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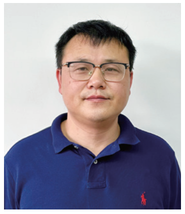
Urban Forest Construction and Vertical Greening Development Under Climate Change



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ABSTRACT

In high-density cities, relatively large area of buildings may accommodate increasing volumes of vertical greening, which will effectively help alleviate global climate change. This article emphasizes that landscape architects and constructors should refresh their understanding of urban forests and realize the role of vertical greening as its vital component. Although current practices of vertical greening are restricted by climatic environment, advances of technology and innovation of materials will provide new opportunities for the development of urban forests. For example, by utilizing a novel type of substrate, "base soil," we can get rid of conventional vertical greening technologies that usually rely on pot-planting and frequent replacement, while enjoying more ecological benefits. This article also suggests employing prefabricated greening technologies to meet the ever-increasing demands of urban forests; establishing a systematic cost-benefit assessment system on vertical greening to measure the ecological, social, and economic values; and encouraging citizens to take a more active part in vertical greening practices by making them aware of environmental and social benefits brought by urban forests.

KEYWORDS

Urban Forest;
Vertical Greening;
Prefabricated Greening;
Functionality;
Growing Substrate;
Materials

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HIGHLIGHTS

- Pointing out that the public's knowledge of the definition and functions of urban forests is lacking
- Introducing the latest technical development of vertical greening, an important component of urban forests
- Suggesting future technical, economic, and social prospects of urban forest development

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1 New Understanding of Urban Forests

Facing the current severe climate challenges, urban forests can contribute to expanding green spaces, enhancing a city's capability of carbon sequestration and oxygen release, improving air quality, and alleviating heat island effect and light pollution in urban contexts. Urban forests also provide habitats for migratory birds and insects, thereby increasing biodiversity of the built environment. Embraced in urban forests, the public would be more likely to pay attention to climate change, raise environmental awareness, and participate in environmental protection.[1]~[5] In urban forest construction, landscape architects and constructors need to further break through their knowledge limitations in two ways. First, broaden the definition of "forests" from suburban forests, shelterbelts, and woods in urban green spaces to "vertical forests" integrated in dense buildings. In 2009, Italian architect Stefano Boeri proposed this new architectural prototype, aiming to create a vibrant ecosystem and inhabitable urban forest that can have the residents break away from the concrete forests.[6] Rapid urbanization has caused more serious scarcity of urban development land; moreover, the construction and maintenance of large-scale urban green spaces is costly. To these problems, vertical forests may be a solution by providing more accessible green spaces and various ecosystem services in limited spaces. Second, urban forests should be built not only to regulate microclimate, but also to meet production, ecological, and living demands. The report to the 20th National Congress of the Communist Party of China pointed out that "we will adopt an all-encompassing approach to food, develop protected agriculture, and build a diversified food supply system."[7] Urban planners and landscape architects may further explore the functional diversification of urban forests by integrating them with urban agriculture development and agricultural infrastructure construction—for instance, utilizing more multi-purpose plants.

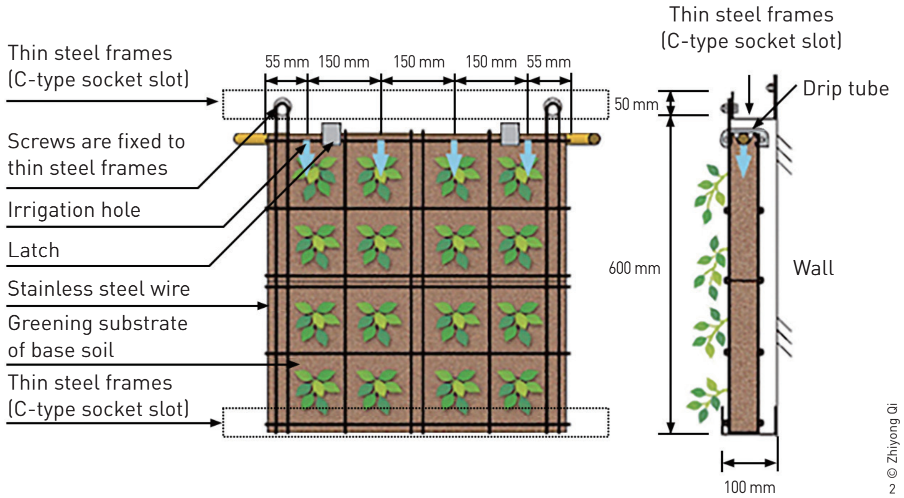
2 Vertical Greening in Urban Forests

Vertical greening is an important component of urban forests. Potentially, built-up areas within high-density cities are capable of providing enormous incremental green spaces (e.g., rooftop greening on public buildings, slope greening, municipal infrastructure greening, balcony greening), so as to mitigate and adapt to climate change. Around the world, Singapore, Italy, Germany, and Japan are leading the development of vertical greening, while Shenzhen, Guangzhou, Shanghai, Hangzhou, and Chengdu are pioneers in China[8]. Although it is possible to apply vertical greening in a relatively wide range of areas, the selection of suitable plant species and the planting forms and performance are usually constrained by geographical conditions (the variety of climatic zones) and technical factors (e.g., freezing prevention of outdoor irrigation systems in winter). Compared with the natural one, urban forest, an artificial ecosystem, can be intervened and accelerated in evolution, benefitting from technological advances and material innovation.

The success of vertical greening depends on four factors: climate, vegetation, moisture, and substrate. As for the climate conditions, usually, we can only adjust microclimate, but hardly alter the climate environment at larger scales; native species are preferred for plant selection; and the water supply mainly relies on drip and automatic irrigation. Restricted by substrates, conventional vertical greening usually use plastic, cloth bags or other containers to hang on the vertical surfaces, which requires frequent replacement of plants or creates short-term stereoscopic visual effect by placing the plants into a designed pattern. Rather than providing ecological benefits to the city, these practices will put more pressure on waste disposal and plant maintenance. Therefore, it is necessary to develop new substrates that are more suitable for high-density urban environments and harsh climates, while meeting the structural load requirements and vertical greening demands.

The breakthrough in substrates such as the emergence of "base soil" (Figs. 1, 2) offers new opportunities for vertical greening practice. Base soil is an ecological planting material made by local resources that can be a substitution of natural soil. With a diversified product portfolio divided by climate zone, regional zone, and planting method, it is capable of meeting varied planting needs of small trees, shrubs, herbs, and vines (Fig. 3). Inspired by soilless cultivation, the technique of base soil performs effectively in vertical greening applications on roofs, walls, and balconies. Its advantages, compared with conventional greening technology, can be elaborated from six aspects. First, the soil is molded, thus can make full use of air to cultivate roots, support vertical cultivation without pots, and avoid soil loss caused by wind, gravity, water flow, etc. Second, the soil is conducive to water retention and air permeability, as it can rarely be hardened due to a net-like percolation path inside. This can also help cool the soil and prevent fast water loss in vertical planting. Third, high plasticity enables the soil to be customized according to the needs of landscape design and planting, and to be adapted to various application scenarios such as roofs, walls, balconies, and high-rise buildings. Fourth, being light-weighted, the soil has low requirements for structural load. When dried, its net weight is about one tenth of the same volume of ordinary planting soil. Fifth, the soil has strong durability in that it can withstand high temperature (80℃) and high humidity (90%) for 5 ~ 26 years[9]. Sixth, it is environmentally-friendly because of being made mainly by recycled gardening waste, crop straw, and other organic fibers, which helps reduce the carbon footprint in the process of vertical greening transformation.

At present, base soil technique has been successfully applied



1. Common sizes of planting blocks utilizing base soil
2. Example of construction method using base soil
3. Base soil can meet a wide range of planting needs

in many vertical greening projects. For example, near the Jiulong Bund in Chongqing located along the Jialing River was a 20-meter-high flood wall, where the huge height difference and concrete slope with rebars (Fig. 4) prevented visitors' access to the riverfront. In this project, the hardened bank was transformed into a green slope with dozens of plants growing on it, creating a vibrant and popular waterfront recreational space (Fig. 5). Another example is the Hangzhou Xiaoshan Airport highway renewal project, which utilized base soil to plant *Rosa chinensis* on the guard bars of the highway, substituting the conventional way of hanging the flowers in pots[10] (Fig. 6). Performance of the vertical greening in the next three years proves that the plants can grow naturally and well under low maintenance (no need to replace the plants or supporting materials). Regarding the effectiveness of base soil technique, the research team found that the carbon sequestration per unit area of base soil was almost equivalent to that of the same plants grown on the ground, basing on the assessment of the maintenance cost, plant biomass, and energy consumption of the vertical greening project at Wuhan Airport Expressway.

Substrate innovation also contributes to the integration of productive landscape in urban forests, by providing suitable growth conditions for vegetables and fruits in the complex urban environment, combining balcony gardening and allotments to create a functional urban forest system. In Qatar, a desert country in the Middle East, the research team has realized the mass production of a dozen types of vegetables at outdoor temperatures of 30°C ~ 40°C (Fig. 7), taking full advantage of local energy sources by using LED lighting and a combination of nutrient film cultivation and base soil cultivation techniques. In this case, superb water conservation and temperature control of plant roots have been achieved, providing an inspiration for the integration of urban agriculture and urban forests.

3 Visions of Urban Forests

At the technical level, the increasing demand of urban green space construction requires standardized and high-efficiency throughout the full cycle of landscape design, construction, and management[8]. In recent years, the technique of prefabricated buildings inaugurates large-scale standardized production in the field of architecture, driving similar exploration in the practice of greening. The prefabricated greening system integrates the related techniques, plant development, intelligent control, and efficiency analysis, aiming at providing batched and modular solutions of greening for varied needs in urban forest construction.[10][11] Future practice of vertical greening should focus more on how to utilize the prefabricated greening system to break barriers between conventional nurseries and landscape design companies by shifting from existing moisture, plant growth, and maintenance monitoring

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4. A section of flood wall of Chongqing Jiulong Bund before vertical greening transformation
5. The transformed Jiulong Bund with vertical greening creates a comfortable environment for visitors
6. Blooming Rosa chinensis on the Expressway of Hangzhou Xiaoshan International Airport
7. Vegetable growing practice in high temperature environments in Qatar

towards ecological benefit monitoring and analysis. This full-cycle intelligent management and control system will require less human input.

From an economic view, although vertical greening has been promoted and popularized in China for more than a decade, the emphasis was put on the form of greening (plant placement) over its actual performance due to economic development problems. This has resulted in neglect of the maintenance and survival of plants, while depriving opportunities for the public to have the benefits brought by such technological advances. In the application of new materials such as base soil, though increased initial investment is often true, a self-sustaining planting and corresponding ecological and social benefits can be achieved. It is vital to encourage technological and material breakthroughs, as well as promote investment to and application of these burgeoning prospects. One more suggestion is to establish a systematic cost-benefit assessment system on vertical greening, taking into account its values to and impacts on varied structures—the extension of their life cycle and the reduction of building energy consumption[12], the saving of land costs compared with developing conventional green space and the revaluation of the surrounding land, and residents' various willingness and use-cost of green spaces within 15-minute living circles and suburban areas.

At the social level, the development of urban forests should be further explored at the community scale. For instance, we can promote and popularize related knowledge of vertical greening, such as the healing and recreational benefits, in a demonstration or learning section of a community. Once more citizens are aware of the impacts of climate change and the necessity of urban forest construction, they will take a more active part in vertical greening practices and create for example balcony gardens and allotments on their own.

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气候变化背景下的城市森林构建与立体绿化发展

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摘要

在高密度城市中，较大的已建成区域能带来相应的立体绿化增量空间，成为应对全球气候变化的有益补充。本文强调，设计师和建造者需要突破对城市森林的传统认知，重新理解“森林”的定义及功能，并认识到立体绿化是城市森林的重要组成部分。目前立体绿化的实践受气候环境条件制约，但技术进步和材料变革可以为城市森林的发展创造新的机遇，例如新型基质“垒土”的研发正在帮助城市摆脱借助盆钵、需要频繁更换植株的立体种植，为城市更新带来更多的生态效益。此外，本文指出，城市森林的未来发展应进一步发展装配式绿化以适应日益增长的城市森林构建需求；构建综合性评价体系，将生态、社会和经济等多方面纳入考量；通过公众可切身感受到的环境与社会效益变化，提高其对城市森林的关注度与参与度。

关键词

城市森林；
立体绿化；
装配式绿化；
功能性；
基质；
材料

文章亮点

- 指出目前公众对城市森林的定义和功能存在认知局限
- 介绍作为城市森林重要组成部分的立体绿化的前沿技术发展
- 指明城市森林未来发展在技术、经济及社会层面需重点关注的方向

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1 城市森林的再理解

面对当前严峻的气候挑战，城市森林有助于扩充城市绿地面积，提升城市固碳释氧的能力；改善城市空气质量；缓解城市热岛效应、光污染等问题；为候鸟、昆虫等提供栖息之所以提高城市生物多样性；引导公众关注全球气候变化，提升环境保护意识和参与环境保护行动。[1]~[5]在城市森林构建的过程中，设计师和建造者需要进一步突破自身的认知局限：首先，要拓宽对“森林”的定义。森林不应局限于郊野森林、防护林和绿地中的林带等，城市中密集的建筑也可以成为“垂直森林”。2009年，意大利建筑师史蒂法诺·博埃里提出这一新的建筑原型。旨在创造一个强大的生态系统和可栖居的城市森林，让人从现代都市的水泥森林中脱离。[6]随着城市化发展，建设用地愈发紧张，大规模的绿地建设和维护成本高昂；而通过“垂直森林”的构建，可在节约用地的同时，提供更具可达性的绿色空间和多样化的生态系统服务。其次，城市森林的营建应不仅仅出于城市小气候调节这一单一目的，而应满足生产、生态和生活的多维度需求。党的二十大报告中指出，要“树立大食物观，发展设施农业，构建多元化食物供给体系”[7]，城市建设者可以结合都市农业及农业基础设施的建设，发展多用途植物的种植，探索城市森林的功能多样化。

2 城市森林中的立体绿化发展

立体绿化是城市森林的重要组成部分。高密度城市中的建成区域可以提供大量潜在的绿地增量空间（如公共建筑的屋顶绿化、边坡绿化、桥梁等构筑物绿化，以及市民的阳台绿化），并为应对气候变化提供有益的自我调节能力。在世界范围内，新加坡、意大利、德国、日本等国家的立体绿化发展走在前沿；在中国，深圳、广州、上海、杭州、成都等城市的发展较好[8]。一般而言，立体绿化的应用范围比较广，但可种植物种的选择、种植形式和最终呈现的效果往往受到地域（气候带）和技术因素（如冬季户外灌溉管网防冻）的制约。相较于原始森林，城市森

林是一个人工生态系统，即一个人工干预和加速进化的过程，技术进步和材料变革会大幅提高这一过程的效率并拓展其功能。

立体绿化的成功有赖于气候、植物、水分和栽培基质四个因素。通常，我们只能人为干预小气候，而不能改变大的气候环境；植物选种原则上以乡土物种为佳；水分的提供主要依靠滴灌和自动灌溉技术；传统的立体绿化受基质的制约，多借助塑料或布袋等容器悬挂在立面上，需频繁更换植株，或者简单进行立体株摆以满足短期的视觉效果需求。这些做法不仅难以提供生态效益，反而会增加城市垃圾处理的负荷及养护压力。因而，研发更加适用于城市高密度环境和恶劣气候、满足建筑荷载要求、适合种植立体绿化植物的新型基质成为关键。

目前，诸如“垒土”（图1，2）的新型基质研发为立体绿化种植的发展提供了新的可能。作为一种就地取材、可替代自然土壤的生态种植新材料，垒土具有按气候带、区域带和种植方式划分的多样化产品体系，可适应小乔木、灌木、草本和藤本的不同种植需求（图3）。其研发源于农业无土栽培，在屋顶、墙面、阳台等立体绿化应用中效果显著。和传统技术相比，垒土具有以下优势：1）固化成型，充分利用空气修根，能实现不需要盆钵的立体栽培，避免受风力、引力、水流等影响而造成的土壤流失和飞散；2）保水透气，垒土内部为网状渗水路线，不易板结，可以克服立面种植水分流失较快的问题，有助于降温增湿；3）可塑性强，造型方便，可根据景观、植物的需要定制，能适应屋顶、墙面、阳台、高层建筑等各类使用场景；4）质轻，对构筑物荷载要求低，其干燥状态自重约是同体积普通土壤的十分之一；5）耐久性强，经过高温（80℃）、高湿度（90%）实验，耐久性可达5～26年[9]；6）环境友好，其原材料主要为回收利用的园林绿化废弃物、农作物秸秆等有机纤维等，有助于减少立体绿化改造过程中的碳足迹。

目前，垒土技术已经被应用于不同地区的立体绿化项目实践中，均取得了良好的成效。例如，重庆市的九龙外滩地处嘉陵江沿岸，有高约20m的陡岸，巨大的高差和钢筋混凝土防洪墙（图4）形成了不适宜观览或停留的滨水空间。通过借助垒土技术实施立体绿化改造，原本大面积的硬质陡岸变成了可供数十种植物生长的绿色坡面，营造了生机盎然、广受市民喜爱的亲水休闲空间（图5）。此外，杭州萧山机场高速道路更新项目抛弃了通常采用的月季盆栽悬挂的做法，利用垒土技术实现了在高架桥两边护栏上的真正覆“土”种植[10]（图6）。在项目实施后的三年多内，植被已实现自然生长，仅需正常养护，无需更换植株或配件。就垒土技术的效用而言，我们的研究团队通过对武汉机场高速的立体绿化项目的后期养护费用、植物生物量，以及能源消耗进行评估，发现垒土在单位面积的碳吸收上几乎与地面种植的同等植物无异。

除此之外，基质的革新也能够帮助我们在城市森林纳入生产性景观的营造。新型基质可以在复杂的城市环境中为蔬果提供适宜的生长条件，结合阳台园艺、市民菜园等实践，形成具有多种功能的城市森林体系。在卡塔尔这一中东沙漠国家，我们的研究团队充分利用当地能源优势采用LED光照，利用浅液流栽培和垒土栽培技术相结合的技术，实现了超级节水和植物根系的温度控制，在三四十度的户外高温下达成了十多种蔬菜的种植及量产（图7），为都市农业和城市森林的结合创造了新的思路。

3 城市森林的未来发展方向

在技术层面上，面对城市中日益增加的绿色空间营建需求，行业需要在设计、施工和管养等各个环节进行规范化、高效化发展[8]。近年来，建筑行业大力发展装配式建筑来进行大规模标准化生产，绿化体系也出现了相关探索。装配式绿化系统指集合了装配技术、植物开发、智能管控和效益分析的绿化体系，旨在根据城市森林建造中的需求或问题，批量式、模块化地提供方案。[10][11]在未来的立体绿化实践中，应进一步关注如何借助装配式绿化系统打通传统苗圃公司与规划设计建造公司之间的壁垒，从既有的聚焦于水分、植物长势和养护的监控体系转向生态效益监控分析，并建立全周期的智能管控系统，从而实现更少的人力投入。

在经济层面上，虽然目前立体绿化在中国已经推广和普及了十多年，但由于经济发展的问题，导致许多“重形式、轻内容”的立体株摆，只重视短期效果而忽略了后期的养护及植株成活率，公众也难以在生活中体会到相应的技术发展。在应用中采用新材料如垒土等，虽然会增加一部分前期投入，但可以实现真正自维持的种植，并带来相应的生态及社会效益。在未来的发展中，应重视技术和材料的突破，敢于投入并积极推广和应用。对立体绿化成本和效益的衡量要构建系统性的综合评价体系，全面考虑其对建筑创造的价值及影响——如对构筑物使用周期的延长与建筑能耗的降低[12]，相较传统绿地所减少的用地费用和对周边土地带来的增值空间，以及居民对城市环境中对15分钟生活圈内和城郊绿地的不同使用意愿及使用成本等因素。

在社会层面上，应当在社区尺度进一步探索城市森林的发展。例如，我们可以开展社区立体绿化展示学习园地推广普及相关知识，如立体绿化可以为居民带来的疗愈、康养功效等，吸引更多的市民关注和参与城市森林建设与气候变化的讨论，通过阳台园艺、市民菜园等形式，更积极地投身于城市立体绿化行动中。

图1. 常见规格的垒土种植块
图2. 垒土基质工法示例
图3. 垒土基质可满足多种植物的种植需求
图4. 重庆九龙外滩立体绿化改造之前的钢筋混凝土坡面
图5. 改造后的重庆九龙外滩，为游人创造了舒适的游览环境
图6. 杭州萧山机场高速上盛开的月季
图7. 在卡塔尔高温环境下的蔬菜种植实践