Proceedings of ICEGEE 2026 Symposium: Sustainable Environment and Ecology
DOI: 10.54254/2753-8818/2026.BH33326

Research Progress and Prospects of Plant-Based Microclimate Creation in Outdoor Spaces

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Abstract. Under the dual background of intensified urban heat island effect and upgraded demand for living environment quality, the regulatory effect of plants on outdoor microclimate has become a research hotspot in the fields of landscape architecture and urban ecology. This article takes the creation of microclimate by outdoor plants as the research core, adopts the method of literature review, sorts out relevant research results at home and abroad, and analyzes the problems in current research, such as the lack of systematic explanation of regulatory mechanisms, fragmented research on community structure driving effects, and disconnection between research and practice. The existing research methods have gradually evolved from traditional field observations to numerical simulations and multi technology integration, but there are still limitations such as difficulty in scale conversion and insufficient evaluation of long-term effects. This article preliminarily explores the coupling relationship between plant community structure and microclimate effects, and proposes that in the future, collaborative benefit research should be carried out around the "dual carbon" goal to promote intelligent and dynamic plant microclimate creation design and monitoring system construction. Plants achieve microclimate regulation through a dual process of thermodynamics and fluid mechanics. The vertical structure, horizontal pattern, and individual plant morphological characteristics of the community are the core elements determining the regulation efficiency. Research provides theoretical reference for the scientific configuration of outdoor space plants and microclimate optimization design, and has important practical significance for improving the quality of urban living environment.

Keywords: outdoor spaces, plant community, microclimate regulation, thermal comfort, community structure

1. Introduction

In the process of rapid urbanization, the continuous expansion of urban hard surfaces has led to drastic changes in the thermal properties of underlying surfaces, and the urban heat island effect is becoming increasingly severe. The deterioration of outdoor microclimate has become a key issue restricting urban livability [1]. Plants, as the core component of urban green infrastructure, can regulate outdoor temperature, humidity, solar radiation, and wind speed through natural processes such as shading, transpiration, and windproof. They are a low-cost and eco-friendly natural solution

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to alleviate the heat island effect and optimize microclimate. In recent years, scholars at home and abroad have conducted extensive research on the microclimate regulation effects of plants, achieving rich results in regulation mechanisms, effect evaluation, technical methods, etc. However, existing research mostly focuses on a single dimension or specific scenarios, and the coupling mechanism between plant community structure and microclimate effects is not yet systematically explained. There is also a clear disconnect between research results and actual landscape design. This article adopts the methods of literature review and systematic induction, focusing on analyzing the driving mechanism of plant community structure characteristics on microclimate, exploring the comprehensive efficiency of plant microclimate regulation and the response relationship between human thermal comfort, summarizing the evolution of research methods and technical means in this field, and proposing design optimization strategies for plant created microclimate based on practice, analyzing current research challenges and future prospects. This article aims to establish a systematic research framework for the creation of microclimates in outdoor spaces by plants, breaking down the barriers between research and practice, and providing theoretical support and practical guidance for the ecological design of plants, microclimate optimization, and improvement of living environments in different types of outdoor spaces such as urban parks, residential areas, waterfront areas, and streets.

Outdoor microclimate refers to the small-scale climate characteristics that are significantly different from the regional climate, formed by the combined influence of underlying surfaces, vegetation, buildings, human activities, and other factors in local urban areas. Its core research indicators include air temperature, relative humidity, solar shortwave radiation, and near ground wind speed. Compared with macro climate, outdoor microclimate has strong spatial heterogeneity and significant temporal dynamics. It directly affects residents' outdoor activity space and is an important indicator for measuring the quality of urban living environment. Its formation and evolution are regulated by both natural and artificial factors. As an important artificial intervention element, plants can achieve targeted regulation of microclimate factors by changing local underlying surface properties and energy exchange processes. The microclimate regulation effect of plant landscape refers to the transformation and optimization of outdoor microclimate factors such as temperature, humidity, radiation, and wind speed by plants through their own physiological characteristics and community structure features. It is the comprehensive result of energy exchange and material cycling between plants and the surrounding environment. The essence of this effect is the intervention of plants in energy processes such as solar radiation transfer and atmospheric convection, as well as the regulation of material processes such as water evaporation and air flow. Its effectiveness is influenced by various factors such as plant species, community structure, configuration, and regional climate, and has obvious spatiotemporal differentiation characteristics. It is the core manifestation of plants creating suitable microclimates outdoors.

Human thermal comfort refers to the subjective perception and physiological adaptation of the human body to the surrounding thermal environment, and is the core focus for evaluating the effectiveness of plant microclimate regulation. The commonly used evaluation indicators in academia are divided into two categories: objective indices and subjective evaluations. Objective indices mainly include physiological equivalent temperature, temperature and humidity index, standard effective temperature, etc. By integrating microclimate elements such as temperature, humidity, radiation, and wind speed, the physiological response of the human body to the thermal environment is quantified; Subjective evaluation mainly relies on questionnaire forms such as Thermal Sensation Voting and Thermal Comfort Voting to obtain the subjective feelings of the human body towards the outdoor thermal environment. The combination of subjective and objective

DOI: 10.54254/2753-8818/2026.BH33326

evaluation indicators is a key method for comprehensively and scientifically evaluating the impact of plant microclimate regulation on human thermal comfort.

Plant regulation of outdoor space microclimate is a complex coupled process of physics and ecology, essentially involving the directional control of microclimate elements such as temperature, humidity, and wind speed by altering local energy exchange and fluid motion, which mainly includes two synergistically interacting core dimensions: thermodynamic and hydrodynamic processes. The thermodynamic process, as the core pathway, achieves cooling and humidification by intercepting solar radiation through plant canopies, branches, and leaves, and reducing local energy balance via plant transpiration that absorbs environmental heat through latent heat exchange, with the effect closely related to plant canopy structure, leaf area, and species. The hydrodynamic process, as an important auxiliary pathway, alters local wind speed and wind field distribution by blocking, reducing, guiding, and reshaping air flow through plant branches, leaves, and community structures, thereby affecting convective heat exchange and pollutant diffusion, with the wind-blocking and flow-guiding effects depending on community density, height, and spatial configuration, together providing an important theoretical foundation for plants to create suitable outdoor microclimates.

2. Influence of plant community structural characteristics on microclimate

Plant community structural characteristics are the core factors determining their microclimate regulation efficacy. Different community structures produce differentiated microclimate effects by altering energy exchange and fluid movement processes. The structural characteristics of plant communities are mainly reflected in three dimensions: vertical structure, horizontal pattern, and individual plant morphological characteristics. These three aspects interact, jointly constituting the core driving mechanism of plant communities on microclimate and are the focus of current research on plant-based microclimate creation in outdoor spaces [2].

2.1. Vertical structure: the key role of stratification richness

The vertical structure of a plant community refers to the hierarchical arrangement of different plants within the community at height. The richness of its layers directly affects the community's interception efficiency of solar radiation, the synergistic effect of transpiration, and its ability to regulate wind fields. It is a key factor determining the effectiveness of microclimate regulation. Layered community refers to a multi-layered community structure composed of plants of different heights such as trees, shrubs, herbs, and ground cover. Compared with single-layer structures such as pure forests of trees and herbaceous communities, it has more significant microclimate regulation benefits [3]. Research has shown that multi-layered communities can achieve multi-level interception of solar radiation, with significantly better shading effects than single-layer structures. In summer, they can reduce near ground temperatures by 2-5 ℃ [4]; At the same time, the transpiration of plants at different levels forms a synergistic effect, and the latent heat cooling and humidification effects are more pronounced, which can effectively improve local air humidity. However, the single-layer structure has limitations in intercepting radiation and transpiration of water due to its single layer structure, resulting in lower microclimate regulation efficiency. For example, research in Kunming Pocket Park has shown that the cooling and humidification effects of a multi-layered community of trees, shrubs, and grasses are significantly better than those of a single layered forest of trees and shrubs, and can still maintain good microclimate regulation ability in autumn and winter seasons. The microclimate effects of vertical structure in plant communities are

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directly influenced by key parameters such as three-dimensional green volume, leaf area index, and canopy closure. As a core indicator for measuring the overall green coverage of plant communities, three-dimensional green coverage is positively correlated with microclimate regulation efficiency. The larger the three-dimensional green coverage, the stronger the community's interception and transpiration of radiation, and the more significant the cooling and humidification effects; The leaf area index determines the interception efficiency of the community towards solar radiation, and an appropriate leaf area index can achieve effective interception of radiation while avoiding poor ventilation caused by excessive density; The canopy closure affects the shading range and internal ventilation of the community. A high canopy closure can lead to low wind speed and heat accumulation within the community, while a low canopy closure can reduce the shading effect. Studies have shown that when the canopy closure of outdoor plant communities is controlled between 0.6 and 0.8, the microclimate regulation efficiency is optimal [5].

2.2. Horizontal pattern: plant configuration and layout

The horizontal pattern of a plant community refers to the planar configuration and layout characteristics of plants in outdoor spaces, including green space ratio, vegetation coverage, layout patterns, boundary enclosure degree, etc. By altering the spatial distribution of plant density and spatial form in local areas, it influences the spatial distribution of energy exchange and air flow, resulting in differentiated microclimate effects [6].

2.2.1. Threshold effects of green space ratio and vegetation coverage

Green space ratio and vegetation coverage are fundamental indicators affecting outdoor space microclimate. Both show a significant positive correlation with microclimate regulation efficacy, but exhibit clear threshold effects [7]. When the green space ratio is below 30%, plants have a weak regulating effect on microclimate and cannot effectively mitigate the heat island effect. When the green space ratio reaches 30%~50%, microclimate regulation efficacy improves significantly, with noticeable cooling and humidifying effects. When the green space ratio exceeds 50%, the rate of improvement in regulation efficacy slows down and stabilizes . The threshold effect of vegetation coverage is similar to that of green space ratio. When coverage is below 40%, the synergistic effects of shading and transpiration are weak. When coverage exceeds 60%, a continuous plant cover can be formed, achieving comprehensive microclimate regulation across the entire outdoor space. Research in Fuzhou Forest Park shows that when vegetation coverage reaches over 70%, summer cooling effects can reach 4~6°C, achieving microclimate optimization across the entire park.

2.2.2. Influence of layout patterns

Plant community layout patterns mainly include intensive type, belt type, and natural type, with significant differences in their microclimate effects. Intensive layout is mainly suitable for small-scale spaces like pocket parks and building surroundings. It achieves strong shading and cooling through high-density plant configuration but requires attention to ventilation design to avoid heat accumulation. Belt-type layout is suitable for linear spaces such as urban streets, waterfront areas, and greenways. It can guide wind field movement, accelerate air circulation, and simultaneously form a continuous shading belt, achieving microclimate optimization for linear spaces. For example, belt-type plant configuration along urban riverside greenways can increase wind speed along the line by 0.5~1.0 m/s and reduce temperature by 3~4°C [8]. Natural-type layout is mainly suitable for

DOI: 10.54254/2753-8818/2026.BH33326

large-scale spaces like urban parks and suburban green spaces. It simulates the distribution characteristics of natural plant communities, achieving a balance between shading and ventilation through patchy or clustered configurations. The spatial heterogeneity of microclimate regulation is lower, allowing for the creation of comfortable and diverse outdoor microclimates [9].

2.2.3. Boundary enclosure and opening direction

The boundary enclosure degree and opening direction of plant communities influence microclimate effects by regulating wind field movement and radiation reception. Highly enclosed community boundaries can effectively block the intrusion of external cold or hot winds, forming a relatively stable internal microclimate, suitable for cold regions or enclosed spaces in hot summers. Low-enclosure community boundaries, on the other hand, facilitate air circulation and accelerate heat diffusion, suitable for hot and humid regions. The opening direction determines the introduction of natural wind and the reception of solar radiation. South-facing openings can receive more solar radiation, increasing winter temperatures, suitable for cold regions. East-facing and west-facing openings can introduce prevailing winds in summer, accelerating cooling, suitable for hot and humid regions. For example, in green space layouts for high-rise urban residential areas, semi-enclosed plant communities set to the southwest can effectively block the summer afternoon sun while introducing southeast winds, optimizing the summer microclimate.

3. Comprehensive efficacy of plant microclimate regulation and human comfort response

The ultimate goal of plant microclimate regulation in outdoor spaces is the improvement of human thermal comfort. Its comprehensive efficacy is reflected in the synergistic regulation of microclimate elements such as temperature, humidity, radiation, and wind speed, and this efficacy exhibits clear spatio-temporal differentiation patterns. Meanwhile, the impact of plant microclimate regulation on human thermal comfort shows differences between objective and subjective evaluations. Integrating objective and subjective evaluations is key to scientifically assessing the efficacy of plant microclimate regulation.

3.1. Thermal comfort assessment

Plants enhance human thermal comfort by synergistically regulating key microclimate factors, supported by combined objective–subjective assessment.

They simultaneously adjust temperature, humidity, solar radiation and wind speed. In summer, shading and transpiration cool air by 2–6°C, lift humidity by 5%–15% and cut radiation by 30%–70%. In winter, windbreaks and moderate shading raise temperature by 1–3°C and lower wind speed by 0.3–0.8 m/s. Data from Shunyi Riverside Forest Park confirms summer forest interiors are 3.5–5.2°C cooler, 8%–12% more humid, with over 60% less radiation.

Plants also improve Physiologically Equivalent Temperature(PET) and TemperatureHumidity Index(THI) significantly. Summer PET falls by 5–10°C and THI by 3–5; winter PET rises by 2–4°C. Huaihua park data shows a 7.2°C PET reduction and 4.1 THI drop in summer; cold-region planting raises winter PET by 3.5°C.

Subjective comfort varies with age, gender, activity and regional adaptation. Scientific evaluation must integrate objective and subjective data to support targeted plant design.

DOI: 10.54254/2753-8818/2026.BH33326

3.2. Spatio-temporal differentiation patterns of microclimate effects

The efficacy of plant microclimate regulation is not constant but exhibits distinct temporal and spatial differentiation patterns. Temporal differentiation is mainly reflected in seasonal differences and diurnal variation patterns, while spatial differentiation is mainly reflected in adaptive differences across different climate zones.

3.2.1. Seasonal differences and diurnal variation

Plant microclimate regulation efficiency varies seasonally with phenology [10]. In summer, lush foliage maximizes LAI and canopy closure, delivering the strongest shading and transpiration for optimal cooling and humidification.In autumn, leaf fall reduces efficiency but retains partial shading and wind protection.In winter, deciduous plants only provide windbreak; evergreens maintain limited effects, resulting in the lowest overall efficiency .In spring, sprouting foliage gradually restores regulation capacity [11]. A study at Southwest University found autumn–winter cooling dropped by over 50% versus summer but still reduced nearground temperature by 1–2 °C, with notable windproof benefits.

Regulation efficacy also follows diurnal patterns matching solar radiation and temperature. Efficiency peaks 10:00–16:00 with strong cooling and humidification; it weakens at dawn/dusk and is lowest at night, when plants mainly act as windbreaks. A Guangzhou residential study recorded summer cooling of 4–5 °C at 12:00–14:00, but only 0.5–1.0 °C at 6:00–8:00.

3.2.2. Adaptive differences across climate zones

The microclimate regulation efficacy of plants exhibits significant adaptive differences across different climate zones, requiring targeted plant configuration based on regional climatic characteristics [12]. The core needs in hot-humid regions are cooling, humidification, and ventilation. Therefore, broad-leaved trees with large leaf areas and high transpiration rates should be selected, using low-enclosure community layouts to ensure air circulation. The core needs in cold regions are winter heat retention and summer cooling. A combination of evergreen and deciduous trees should be used, utilizing evergreens for wind protection in winter and deciduous trees for shading in summer. The core needs in arid and semi-arid regions are cooling, windbreak, and sand fixation. Plants with moderate transpiration rates and strong drought resistance should be selected, using intensive community layouts to achieve both shading and windbreak effects. For example, waterfront greenways in subtropical hot-humid regions using belt-type layouts dominated by broad-leaved trees can achieve summer cooling effects of 3~4°C. In contrast, waterfront parks in cold-region cities using semi-enclosed layouts combining evergreen and deciduous trees show significant winter heat retention effects and also provide effective summer shading [13].

4. Research methods and technical approaches

Research methods for plantbased outdoor microclimate creation have evolved from traditional field observations to numerical simulation and multitechnology integration, improving accuracy, efficiency and systematicness. Current methods mainly include data collection and numerical simulation, providing technical support for mechanism analysis, effect evaluation and design optimization.

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4.1. Data collection methods

Data collection is fundamental. Methods have advanced from fixedpoint manual observation to mobile sensing and automatic monitoring. Traditional fixedpoint observation is lowcost but limited in range and continuity. Mobile measurement and automatic stations enhance data comprehensiveness and continuity; drone measurement improves spatial coverage by over 80% in street green space studies. Subjective questionnaires collect thermal comfort perceptions, shifting from paper to online forms for big data analysis.

4.2. Numerical simulation technology

Numerical simulation is a core tool for predicting and optimizing microclimate effects, with computational fluid dynamics software being the most widely used.

Common computational fluid dynamics tools include ENVImet, FLUENT and PHOENICS; ENVImet is most popular for urban microclimate research due to its usability and accuracy. Based on fluid dynamics and thermodynamics, it builds 3D models to simulate airflow, heat transfer and evaporation, predicting temperature, humidity, wind speed and radiation. The workflow includes model construction, parameter setting, simulation and.

Plant model parameters determine simulation accuracy and should be set based on field data. Simulation validation uses error indices to compare simulated and measured data; parameters are adjusted until results match observations.

4.3. Trend of multi-technology integration

Research is moving toward multitechnology integration, improving precision and efficiency. Remote sensing provides largescale vegetation and surface temperature data; GIS enables spatial analysis and visualization. Their integration with field measurement supports macrotomicro multiscale research, revealing the spatial coupling of vegetation and microclimate.

Big data and artificial intelligence enable datadriven prediction models for rapid microclimate effect evaluation. Combining machine learning with computational fluid dynamics optimizes parameters and improves accuracy, supporting fast screening and verification of optimal plant configurations.

5. From research to practice: applications, challenges, and prospects

Research on plant-based outdoor microclimate creation should be applied to landscape practice to support scientific plant configuration. Findings have been preliminarily used in urban parks, residential areas, waterfronts and streets, but challenges remain in scale transformation, dynamic research and interdisciplinary integration. Future research should focus on the "dual carbon" goal, intelligent technologies and nature-based solutions to deepen research-practice integration and realize scientific, refined and intelligent microclimate creation.

5.1. Evidence-based design optimization strategies

Targeted plant configuration strategies should be developed based on spatial functions and regional climates. Urban parks can use natural multi-layered communities to balance shading and ventilation; residential areas can adopt tree-shrub-herb structures and semi-enclosed communities; waterfronts apply belt-type layouts to guide winds and form shading belts; streets use row trees for continuous

DOI: 10.54254/2753-8818/2026.BH33326

shading and ventilation. Refined design should prioritize comfortable microclimates for the elderly and children, and select plants and layouts for hot-humid, cold and arid regions to meet cooling, heat preservation or sand-fixation needs.

5.2. Challenges and limitations in current research

Current research faces four major limitations: difficult scale transformation, insufficient long-term effect assessment, neglected plant growth dynamics and feedback, and inadequate interdisciplinary integration.

Most studies focus on small-scale spaces, and findings cannot be directly extended to medium and large scales due to macroclimate and underlying surface differences. Most observations are short-term, failing to reflect long-term changes in regulation efficiency caused by plant growth.

Plants are often treated as static objects, ignoring dynamic growth and two-way feedback with microclimate. Fixed plant parameters ignore differences between seedling and mature stages, causing deviations between simulations and reality.

This interdisciplinary field lacks deep integration of landscape architecture, meteorology, ecology and fluid dynamics. Disciplinary perspectives are separated, reducing the practicality of research outcomes for landscape design.

5.3. Future research prospects

Future research should focus on synergistic benefits, intelligent technologies and nature-based solutions to deepen research and integrate theory with practice.

Research should link microclimate regulation with carbon sequestration, oxygen release, cooling and energy saving. Quantitative synergistic benefit studies and comprehensive evaluation systems will help screen efficient plant types and communities for urban "dual carbon" goals .

Artificial intelligence, the Internet of Things and big data will support intelligent design platforms and dynamic monitoring systems. Combining machine learning, numerical simulation and digital twins will realize real-time simulation, prediction and optimization of plant configuration and microclimate.

Future research should adopt Nature-based Solutions and build integrated design paradigms. It will combine microclimate creation with green space systems, sponge cities and ventilation corridors, integrating ecological, social and cultural benefits for city-wide microclimate optimization.

6. Conclusion

This paper systematically reviews global research on plantbased outdoor microclimate creation. It clarifies the physical and ecological regulatory mechanisms, analyzes how plant community structure drives microclimate effects, explores regulation efficiency and human comfort responses, summarizes methodological advances, and identifies practical strategies, challenges, and future directions.

Plants regulate microclimate via thermodynamic processes and hydrodynamic processes , which act synergistically as the core mechanism. Key determinants include vertical structure, horizontal pattern, and plant morphological traits; multilayered communities, suitable green ratios, rational layouts, and largecanopy trees show stronger effects.

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Plant regulation optimizes temperature, humidity, radiation, and wind speed, significantly improving PET and human thermal comfort, with clear seasonal, diurnal, and climatic zonality differences. Research methods have shifted from fixed observations to mobile sensing and numerical simulation, featuring integration of remote sensing, GIS, and datadriven prediction. Findings have been applied in diverse outdoor spaces, yet gaps remain in scaling, longterm evaluation, dynamic plant–microclimate feedback, and interdisciplinary integration.

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