LIVING ARCHITECTURE: VERTICAL PLANTING ON FACADE WALLS IN CONCRETE JUNGLES

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Abstract
Large cities commonly face conflicting land demands for housing and urban landscaping. Rooftop gardens have been extensively advocated as a greening solution, but their effectiveness has been limited by the compacted footprint of tall buildings, and roof greenery is competing space with other roof facilities and green energy installations. With the development of high rise blocks which have high wall to roof ratio, and consequently large potential surface area, vertical planting appears to be a better alternative for urban greening. Vertical planting can be categorized grossly into facade greening which involves the spreading of climbers on wall surfaces, and wall planting which usually uses modular planters in pots or trays for plant growth to form a living cover. Soil and water retention are the major design attributes to the success of vertical greening, and carbon emission must be carefully addressed in designing vertical gardens for urban greening. To illustrate the thermal performance of a vertical vegetation system, a prefabricated turf-based modular system which constituted a vegetated cladding on the facades of a public residential building was taken as an example. Cooling effect was closely associated with the green coverage and moisture in the growth medium, which demonstrated the value of maintaining a healthy vegetation cover beyond visual amenity. Drought stress was the major threat to vegetation sustainability and various environmental factors were identified. In contrast to horizontal planting, a distinct pattern of moisture distribution was observed, which may deserve special attention when determining watering regime. The constraints of vertical planting and their solutions would be discussed in biological and ecological perspectives.

1. URBAN LANDSCAPING
Many metropolitan areas are facing the adverse impacts of urbanization, which include population growth, pollution, climate change, land degradation and habitat loss. Owing to the dense population, there is a pressing need to create more open space by overcoming constraints in housing and infrastructure development. Advances in building technology
transform our city landscape and skyline to one dominated by skyscrapers which protect us
from extreme weather conditions, but the concrete jungles so formed have created an urban
climatic phenomenon characterized by higher humidity and night time temperatures, as well
as polluted air with increased concentrations of particulates [1]. Buildings and paved surfaces
provide extra surface that traps solar energy. This, when added up with the heat liberated
from human activities, can hardly be dispersed in the urban canyon which limits
evapotranspiration and restricts airflow. It has been reported that urban air temperatures can
be 5.6°C hotter than the surrounding countryside [2]. The heat island effect aggravates the
massive use of air conditioning in a vicious cycle. Heat stress causes discomfort, but
electricity consumption in restoring thermal comfort returns even more heat to the atmosphere.
This problem is expected to be further exacerbated by global warming as a result of
greenhouse gas emission.

Vegetation can assist to break the cycle by directly dissipating the solar heat through
transformation to latent heat of vaporization or reducing the reliance on air conditioning
through alleviation of heat strain. The vision of increasing urban greenery has received public
acceptance with raising awareness on environment and social well-being. However, most
cities are running out of space for greening. Urban planners always face competing demands
for different land uses and thus leading to exploration of alternative landscaping solutions
such as roadside planting and roof greening. Wall planting has emerged as a newest option for
urban greening. This paper discusses the potentials of vertical planting as a remedy for open
space deficit. In addition to the design and management considerations of these vertical
living green wall systems, findings of a thermal performance study are presented to provide
an insight into its attractiveness beyond aesthetic benefits.

2. LESSONS LEARNT FROM ROOF GARDENS

The beneficial values of urban greenery have drawn substantial attention with the growing
popularity of roof gardens in the late 90s. A vegetation cover on the rooftop provides a milder
microclimate for the building envelope [2-6]. Liu and Baskaran [7] addressed several thermal
characteristics of green roofs, including shading, evaporative cooling, insulation from the
plant canopy and growth medium, and the thermal mass of the growth medium. Tan and his
colleagues [8] reported the capability of green roofs with Raphis species in cooling from 57°C
to 27°C in tropical Singapore. The benefits of greening on buildings can be extended to a
metropolitan level in counteracting the heat island effect. Computer modeling suggested that
cooling of approximately 5°C would result in a negligible heat island effect when half of the
roofs in the Toronto city centre are vegetated [9].

It is generally known that planting helps to cool the city. Unfortunately, residential
buildings are squeezed to go high rise owing to land scarcity and large population. It is not
uncommon to find housing development with several 30 or 40 storey blocks on a compacted
footprint, which limits the effectiveness of roof garden as an urban greening measure. Large
area of rooftop is occupied by water storage tank, piping system and lift tower, resulting in
lesser space for greening. Roof space is also under competition for other green building
devices such as solar panels. Only small proportion of the community can benefit from a
vegetated roof as most rooftops are inaccessible to the public. Vertical greenery is certainly an
alternative to roof greener in a city composed of tall building blocks which have high wall to
roof ratio, and consequently large potential surface area for greening. Moreover, many facade
walls are lined with insulation layer as on the roofs. Solar heat poses a more acute effect on
the building envelope. More residents and community members will benefit if a vegetated cladding can exhibit efficacy as good as a green roof.

3. VERTICAL GREENING AS AN ALTERNATIVE

Vertical planting refers to horticultural practices that expand and extend vertically in space. Stacking culture containers is the simplest form of vertical planting. In fact, gardening on vertical walls is not a totally novel idea. It is believed that the ancient Babylonians created the Hanging Gardens in around 600 BC, from which various contemporary planting systems conceptualized and developed.

In addition to visual appeals, vegetated walls have many of the advantages of their horizontal counterparts. Interior vertical gardens serve to provide planting opportunity and add a touch of nature to the indoor environment, which is mostly decorative in function. Outdoor vertical planting on facade wall offers more regarding urban climate mitigation, landscaping function and even wildlife support. It lessens the solar heat load on a building through insulation and dissipation, provides sound absorption and air purification, and to a lesser extent intercepts storm water and reduces runoff [10].

3.1 Types of vertical greening

Vegetated wall systems can be broadly categorized into two major types according to the position of the planters which contain the substrate in relation to that of the plants: 1) facade greening which involves the growth of climbing or woody plants which root on the ground, or herbaceous plants on planters on elevated wall surfaces, and 2) wall planting which usually uses prevegetated modular planters in pots or trays interconnected and fixed to a standing wall for plant growth to form a living curtain. In general, living walls allow a greater plant variety which includes herbaceous ground covers, perennial flowers, ferns and small shrubs than green facades which use mostly vines and creepers. These two broad categories can be further divided into different types based on the planted vegetation, supporting layouts and possibly irrigation modes. The support methods provide structures such as frame, net or mesh for climbers which grow on planters to cling on, while the carrier techniques use modular planters which are preplanted in nurseries and mounted to wall surfaces [10]. Planting methods can also be mixed to suit different topologies or levels of a building and provide a vivid visual effect.

3.1.1 On-the-ground planters

Vertical greening using aboveground planters is no different to conventional planting. Trees and shrubs are lined into closely spaced plants such that their crowns can be interlaced, forming a hedge in front of a wall (Figure 1a). This can achieve wall greening in a loose sense. Trees with dense foliage, limited horizontal spread and crowns very close to the ground are preferred for a compact hedge with less space between canopies. Hedges take a long time to establish, though their maintenance is relatively simple. Care should be taken when large plants are placed near structures as roots can penetrate walls and foundations. Depending on crown height, hedges can only provide a vertical greening system not exceeding several meters, and are good only for low walls.
Climbing and hanging plants can grow to a distance and overcome the limitation in height to cover a greater area on the wall. Vines have the tendency to attach onto their hosts by nature. Their creeping and climbing habits allow the plants to trail and grow on walls (Figure 1b), fences and pergolas. This is in fact the simplest and perhaps the oldest form of wall greening. Climbers are traditionally used for effective decoration in gardening to produce a living display, as they cost less in installation and maintenance. However, their ability to hold on to the surface by their aerial roots or suckers affects its growth. Special attention is required when being used for facade wall greening. Some species such as Parthenocissus himalayana can directly attach to brick or concrete surface, and a planter is sufficient for their establishment. Other vine species may need rough surfaces or structures mounted on the wall to assist climbing and prevent the wind from slapping the plants. Metallic lattice provides a lightweight, durable solution but thin stainless steel wire may cut the vine. Bamboo or wooden lattice can be more economical, especially when greening is done near ground level. With its larger surface area and ability to break under intense pressure, it protects the plants from injury by steel wire. Like greening with trees, climbers need several months to give a satisfactory vegetation cover during which on-site training is required to ensure that they twist and grow correctly at the desired direction. Sometimes, cucurbits are grown to cover on nets over walls or buildings. In other types, hanging plants may grow from the top to cover walls...
by their pendent growth habit. Owing to their relatively slow growth rate, they may take time to cover the entire wall, which requires frequent onsite attendance, hence a higher labor cost.

3.1.2 Elevated planters
These are the miniature version of aboveground planters, using raised planting beds or elevated boxes at different height levels. Small shrubs, tall herbs and weeping plants which can be established on thinner soil can be grown in the elevated planters (Figure 1c). A series of planters are usually used, e.g. planters at consecutive floors, to achieve the wall greening effect. Weight load on the structure is a major concern and therefore the volume of soil is minimized and sometimes soil is substituted by or blended with other light materials such as peat, perlite, coconut fiber, vermiculite and mature compost. However, thin substrate may result in water stress. The water supply capacity of substrate may be inadequate for plant absorption between irrigations. Although addition of polyacrylamide gel, rockwool or mulch can improve water availability, a carefully designed irrigation schedule is required for plant survival.

3.1.3 Modular planters
Modular planters in mosaic or tessellation design is the most innovative and challenging method in vertical greening. The plants are initially grown horizontally in planters which can be pots or trays filled with lightweight substrates. After early establishment, the whole soil-plant system is rotated at an angle to the ground by fixing the planters on walls to give a complete cover (Figure 1d).

The carrier units come in various sizes and shapes, and can have different positioning and orientations after installation. Aboveground and elevated planters are usually big, but modular planters on wall will be thin or small to reduce weight load and are usually placed on walls. Unit panels, geotextile pockets or wire mesh cassettes on which plants grow can be mounted vertically to cover the wall, or pots/boxes arranged horizontally or more often at an angle to the wall in a nearly upright position to give an advantage of holding the soil in place and retaining moisture at an appropriate level. They are usually grouped in clusters to offer higher flexibility in design and maintenance.

For vertical panels, turf which forms a mat is amenable to produce a green cover, though herbaceous ground cover species could be planted, alone or intermingled in the sod, as long as the growth media used are kept in position using wire mesh or bar frame. There is no specific growth form specification if pots are used for wall planting; common horticultural nonwoody species are good candidates if they meet the growth requirement and aesthetic provisions.

Tessellation with plants is a very flexible way of vertical greening for housing development within a tight schedule and a compact site. The prefabricated plant modules can be installed in weeks, creating an instantaneous vegetation cover. The degree of coverage can be determined by the placement of carriers. Modular configuration not only facilitates maintenance, but also consolidates the time consuming, labor intensive jobs in the preparation of vegetation to an off-site nursery, giving an instant greening effect.

3.2 Growth media
The major factors deciding the success of vertical planting lie in the appropriate selection of soil and plant, both under the influence of the design of the planting systems. The system design determines the configuration of the planting containers, which in turn affects the soil thickness and soil material used, hence the rooting volume and water availability. These are
important factors that affect the growth and development of the vegetation planted. Lightweight materials offer an advantage in terms of mechanical load; artificial soil mixes and hydroponic substrates are commonly used. They provide a good range of water and nutrient retention capacities for sustained plant growth.

Growth media or substrates can vary according to the planting systems. Loose media such as soil mixes are used in horizontal planters and hanging trays, bags or woolly pockets. Mat media are usually sphagnum moss or coir fibers, which are common for inclined pots or modular panels with mesh and net. For green panels, structural fabricated blocks that have desirable water holding capacity and come in different sizes and thicknesses can be tailored to fit the dimension of the planting modules and easily held in position for both exterior and interior applications.

3.3 Delivery of water and nutrients

Watering is essential both in terms of plant growth and system design. Some wall planting systems are run as a continuous vertical hydroponic culture with water being collected at the bottom and pumped back to the system from the top. This is good in sustaining vegetation growth, but is relatively more energy consuming. Living walls are usually designed in such a way that the planters are watered by cascading irrigation by which water drips from the top to move vertically downwards through carrier cells or units internally, or by individual irrigation by which water is fed to each pots via plastic tubing network. The dripping systems can be fully automatic in flow and timing control. When water saving is to be achieved, the frequency and volume of watering are critical in governing plant growth in the various panels, which may be wetted to different extent, especially when a cluster of panels rather than individual ones are fed by irrigation pipes.

3.4 Successful vertical greeneries

Vertical greening has been popular in some European and North American countries. Patrick Blanc, a French botanist, is renowned as the pioneer of modern vertical planting. He developed a gardening technique on walls, which he coined le mur vegetal, in a 10-mm PVC tray, using two layers of polyamide felt each 3 mm thick to support the roots and are held by metallic frames. Nutrient solution is fed from a drip irrigation system in a closed circuit. He started in 1988, and has finished about 30 projects, both outdoor and indoor. In Asia, Japan is leading the research and development of wall planting techniques, while Singapore and Taiwan are also keen to build more vegetated walls in the tropics and subtropics respectively. Many of the original green roof suppliers are shifting their business to green walls, with sales going up to almost trebled in the last 2-3 years all over the world.

There are many other good examples of creative vegetated facade walls such as the Gherkin Tower in London, PNC Plaza in Pittsburgh, Eslite Mall in Tai Chung, SkyTrain station in the Vancouver International Airport and Changi Airport in Singapore. Vertical greenery is emerging as one of the major themes in many displays and projects in big international events such as the 2005 World Expo in Aichi, Ecobuild Expo in London, 2010 World Expo in Shanghai and the coming Flower Expo in Taipei.

4. THERMAL PERFORMANCE OF A VEGETATED FACADE WALL

The benefits of a vertical planting extend beyond mere landscaping and visual appeals; there are positive environmental impacts. With the hope of deploying vertical planting
technology in our housing development, The Chinese University of Hong Kong launched a technical study in 2009 under the commission by the Hong Kong Housing Authority. A vegetated cladding was established outside a public housing apartment using lightweight planting modules. An experimental approach was adopted to compare the solar heat interception of a vegetated facade wall versus a bare concrete wall [11].

The lower latitude of Hong Kong, more intense solar radiation on westerly-facing surface and lack of insulation layer result in heat flux even greater than that observed in some studies on roof garden [7, 12, 13]. The heat flux to the interior could reach 40 W m\(^{-2}\) in some hot afternoons (Figure 2). The rise in temperature and heat flux continued after sunset, which could be delayed by 6 hours after the peak temperature of the exterior facade wall surface. A lag in heat transfer may lead to prolonged thermal discomfort or excessive load to air conditioning as occupants usually stay indoors in the evening. Vegetation cover quenched 60% of daily heat flux, from 595 Wh m\(^{-2}\) of a bare wall to 182 Wh m\(^{-2}\), which is very pronounced. Besides a continuous cooling effect, the vegetation cover buffered the temperature fluctuation of the facade wall, which in turn minimized weathering by thermal expansion; the heat flux only fluctuated narrowly at 5 W m\(^{-2}\) in the presence of a green cladding.

In addition to the thermal mass and shading effect of the greening system, the cooling role of vegetation is substantial. The temperature difference had significant association with both green coverage (r = 0.640, n=30, p<0.001) and moisture (r=0.639, n=24, p=0.001) implying that maintaining a healthy plant cover by efficient moisture delivery is crucial for optimizing the cooling effect of the living wall.

5. DESIGN AND MANAGEMENT CONSIDERATIONS

Vertical greening is not only innovative in terms of planting technique; it also provides a new habitat for vegetation to grow on, especially in the densely packed urban environment. Although conventional management principles such as selecting appropriate species for local climate apply when designing vertical greening systems, some specific limitations on the vertical terrain may be conflicting to common rules, which must be compromised or modified. Maintenance of vertical greenery is costly compared with landscaping on the ground, as the elevated surface may not be accessible without a scaffold or special equipments such as aerial work platform. Careful planning for a low maintenance or even maintenance-free vegetation cover is therefore deemed desirable. Arbitrary decisions for plant care may either stunt plant growth if resources are inadequate or result in wastage of water and fertilizer.
The vertical planting systems are designed to be lightweight, especially for those established on building structures. Thin artificial growth media or soil-like substrates such as rockwool, peat, perlite and vermiculite are usually preferred to soil to reduce loading but this inevitably restricts water and nutrient supply which are essential for plant growth. Water and fertilizer cannot be applied simply on vegetation surface by traditional irrigation methods like sprinkling. Vertical greening system often relies on automatic irrigation system and gravity to deliver water and dissolved nutrients but plant roots, deformation of growth medium or even gravity itself may make the distribution uneven. Our recent study on watering regime observed that gravity could shaped a marked variation in the moisture content within planting module and among modules within an hour after irrigation (Figure 3). The upper region of the lowest module which lived on the surplus moisture from the modules above was prone to dehydration. Adding irrigation points along the height may improve the evenness of water distribution and identification of the threshold moisture for wilting in the particular substrate type and dry spots in a system can provide clues to the irrigation schedule and placement of moisture sensors for the early detection of desiccation.

Failure of the vegetation to sustain is not uncommon, even in the hands of professionals. Choosing the right plants is half way to success. Landscape architects may find it difficult to select plants for vertical greening, though catalogs of commercial species under different climates are always available. The growth habits and characteristics of the plant species used should be considered to match the planting system and the designed effect of the green wall. Plants can be climbing, prostrate or erected, and weeping or upright. Plants with foliages or flowers of different colors can be picked to achieve certain decorative patterns. Perennial...
evergreens are preferred to provide a long-lasting landscaping effect. Hardy species and those that are drought-resistant are sometimes advantageous especially when the system is not excessively irrigated to save water. Planting of natives has been advocated, but this is not a must unless wildlife conservation is an important function of the vertical greenery.

Figure 3. Substrate moisture measured one hour after irrigation in different panels and at different (upper and lower) positions of a modular vegetated cladding outside a housing apartment (right). The vertical greening system was composed of 10 turf panels measuring 100 x 50 x 7.5 cm³ each mounted on a facade wall in two columns (left).

Thickness of growth media is critical to vegetation performance and hence plant selection. Sedums which are succulents may be the best candidate in very thin (< 5 cm) substrate though they do not tend to spread, while perennial grasses, herbs and low shrubs can flourish in thicker (10-20 cm) substrate. The composition of the substrate also matters; the presence of soil usually benefits root anchorage and growth, but how soil is included in the substrate layout is also important, which is affected by the design of the vertical planting systems. Thin panels, which restrict the thickness of the substrate and are difficult to hold soil, will preclude the use of deep-rooted species. Some species exhibit geotropism by growing upward or forming new buds at the upper side few weeks after being transplanted, while many species, being nursed horizontally on ground, fail eventually after mounting on walls. Vegetation planted on elevated height is more prone to wind drift and cold injury. Strong wind blowing over foliage accelerates evaporation and consequently intensifies the chilling effect. On the other hand, care should also be taken to protect the vegetation with prolonged sunlight illumination from drought and heat shock. There is a paucity of information about the adaptability of plants to vertical planting and thus species screening prior to planting may help to find a perfect match. As a rule of thumb, perennial species which are resilient to occasional dry spells and heat should be good candidates. Small plants with small but dense foliage withstand better under wind than those with large board leaves. Ambitious landscape architects may consider blending flowering species or foliages of different colors to produce a vibrant green wall. It should be noted that vegetation on vertical greening is more susceptible to shading from surrounding topology compared with those on ground owing to a narrower
azimuth and zenith. Sun path analysis may help addressing shadows and, if necessary, shade tolerant species should be considered.

Maintenance is another headache for landscaping practitioners. Problems in both system design and maintenance can lead to frustrations in plant replacement. Fortunately, routine work involving irrigation and application of fertilizer through irrigation pipeline can be carried out by an automatic system. Colonization by ruderals is unavoidable even on a well managed green wall. A dozen of new species can be found colonized a green wall within the first year of establishment. Species in the recruitment depends largely on the seed source in the surrounding floral habitats, but wind and birds should be the major dispersal agents as indicated by their life habit. Some trees and shrubs like *Macaranga tanarius* and *Acacia* spp. can grow to considerable size in several months if left unattended. Regular inspection and trimming of the plants are advisable to prevent invading plants from growing too large but the need of frequent weeding or panel replacement depends largely on aesthetic and landscaping considerations.

6. PROSPECTS AND POTENTIALS OF VERTICAL GREENING

Vegetated verticals provide an entirely new dimension in both urban landscaping and green building development. Recent market research addresses dozens of proprietary greening systems but decision makers so far are still hesitant to a massive deployment of vertical planting as an urban greener solution owing to a lack of practical information regarding operation and reliability. Uncertainties associated with cost effectiveness have made decision solely for the purpose of aesthetics sometimes hardly justified. The hidden values in addition to aesthetics are awaiting exploration and, more importantly, quantitative assessment such as comprehensive cost effectiveness analysis is beneficial. Preliminary research has demonstrated the efficacy of a vegetated facade wall in cooling the building. Impacts on human bioclimate as a consequence of reduced radiant heat, energy consumption pattern and thus the carbon dioxide footprint should be the focuses of further research. Advancement can be achieved at the development of vertical planting systems which are economically attractive for large-scale application. The ecological value and compatibility of vertical greener to the surrounding habitats would be the interest of industrial ecologists.

It is envisaged that vertical greeneries will be one of the future directions in urban landscaping and building design. Some topics related to vertical greening are under investigation and hopefully the findings can facilitate the weighing of costs and benefits, and justify the development and use of vertical greening technologies. Variables like architectural layout, climatic factors, geographical location, planting design, choice of floral species and management practice are expected to have marked influence on the outcomes, and consequently provide plenty of room for interdisciplinary collaboration and knowledge exchange.

REFERENCES