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An Appraisal of Simple Shading Devices to Mitigate the Effects of Urban Heat Islands on Buildings in Nigeria

Ella II, Gaiya SN, Gofwen CN, Ola-Adisa EO

Department of Architecture, University of Jos, Jos, Nigeria

Abstract With the effects of global warming and urban heat islands, the maintenance of thermal comfort in houses is likely to be challenging in some Nigeria states without relying on active cooling systems. This paper proffers simple shading components which can reduce heat gain in houses due to solar radiation, which in turn has the potential to reduce the use of air-conditioning systems for thermal comfort purposes. Trees make ideal shading devices generally because they provide a pleasant shade and relief from intense sunlight, especially if utilized intelligently. The transpiration which occurs in the trees, provide additional cooling to their immediate outdoor environment by as much as 5.4 °C when compared to a similar unshaded building. A draught resistant tree such as the Umbrella Thorn is ideal for Nigeria, they have high canopies which have the tendencies to shade both the roof and sides of the building. But because trees are living organisms, they have certain drawbacks which include time to mature, intrusive root systems and initial nurturing process. Another shading component with impressive results is a Sierpinski tetrahedron fractal canopy. A typical fractal object with a fractal dimension of 2 is a Sierpinski tetrahedron while that of a natural tree is "approximately" 2, meaning that Sierpinski tetrahedron fractal canopies mimic natural trees and provide shade from sunlight without being heated themselves. Results showed that the fractal roofs were effective in reducing surface temperatures in sunlight. The ground surface temperatures under the fractal roofs were also significantly reduced by as much as 10 °C even though they did not provide complete shade. Consequently, they provide a comfortable environment and significantly reduce thermal stress in urban areas. The canopies also provide an open-air feeling by allowing nice breeze to flow through while creating a luminous environment. Because fractal membranes are porous, they are not swollen with the wind and do not suffer from strong wind drag force. This property makes it possible to use thin frames to support fractal roofs. This paper recommends that trees and fractal canopies be employed to mitigate against the effect of urban heat islands in a manner that is green. In certain instances, where trees cannot be used for shading purposes, Sierpinski Tetrahedron fractal canopies can be adopted as an equally effective alternative.

Keywords Shading, urban heat islands, thermal comfort, trees, fractal canopy, Sierpinski tetrahedron

Introduction

Due to the factors such as global warming, heat waves and urban heat islands (which Nigeria contributes its fair quarter by continued gas flaring), the maintenance of thermal comfort in houses in an affordable manner is likely to be challenging and can have implications not only for the health and comfort of the occupants but also for peak energy loads. While new buildings can still adopt bioclimatic approaches to tackling climate change and the effects of urban heat islands, existing buildings have to be retrofitted to maintain adequate interior thermal conditions [1].

Many existing buildings in Nigeria today, are so called "modern buildings" which cannot provide thermal comfort for their inhabitants without relying on active cooling systems; because they are not bio-climatic in design and materials. These active cooling systems add to the carbon footprint of the building, increase energy use and since only about 50% of buildings are connected to Nigeria's unstable electricity grid, cannot be deemed a reliable solution within the Nigerian context [2-4].

It is clear that heat gain in buildings can be caused by several environmental factors including solar radiation. This paper seeks to proffer simple scalable retrofits to reduce heat gain as a result of solar radiation in existing buildings in Nigeria. The world over, the strategy to reduce solar radiation on existing buildings is simple; keep out heat by insulating the building envelop or by shading the envelop of the building from direct sun rays [5]. As simple as it may sound, the challenge of reducing heat gain as a result of solar radiation is complex, when several dynamics are considered.

Heat gain by Solar radiation in buildings is the direct rays of the sun hitting a building's envelop which eventually heats up the building's interior over time. Therefore, the materials that make up the buildings envelop becomes crucial in preventing the transmission of heat from the outside surface to its interior. Many buildings in Nigeria adopted the international style of building which is non bio-climatic to our region; mainly consisting of sandcrete hollow blocks, glass and aluminium roofs, and according to Adaji,Watkins, & Adler [6] are the reasons for the higher indoor temperature levels that are above thermal comfort levels for Nigerians which ranges between 17– 27 °C. Aluminium rapidly transmits heat while sandcrete blocks have about an 8 hour delay before heat is transmitted from the outer surface to the interior surface; which may be advantageous in climates with high diurnal temperature differences, but not for hot/warm humid climate with low diurnal temperature differences.

Therefore, in Nigerian towns/cities which have low diurnal ranges and numerous non-bioclimatic buildings, retrofitting for better thermal comfort becomes essential. The proposed retrofits will entail shading of the building envelop in order to reduce direct sun rays from reaching the building. This approach of shading the building from sun rays is deliberate and this is due to the fact that other forms of reducing or eliminating heat transfer due to solar radiation requires using insulation materials, altering fenestrations on the east and western sides of the building, or re-orientating the building itself [7]. All of the above mentioned require a great amount of building modification. Secondly, some insulation materials like rock wool may be cheap by themselves, but the process of the installation is expensive. Another major point worthy of note is that many Nigerians live in rented accommodations and thus limits or discourages expensive building retrofits [8]. Therefore, any proposed solution should shade the building from the exterior, be scalable, somehow reusable and most importantly cheap (affordable).that for any material to be cost effective, several parameters must be considered [9-12]:

1. Materials must be sourced locally
2. Materials should be durable
3. Materials should be scalable/malleable
4. The technology should be local (manufacturing process)
5. Materials should be reusable/transferable

Consequently, this paper proposes two simple shading components which meet the criteria mentioned above

Trees

A tree is living organism, consisting of a trunk and a canopy which comprises of branches and leaves. They give off oxygen and store carbon, stabilize the soil and their canopy provides shade from sun rays. Due to the transpiration which occurs in the trees, they provide additional cooling to their immediate environment. Trees situated in urban environments can significantly influence ambient air temperatures through evapotranspiration and shading [13]. However, this cooling strategy is unsuccessful in case of intense sunlight and inadequate water. Therefore, trees utilise an alternative approach to cool their leaves and preserve enzymes required for photosynthesis. Trees have small leaves which are distributed in a fractal structure in a three-dimensional (3D) space. This strategy is appropriate for cooling surface temperatures without using water. The heat from the sun is swept away by air flowing through clusters of leaves and is carried from the ground level to higher altitudes by atmospheric convection.

Trees are therefore an ideal shading device generally because they provide a pleasant shade and relief from intense sunlight, especially if utilized intelligently. It is common knowledge that people are cooler standing or sitting under a leafy tree than directly under the sun on a hot day. The same goes for a house that is shaded by trees; they have cooler exterior surface temperature which also translates to a cooler interior temperature when compared to a similar house exposed to direct sun rays [14].

Another advantage of trees includes increased air quality; they act as a filter of large air borne particles, as wind breakers and increase oxygen levels around the building. The technology to plant a tree is simple and many Nigerians who happen to be farmers are conversant with plant cultivation. Although trees are not easily scalable, they can be pruned and used to shade specific parts of a building [13].

Tree Planting Patterns

Due to expanding urbanization, characterized by greater use of impermeable surfaces and reduced tree canopy, urban areas now experience increased temperatures. This trend has repercussions in energy consumption and human health, which trees can help mitigate by casting shade upon building surfaces. Intelligent use of trees with respect to form and placement can effectively offset this trend. Trees can be planted on the east or western façade of the building; where the sun's rays have greater access to the building's envelop. The canopy of the tree blocks majority of the sun rays resulting in a cooler façade and micro-environment [15].

The provision of shade by a single tree onto a building is a function of two factors: tree form and tree placement. The form describes the physical attributes of a tree, while tree placement describes its location in relation to the building targeted for shading. The relationship between the tree form and tree placement relative to a building establishes a unique tree planting configuration. The interaction between a particular tree planting configuration and the diurnal and seasonal patterns of sunlight in a particular geographic location dictate the subsequent shade cast upon a building. According to Rudie and Dewers [14] the height and distance of a tree from a building are significant variables in shade provision. Many other studies have shown that large, dense-canopied trees positioned on the west aspect of a building are commonly reported to provide the greatest cooling benefits [16-17]. Studies have found that trees on the west aspect of buildings saved the most cooling energy; as much as 554 kWh annually. This is followed by trees on the east and south aspects [18].

Table 1: Regional tree planting guidelines for energy conservation published by authoritative sources [19]

Area	General
Tree placement	West
Tree form	Trees with crown lower to the ground; Deciduous trees with high spreading crowns
Direction (distance)	6m to 21m

There are different types of trees; short and tall, deciduous and perennial, trees with heavy canopies all over, while others spread their canopies mainly at higher levels. One tree that is ideal for shading buildings in Africa and Nigeria specifically, is the Umbrella thorn (*Acacia tortilis* or *Vachellia tortilis*). The high exaggerated umbrella-shaped crown enables the trees to capture the maximum amount of sunlight, creating elaborate shading as a result (Table 1). The umbrella tree also endures extensive hot-season heat and drought. It survives on as little annual precipitation as 380mm to as much as 1194mm. The Thorn Acacias shallow roots can extract any moisture from the soil above the hard core as it grows up to a height which range from 6m to 21m.One advantageous attribute of this tree is that it allows for an almost unimpeded visibility from the building it shades due to the tree's high level canopy [20].

Drawbacks

The main drawback to any living organism is maintenance and in some cases several years to reach maturity. Trees need water and nutrients to sustain them. A large number of Nigerians have poor access to water supply and are living with acute water shortages. Consequently, the use of trees as shading devices cannot be easily implemented and sustained by many Nigerians, especially at the onset. Secondly, due to the time required for trees to reach maturity, their implementation has to be predetermined and planned well in advance, which is ideal for new developments, while alternatives would have to be used before the plants reach maturity for existing buildings. Trees usually take an average of 3 years to provide reasonable foliage that can provide shade. In simpler words, the implementation of trees to provide shade takes time [21]. Other drawbacks include foliage, impeded view from windows and the increased possibility of insects, birds or reptiles near the home (although almost all houses in Nigeria have mosquito nets due to the malaria epidemic). Additionally, the roots of the trees can create structural problems to buildings, by growing their roots under the building and forcing it upward, which can cause the foundation to heave. Consequently, trees that grow long, lateral roots should not be installed to close to the house. As general rule, it is best to plant trees that have taproots or trees with short root spread.

Therefore, trees generally should be installed a recommended distance of 4.5 metres or more away from the targeted building, while trees with large root systems, should be positioned a minimum of 6 metres away from the building, although 15 metres is recommended, if possible. This is because the spread of tree roots can be two to four times greater than the drip line of the branches.

Apart from causing problem for the foundation, roots can cause other problems to underground utilities. It recommended that trees be installed a minimum of 1.5 to 3 metres away from utilities. Landscape elements such as driveways or sidewalks could also be affected by trees with large roots and it is best to plant them at a distance of 1.8 to 2 metres away for a medium-sized tree, and up to 6 metres away if the tree is known for having large, encroaching roots. However, it may be advantageous to install a root barrier to protect the house and other landscape elements from damage, although at a cost [22].

Comparing the Effect of Trees on Thermal Conditions of Urban Buildings

Results from a study done by Morakinyo, Balogun, & Adegun [23] shows the relationship between indoor and outdoor thermal conditions and vegetation (trees) with the case of these two typical buildings located on the campus of a Nigerian University. A comparison of outdoor temperatures shows all-time higher temperature values for the un-shaded building when compared to the tree-shaded building. Under any sky-condition, outdoor temperature in un-shaded building was more than the shaded one although the value reduces with cloudiness. The outdoor temperature difference of 3.1°C–5.4°C between the two buildings shows the effect of vegetation at reducing outdoor temperature. The figures for indoor–outdoor temperature also resonate with this fact. Indoor–outdoor temperature shows a higher value during the day which ranges from 0.2°C to 5.4°C for un-shaded building and not more than 2.4°C for the tree-shaded building. The effect of the shade is more evident during summer while it was not so evident in the dry season because of transpiration and leaf shedding by trees.

The observed contrasts on air temperature and wall temperature as measured inside and outside the shaded and unshaded buildings were made. Air temperatures were higher and for longer hours throughout the study period inside the un-shaded building. Indoor–outdoor temperature differences show a peak of 5.4°C for the un-shaded building while the tree-shaded did not exceed 2.4°C. The results show that tree-shading constitutes an excellent passive cooling system for buildings, potentially enhances thermal control and conserves energy in buildings.

Fractal Membranes (Sierpinski Tetrahedrons)

Analogous to the cooling strategy of trees, is a Sierpinski tetrahedron membrane/canopy that has cooling properties and is composed of fractal shapes. This membrane consists of many Sierpinski tetrahedron units and blocks 100% sunlight from a certain direction. The fractal dimension of a Sierpinski tetrahedron is similar to that of natural trees, providing an environment similar to a natural forest. This new membrane can be used as roofs and offer a physically comfortable environment underneath [24].

Trees provide a pleasant shade and relief from intense sunlight. It is generally acknowledged that this is due partly to the transpiration effect which causes cooling around trees. However, this cooling approach alone is not effective in a scenario of intense sunlight and insufficient water. Hence, trees use an alternative strategy to cool their leaves and surrounding. Because their leaves are small and distributed in a three-dimensional space, some leaves shade other leaves from the rays of the sun and the heat from the sun is blown away by air flowing through the clusters of leaves which is then carried from the ground level to higher altitudes by atmospheric convection. This strategy is very effective for cooling surface temperatures without using water [25].

Sierpinski Tetrahedrons

A Sierpinski tetrahedron is made up of a network of triangular components linked together in 3-dimensional space. An array of the Sierpinski components can form a membrane large enough to shade exiting roof and buildings from the rays of the sun and aid cooling. PVC Sierpinski tetrahedron membranes block 100% sunlight from a particular direction. The sunlight from other directions partly penetrates the membrane, creating a leafy shaded area under the roof. Compared with ordinary flat roofs, these roofs greatly reduce surface temperature and consequently provide a cool environment devoid of strong heat radiation. The fractal structure of the tetrahedron units is similar to that of natural trees [24].

Scale Effect

It is well known that external surfaces of large metal surfaces get very hot in sunlight. However, the same is not true for a miniature of the larger metal. In an experiment by Sakaia [24] shows the surface temperature of a large car and two miniature cars in sunlight. The temperature of the large car is higher than that of the small cars by approximately 20°C. This can be explained by the effect of scale. Any object in sunlight becomes hot because of strong radiation. However, large monolithic materials get hotter than small materials, indicating that large objects have small heat transfer coefficients at high temperatures. Although this rule was obtained from laboratory experiments in which the experimental conditions are precisely controlled, it holds well even outside where the wind speed changes frequently and conditions seem to be very complicated. This simple principle can be applied to the natural leaves of trees and artificial objects. The usual length of a tree leaf is several centimetres while the typical size of artificial objects, such as buildings, roads or pavements in urban areas, are several tens of meters. This difference in size causes a significant difference in surface temperatures [24].

Taking into consideration the effects of scale defined above, small leaves are strategic for maintaining low surface temperatures of trees. However, trees need many small leaves to absorb sunlight for photosynthesis, and the leaves have to be distributed to minimize thermal interference. If the leaves are laid on a two-dimensional (2D) surface, the surface temperature will be same as that of any large flat surface. However, the leaves of trees are distributed in a three dimensional (3-D) space with a fractal dimension within a specific fractal range of 1.8 to 2.4 depending on the scale. Therefore, it can be inferred that the fractal dimension of a natural tree is "approximately" 2. The results of the above measurement indicate that the trees have 2D areas but do not have 3D volume. This geometry is favourable for absorbing sunlight in 2D areas with minimum interruption of air flow.

A typical fractal object with a fractal dimension of 2 is a Sierpinski tetrahedron. This fractal object forms a regular rectangular shade when sunlight comes from a certain direction, otherwise it partly transmits sunlight from other directions. By distributing many small leaf-like structures in the shape of a Sierpinski tetrahedron, we can obtain low surface temperatures. On the basis of this idea, Sakaia [24] created fractal roofs from different materials (PVC and fabric) and tested their effectiveness at two sites.

PVC Sierpinski Tetrahedrons

A Sierpinski tetrahedron fractal membrane can be made from PCV or fabric (Figure 1). The PVC fractal membranes (fractal canopy) is formed by the Sierpinski tetrahedron units. Four Sierpinski tetrahedron units can be joined to form a self-similar tetrahedron twice as large as the original. In the same manner, larger self-similar units can be assembled. The smallest basic tetrahedron consists of two surfaces. The other two surfaces are omitted because only two surfaces are required to block sunlight from a certain direction.

Figure 1: A Sierpinski Tetrahedron [24]

This porous structure ensures ventilation of heated air and keeps the surface temperature low. The tetrahedron is asymmetric to block typical sunlight at noon in summer from an angle of 70° altitude. In full scale experiments by Sakaia [24], a fractal membrane (Sierpinski's forest) was built and positioned at the front of the main entrance of the National Museum of Emerging Science and Innovation (Miraikan) in Tokyo, Japan, in the summer of 2009. The primary purpose of the roof was to provide shade for visitors in the mornings and afternoons. As the sun moved over the membrane, sunlight partially penetrated under the roof, creating geometrical patterns. The shade covered an area of approximately 250 m^2.

Figure 2 shows thermal images of the Sierpinski's forest around noon when the atmospheric temperature was about 30°C. For comparison, part of the roof was constructed with flat PVC panels. It is obvious that the surface temperature of the fractal roof was significantly lower than that of the flat roof as shown in Figure 3. The temperature of the ground surface under the Sierpinski's forest was also significantly lower than that of under direct sunlight (Figure 4). The fractal roof was even cooler than the grass field beside the roof and this indicates that the fractal roof provides a more qualitative environment with low thermal radiation.

Figure 2: A view of the Sierpinski's forest at Miraikanshowing the shade pattern under the roof [24]

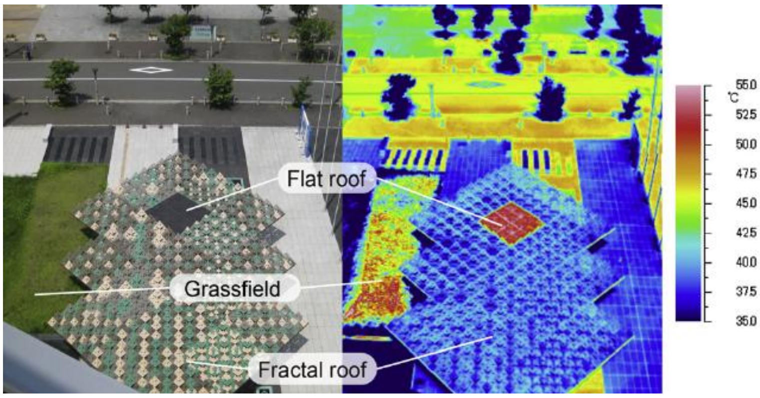

Figure 3: Visible photographs (left) and thermal images (right) of the Sierpinski's forest at Miraikan. The temperature scale of the thermal image is shown on the right hand side [24]

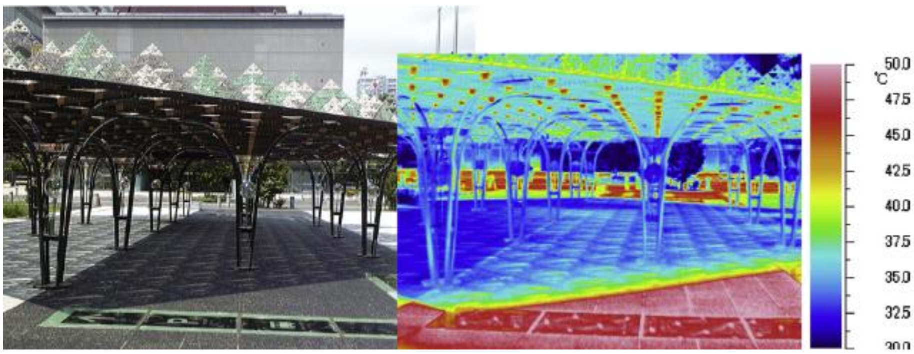

Figure 4: Visible photographs (left) and thermal images (right) showing the shade under the Sierpinski's forest. The temperature scale of the thermal image is shown on the right hand side [24]

Fabricsierpinski Tetrahedrons

A fractal shade can also be made of fabric. A plain fabric is perforated with shapes derived from a Sierpinski tetrahedron at an angle. The perforated fabric is then spread over a frame in a zig-zag configuration. Because it is difficult to make the fabric shade asymmetric, which is possible with the PVC shade, the angle for maximum shade was directed to the zenith. Additionally, the shape of a fabric shade is easily deformed and it cannot completely block sunlight even at the maximum shading angle. Because of the shortcomings of the fabric shade when compared with that of the PVC shade, some sunlight always penetrates the shade.

However, when a fabric fractal sunshade was placed at the roof garden of a shopping centre in Kagoshima, Japan (Figure 5), in early summer 2010, the results were surprisingly favourable [24]. The shade covered approximately 70 m^2 of the roof-top of a six-story building. However, the surface temperature of the roof-top under the shade was significantly lower than that of outside the shade as shown in Figure5. The atmospheric temperature was approximately 32°C when the thermal images were taken. The surface temperature of the fabric shade itself was low despite strong sunlight (Figure 6), although the surface temperature was non-uniform. This was because each piece of the fractal fabric was not uniformly exposed to sunlight and the ventilation of the heated air was not as good when compared with that of the PVC shade owing to structural restrictions. However, the average temperature difference between the surface of fractal fabric and air was approximately 10°C, which is almost same as that of the PVC shade.

Figure 5: Fabric fractal sunshade at the roof garden of a shopping centre in Kagoshima, Japan [24]

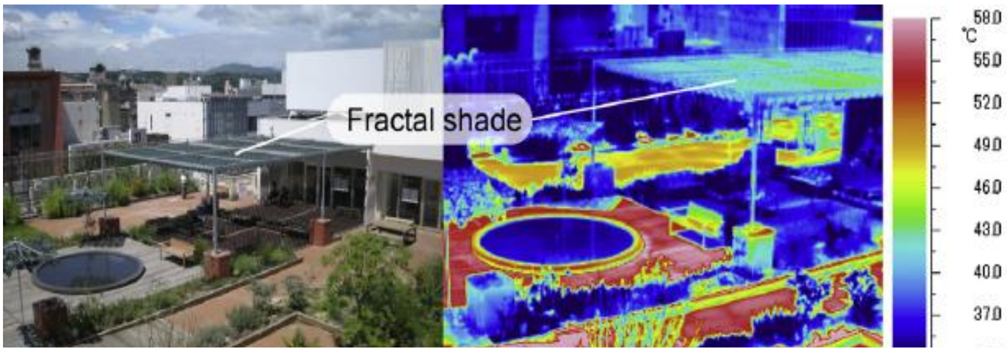

Figure 6: Visible photographs (left) and thermal images (right) of the Sierpinski's forest at Miraikan. The temperature scale of the thermal image is shown on the right hand side [24]

Conclusion

Owing to the factors such as global warming, heat waves and urban heat islands, the maintenance of thermal comfort in houses in an affordable manner is likely to be challenging and can have implications not only for the health and comfort of the occupants but also for peak energy loads; of which Nigeria still strives to generate and transmit. Trees planted for the purpose of shading buildings and altering microclimates will not only mitigate the effects urban heat gains but also reduce energy demand for thermal comfort purposes which in turn reduces the carbon foot print of a community. However, it should be well thought-out, taking into consideration the form and placement of a tree among other parameters. Once people have a proper orientation about the benefits of trees, their uptake as thermal regulators for buildings and urban environments will be embraced. The skills to plant and cater for a tree or trees are well known by many Nigerians due to large population of farmers. Drought resistant varieties are proposed and should perform well if they are planted at the unset of the rains. However, not all existing buildings can incorporate trees as shading devices, let alone for any other function. This is largely due to a lack of space and water. Taking into account that trees cannot be placed too close to the building due to underground and surface utilities, as well as some landscape elements such as driveways and sidewalks, it might not be a viable option for all. For this reason, a fractal canopy made of Sierpinski tetrahedrons is considered a viable alternative. It is very effective for cooling surface temperatures without using water and possesses pretty much all the benefits of trees without the draw backs of intrusive roots systems, the need for nurturing and also time to mature. Both possess the unique capabilities to create shade without gaining considerable heat, allow for relatively free passage of air and do not completely block out sun rays during the course of the day. The result in either case is an environment similar to a natural forest which offers a physically comfortable environment underneath.

Recommendations

1. Buildings that are non-bio-climatic and cannot provide thermal comfort for their occupants should have trees planted on the western and eastern axis of the buildings to reduce heat gain.
2. In circumstances where trees cannot be planted to shade buildings for reasons such as limited space, water shortage or fear of damage to the building and utilities, Sierpinski tetrahedron fractal canopies can be installed to provide shading.
3. Trees and fractal canopies should be installed along streets and roads within urban centres to mitigate against the already elevated urban temperatures.
4. Policies should be made by government to ensure passive cooling systems are installed in public and private buildings before active cooling systems are employed.
5. Government should enforce its policy against cutting down public trees in order reduce the effects of urban heat islands.
6. Architects should ensure that the landscaping elements in their designs are adhered to as strictly as the design of the building itself.

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