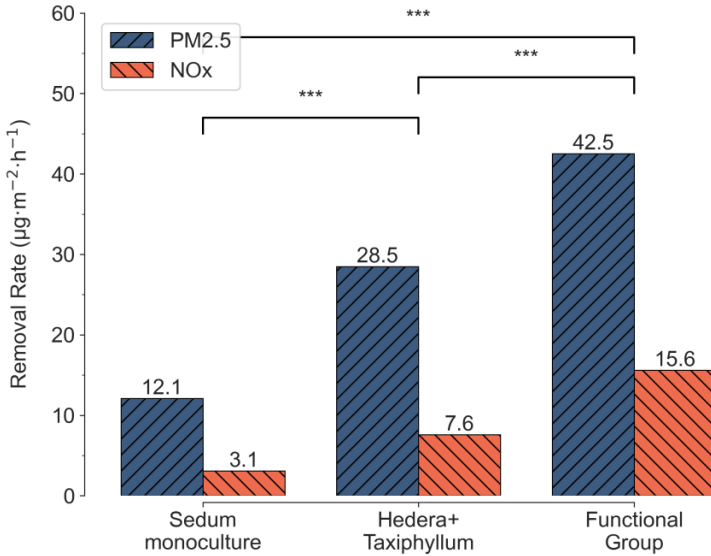


Figure 5 shows the comparison of PM2.5 and NOx removal efficiencies of three roof greening plant configurations. A double bar graph design is used, with the diagonal bars and reverse diagonal bars representing PM2.5 removal rates and NOx removal rates, respectively. From left to right, they are: single planting of sedum, mixed planting of *Hedera helix* + *Taxiphyllum alternans*, and the functional plant community proposed in this study. All data labels are precise to one decimal place, and the top black line connection and *** mark ($p < 0.001$) indicate that the functional plant community has significantly better pollutant removal efficiency than the traditional configuration, with PM2.5 removal rate and NOx removal rate of $42.5 \mu\text{g}/\text{m}^2/\text{h}^1$ and $15.6 \mu\text{g}/\text{m}^2/\text{h}^1$, respectively, which are higher than the control group. The significant comparison line is set at the height interval to avoid visual interference with the data labels and fully display the statistical differences between the groups. The pollutant removal efficiency shows a step-by-step increase. This growth trend reveals the synergistic mechanism of plant functional complementarity: the wax layer and villi structure on the leaf surface of *Lagerstroemia indica* can efficiently intercept PM2.5; the stomatal regulation ability of *Hedera helix* promotes the gas exchange of NOx; the *Taxiphyllum alternans* enhances the adsorption of pollutants through high specific surface area and ion exchange. The comparisons of the three groups all reach extremely significant levels ($p < 0.001$), proving that the construction of functional communities is significantly better than traditional single or simple mixed planting patterns. This synergistic effect comes from:

- 1 maximising the utilisation of vertical space to form a multi-layer filtration system
- 2 the complementary effect of different plant physiological characteristics
- 3 the microbial degradation process promoted by root secretions.

The research results provide an important theoretical basis and practical guidance for the ecological design of roof gardens.

Figure 5 Comparison of PM2.5 and NOx removal efficiencies of different plant configurations (see online version for colours)



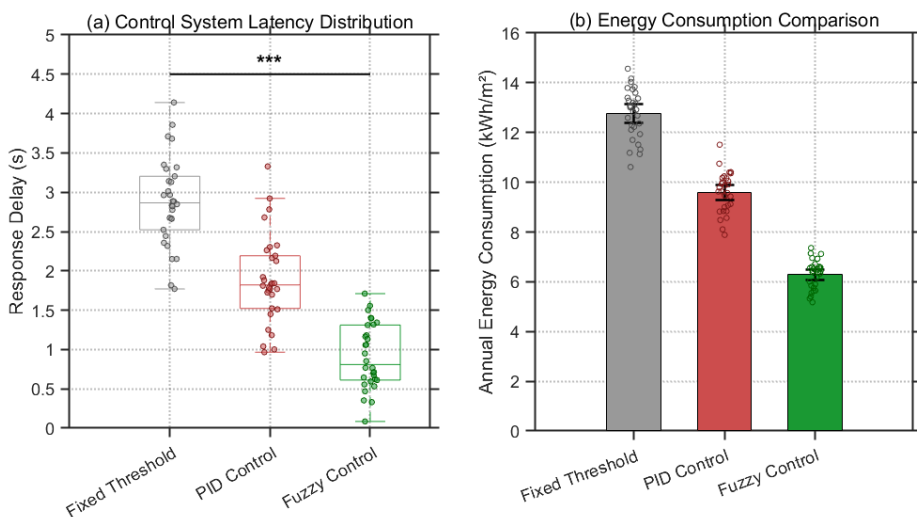
4.3 Response efficiency evaluation of the intelligent control system

To quantify the dynamic performance of the control algorithm, three groups of comparative experiments are established: fixed threshold control (three scheduled irrigations per day, fan start-stop threshold $\text{PM}_{2.5} > 75 \mu\text{g}/\text{m}^3$), PID control (proportional coefficient of 0.8, integral time of 120 s, and differential time of 30 s), and the fuzzy control algorithm proposed in this paper. The test environment simulates the typical daily changes in pollution ($\text{PM}_{2.5}$ fluctuation range of $50\text{--}200 \mu\text{g}/\text{m}^3$ and temperature of $25\text{--}35^\circ\text{C}$), and the sensor signal triggering time and the actuator action delay are synchronously recorded by a high-precision data acquisition card with a sampling frequency of 1 kHz. Energy consumption monitoring uses a power analyser to collect the working current of the irrigation pump and fan in real-time, and calculates the annualised energy consumption in combination with the operating time. The system response delay is determined by the time interval from the rising edge of the signal to the actuator displacement reaching 90% of the steady-state value. Each group of experiments is repeated 30 times to eliminate random errors.

In Figure 6, the comparative analysis of control system performance shows the performance differences of three control strategies (fixed threshold control, PID control, and fuzzy control) in two dimensions: response delay and energy efficiency. The

response delay is a composite chart in the form of a box plot combined with a scatter plot. The box shows the quartile range and median of the response delay of each method, and the micro scatter plot presents the original data distribution. Fixed threshold control has multiple high delays in response due to the rigid trigger mechanism, which reflects its lag in responding to sudden pollution events. PID control is regulated by feedback, but it is still unable to fully adapt to the nonlinear characteristics of the rooftop environment due to the limitations of linear control theory. Fuzzy control, with its rule-based reasoning mechanism, not only achieves the lowest median delay (0.9 s), but also effectively suppresses delay fluctuations through nonlinear mapping. This stable and rapid response capability is crucial to achieve real-time and precise control of pollutants. The statistical significance mark (***, $p < 0.001$) verifies this difference. Energy efficiency shows annualised energy consumption through a combination of a bar chart and error bars. The error bar at the top of the bar represents the 95% confidence interval, and the micro scatter plots show individual experimental data. The high energy consumption of fixed threshold control stems from its timed full-power operation mode, which results in a large amount of energy wasted in unnecessary periods. PID control reduces invalid operations through proportional-integral regulation, but the cumulative effect of the integral term still generates additional energy consumption. Fuzzy control uses an event-driven mechanism and membership weighting strategy to activate equipment and dynamically adjust power only when actually needed. This “supply on demand” mode reduces its energy consumption compared with traditional methods and achieves the lowest energy consumption (6.28 kWh/m²). Both response delay and energy efficiency use a colour palette (grey-red-green) to distinguish method categories, which overall presents the dual advantages of fuzzy control in dynamic response speed and energy efficiency, providing a quantitative basis for the optimal design of the intelligent control system of the roof garden.

Figure 6 Comparison of response delay and energy consumption (see online version for colours)



4.4 Extreme environment adaptability test

The environmental chamber is used to construct a continuous stress environment of high temperature ($42 \pm 1^\circ\text{C}$) and high pollution ($\text{PM}_{2.5} \ 380 \pm 15 \ \mu\text{g}/\text{m}^3$), and two groups of comparison systems are set up: the traditional activated carbon filtration + drip irrigation shading net combination (control group) and the plant-intelligent system-lightweight matrix synergistic system of this study (experimental group). The test cycle lasts for 72 h, and the physiological state of the plants (chlorophyll fluorescence parameters F_v/F_m , relative conductivity) and equipment operating parameters (sensor drift, microclimate uniformity) are recorded. The plant survival rate is determined by the recovery growth status 7 days after the stress ended, and quantified by the necrotic area ratio method; the equipment failure rate is based on the IEC 60068-2-14 standard, and the ratio of the cumulative duration of system function abnormality to the total operating time is calculated. A three-dimensional ultrasonic anemometer is set up in the environmental chamber to monitor the canopy microclimate field and verify the stability threshold of the intelligent control system under extreme conditions. The failure mode differences of the two groups of schemes are analysed by Weibull distribution fitting.

Table 4 Comparison of extreme environment adaptability test results

<i>Evaluation metric</i>	<i>Test group</i>	<i>Control group</i>	<i>Experimental group</i>	<i>Testing standard/Method</i>
Plant survival rate (%)	72-hour continuous stress	62.3 ± 5.8	89.7 ± 3.2	Necrotic Area Ratio Method
F_v/F_m Ratio	Instant measurement	0.51 ± 0.07	0.73 ± 0.04	Chlorophyll Fluorescence Imaging
Relative conductivity (%)	72-hour measurement	68.2 ± 6.1	34.7 ± 4.3	Electrolyte Leakage Method
System Failure rate (%)	Cumulative 72-hour faults	23.5 ± 3.7	5.2 ± 1.4	IEC 60068–2–14 Standard
Sensor drift	$\text{PM}_{2.5}$ monitoring error ($\mu\text{g}/\text{m}^3$)	38.6 ± 12.4	9.3 ± 3.8	Standard Gas Calibration
Microclimate uniformity (%)	Canopy temperature variation	28.7 ± 4.2	12.5 ± 2.6	3D Ultrasonic Anemometry
Recovery growth (cm)	Post-stress shoot length (7 days)	1.2 ± 0.4	3.8 ± 0.6	Digital Image Analysis

Table 4 shows the adaptability test results of the roof garden system under extreme environments (high temperature $>40^\circ\text{C}$ and high pollution of $\text{PM}_{2.5} > 300 \ \mu\text{g}/\text{m}^3$). By comparing the traditional activated carbon filtration system (control group) with the plant-intelligent system-lightweight matrix synergistic system (experimental group) proposed in this study, the data show that the optimised system has significant advantages in key indicators. The plant survival rate in the experimental group reaches $89.7 \pm 3.2\%$, which is higher than that in the control group. The deep roots of *Lagerstroemia indica* maintain water absorption under high temperature; the waxy leaves of *Hedera helix* reduce transpiration loss; the *Taxiphyllum alternans* layer dissipates excess light energy

through non-photosynthetic pigments. The chlorophyll fluorescence parameter F_v/F_m ratio is maintained at 0.73 ± 0.04 , indicating that the degree of damage to the photosynthetic system is significantly reduced. The flavonoid compounds of *Lagerstroemia indica* remove reactive oxygen, and the enzyme activity of *Hedera helix* reduces oxidative damage. In terms of equipment reliability, the system failure rate of the experimental group is only $5.2 \pm 1.4\%$, and the sensor drift is controlled at around $9.3 \mu\text{g}/\text{m}^3$, proving the stability of the intelligent control system under extreme conditions. The performance of the coefficient of variation of microclimate uniformity of $12.5 \pm 2.6\%$ indicates that the multi-layer plant community and ventilation strategy effectively alleviates the heat accumulation effect. Seven days after the stress is relieved, the new shoot growth of the experimental group reaches $3.8 \pm 0.6 \text{ cm}$, confirming its rapid recovery ability. The data results verify the effectiveness of collaborative optimisation design in improving the environmental resilience of roof gardens and provide technical support for coping with climate extremes.

5 Conclusions

This study proposes a roof garden collaborative optimisation scheme that integrates functional plant communities and intelligent response systems, providing an innovative solution for coping with urban environmental pollution. By constructing a “multi-layer-multi-target” plant functional group, the synergistic enhancement of pollutant adsorption, degradation, and microclimate regulation is achieved, breaking through the limitations of traditional single plant purification efficiency. Based on the dynamic control system of the multi-parameter environmental sensor network, the fuzzy control algorithm is used to achieve the precise linkage response of irrigation and ventilation equipment, significantly improving the system adaptability and energy efficiency. The design of lightweight substrates and modular planting units solves the engineering problems of building load and maintenance convenience while ensuring the pollutant adsorption performance. Experimental verification shows that this integrated solution has significant advantages in terms of pollutant synergistic removal, system response speed, and long-term ecological benefits, providing a theoretical basis and technical support for the intelligent upgrade of urban building three-dimensional greening systems. Future research can further explore the multi-interface synergistic mechanism of plants, microorganisms, and materials, as well as system optimisation methods based on digital twins, to promote the transformation of roof gardens from a single ecological function to an intelligent environmental control platform. At the same time, modular units support flexible splicing and functional expansion, and can be deployed on a large scale in different building types in the future. They can also further expand ecological control capabilities by integrating new sensors and actuators, and promote the evolution of roof gardens into smart ecosystems.

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Innovative Research Project on Horizontal Topics of Garden Flowers of “Xianghuan-Bailin”: Study on the Selection and Application of Rooftop Garden Plants

Conflicts of interest

The authors declare no conflict of interest.

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