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Urban Heat Mitigation Through Intelligent Green Design: A Case Study of Terminalia Mantaly Using AI And Environmental Sensing

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Abstract

The increasing rate of global warming due to urbanization, greenhouse gas emissions, and deforestation has amplified the urban heat island (UHI) effect, particularly in tropical and semi-arid areas. Strategic tree planting has become an essential nature-based solution for climate mitigation. In this study, the cooling capacity of Terminalia mantaly, a quick-growing, evergreen tree with broad canopy, is assessed using advanced AI tools, remote sensing methodologies, and in-field sensor observations. A multi-modal research methodology was used to investigate the influence of the tree on its microenvironment. Thermography and deep learning-based algorithms (YOLOv8, Mask R-CNN) indicated that Terminalia mantaly lowered surface temperatures under its canopy by a maximum of 4.8°C, the largest effects occurring around midday. Satellite-based NDVI and LST analysis showed that tree-covered zones had NDVI values of 0.74 and LST reductions of 3.5°C compared to adjacent unvegetated areas. AI models, particularly Random Forest and LSTM networks, achieved over 88% accuracy in predicting thermal changes and temporal cooling patterns. Ground-based environmental sensors confirmed a 3.0°C drop in ambient temperature, 7% increase in relative humidity, and 100% increase in soil moisture beneath the canopy. Simulations with Unity 3D and finite element modeling demonstrated a radial cooling effect up to 5 meters, and a 45% reduction in radiative heat absorption because of leaf structural scattering. Significantly, Terminalia mantaly had foliage year-round, providing consistent shade and cooling without the loss of seasonal canopy. The research concludes that Terminalia mantaly is a viable species for urban climatic resilience. Its high growth rate, dense canopy, minimal leaf shedding, and constant coverage make it the best for heat stress mitigation, energy savings, and ecological sustainability in urban areas. This research recommends the use of AI-supported afforestation as well as precision ecological planning in fighting global warming.

Keywords: Urban Heat Mitigation, AI tools, YOLOv8, Mask R-CNN, NDVI, LST, Terminalia mantaly

Introduction

A new International Labour Organization report, also published Thursday, reported that over 70 percent of the world's workforce is exposed to heat stress, and that 4,200 workers worldwide lost their lives in heat waves in 2020 [1].

Extreme heat has also become the world's deadliest weather-related killer. It has caused around 489,000 fatalities each year since 2000, as estimated by the U.N [2]. A total of approximately 18,970 deaths each year are related to workers being exposed to hazardous temperatures. Even though its perilous, extreme heat has long been relatively under-covered and under-resourced compared to other climate catastrophes like hurricanes and wildfires. That is no longer the case. Over the last several years, policymakers globally have started to give special prominence to the threat of escalating heat waves [3].

Terminalia mantaly (family: Combretaceae), commonly known as the Madagascar almond or umbrella tree, is a fast-growing deciduous tree native to Madagascar and increasingly cultivated across tropical and subtropical regions [4, 5]. With its symmetrical, layered branches and dense, umbrella-like canopy, T. mantaly is highly valued for ornamental landscaping, urban greening, and ecological restoration efforts. Its flexibility to diverse soils, high growth rate, and ability to offer constant shade with moderate leaf dropping render it a most suitable species for reducing the negative impacts of urban heat and land degradation.

In the 21st century, the planet is experiencing unprecedented climate changes. The global temperature has increased by about 1.1°C from the pre-industrial period, and the rate of warming is increasing. The main drivers are overconsumption of fossil fuels, deforestation, industrial pollution, land use that is unsustainable, and the buildup of greenhouse gases—specifically carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [6]. They heat the atmosphere with the greenhouse effect, upsetting the Earth's energy balance and creating a cascade of environmental effects: sea-level rise, glacier loss, heatwaves, desertification, and loss of biodiversity.

Urban regions are especially at risk from the "urban heat island effect,"[7] in which concrete buildings, asphalt, and lower vegetation enhance temperature extremes [8]. In these conditions, air temperatures can be several degrees warmer than in surrounding rural areas. Deforestation and removal of green cover also directly add to increased surface temperatures, soil erosion, polluted air, and decreased rainfall, further destabilizing local and regional climates.

In the midst of these challenges, climate change mitigation—measures designed to reduce or avoid the release of greenhouse gases—has emerged as a global necessity. Among a suite of mitigation techniques, afforestation and reforestation are nature-based solutions with short- and long-term payoffs. Trees form a critical component for climatic stabilization by:

- Capturing carbon dioxide from the atmosphere through photosynthesis
- Reducing ambient temperatures through canopy shading and evapotranspiration
- Enhancing soil fertility and water retention

- Reducing air and particulate pollution
- Maintaining biodiversity and ecosystem resilience

Tree species that have dense and wide canopies are best for cooling the climate and decreasing radiation at the ground level. Quick-growing trees with drought tolerance that keep their foliage during most of the year are best for climate resilience and greening the urban area.

Terminalia mantaly is a highly potential species here. It can survive under severe heat and dry conditions of water, yet yield regular shade and minimal litter. It reaches 10–20 meters in height in a few years and is ideal for both rural afforestation and urban landscape architecture. Furthermore, its moderate deciduousness minimizes maintenance and makes it ideal for road sides, institutions, parks, and agroforestry [9]**. Table 1**

Other tree species that have similar advantages and can aid climate mitigation are:

- Azadirachta indica (Neem) – Evergreen, hardy, carbon-sequestering, medicinal
- Polyalthia longifolia (Ashoka) – Narrow canopy but dense, little leaf fall
- Ficus benjamina (Weeping Fig) – Wide canopy, urban-tolerant, evergreen
- Albizia lebbeck (Siris) – Shade-providing, nitrogen-fixer, semi-evergreen
- Delonix regia (Gulmohar) – Ornamental, fast-growing, good canopy, seasonal leaf fall
- Melia dubia (Malabar Neem) – Fast carbon fixation, rapid biomass growth
- Moringa oleifera (Drumstick Tree) – Multipurpose, xerophytic, edible leaves

Aside from its environmental importance, T. mantaly possesses substantial traditional medicinal properties. Its bark, leaves, and roots find application in different African and Malagasy health systems in the treatment of fever, respiratory diseases, malaria, and gastrointestinal disorders. Phytochemical studies have isolated bioactive phytochemicals like flavonoids, tannins, saponins, and alkaloids—most of which exhibit antimicrobial, antioxidant, and anti-inflammatory activity[10].

This review is a thorough integration of existing information on Terminalia mantaly in terms of botanical description, ecological roles, culturing potential, ethnomedicinal significance, phytochemical composition, and pharmacological characteristics. It delves into its application in counteracting climate change, particularly with green infrastructure and community-scale afforestation initiatives. In the process, it presents T. mantaly as much more than just a medicinal species but also an effective ecological friend in the mitigation of global warming.

Materials and Methods

In this research, the microclimatic cooling impact of Terminalia mantaly is to be evaluated using AI-augmented thermal imaging, satellite remote sensing vegetation analysis, and environmental sensor data modeling **Table 2**. The methodologies for integrating cutting-edge tools, remote sensing technologies, and AI algorithms for data processing are described in the following steps.

1. Study Area and Plantation Planning

Location: Urban and semi-urban localities in MIDC, Miraj, Maharashtra, India.
Tree Specimens: 3- to 7-year-old Terminalia mantaly trees.
Control Plot: Same area with the same landscape but without tree canopy.
Plot Size: 10m × 10m per monitored zone (tree vs control).
Number of Trees Studied: 30 trees in 3 climatic zones.

2. Data Collection Techniques

2.1 Thermal Imaging Monitoring

Tool: FLIR Thermal Camera

Purpose: Record surface and ambient temperature gradients near the tree canopy.

AI Algorithm Utilized: YOLOv8 + Mask R-CNN for segmentation and temperature difference maps with OpenCV and NumPy.

2.2 Satellite Remote Sensing

Tools: Sentinel-2 & Landsat 8, Google Earth Engine (GEE)

Indices: NDVI (Normalized Difference Vegetation Index), LST (Land Surface Temperature, SAVI

AI Integration: GEE ML module with K-means, DBSCAN, and Random Forest Regression.

2.3 Environmental Sensor Grid

Sensors: DHT22, Soil Moisture (YL69), Pyranometer, Anemometer

Deployment: 3 sensors per tree plot and control plot.

AI Processing: LSTM (Long Short-Term Memory neural network) for predictive cooling curves with TensorFlow.

2.4 AI-Based Canopy-Cooling Simulation

Tool: Unity + Python with NVIDIA PhysX engine

Simulation: Radiative cooling using finite element methods (FEM)

Algorithm: 3D LiDAR (Light Detection and Ranging) import, solar radiation simulation, chlorophyll reflectance, heat dissipation mapped and calibrated with actual data.

3. Statistical Analysis

Tools: RStudio, Python (Pandas, SciPy)

Metrics: ΔT (temperature difference), %Reduction, correlation with NDVI and LAI (Lea Area Index)

Tests: Paired t-test, ANOVA, Pearson correlation.

Results:

Terminalia Mantaly Cooling Effect Study

1. Thermal Imaging Monitoring

Thermal imaging showed a uniform 3.2°C to 4.8°C decrease in ground temperature under Terminalia mantaly canopies **Image 1**. YOLOv8 and Mask R-CNN segmentation models effectively separated canopy regions with 92%-pixel accuracy. Heat maps showed cooler regions up to 5.1°C under mature trees, particularly over hard surfaces. Optimum cooling effect was seen between 1 PM and 3 PM, with more dense trees doing 20–30% better. **Graph-1**

2. Satellite Remote Sensing Analysis

NDVI ranges from 0.52 to 0.78 for Terminalia mantaly plots, showing strong correlation ($R^2 = 0.71$) with cooling effects. Land Surface Temperature (LST) in plots with Terminalia was 3.5°C lower than that of neighboring non-vegetation plots. Cooling effects were predicted by Random Forest Regression with an accuracy of 88%.

3. Environmental Sensor Grid Results

Ground sensors indicated a 3.0°C decrease in ambient temperature and a 5–7% increase in relative humidity under canopies. Soil moisture under the tree was twice that in control plots. LSTM neural networks precisely predicted cooling patterns with a mean absolute error less than 0.4°C. Optimum spacing for heat mitigation was determined to be 5–7 meters between trees.

4. AI-Based Canopy-Cooling Simulation

3D Unity-based simulations showed a cooling radius of up to 5 meters and vertical cooling plumes of 2.5 meters. FEM analysis revealed a 45% decrease in radiative heat absorption. Leaf structure of the tree allowed for broad diffuse radiation scattering. Chlorophyll reflectance modeling demonstrated enhanced cooling with reduced IR reflection. **Image 2, 3**

5. Statistical Analysis Summary

Major comparative data is listed in the **Table 3**

6. Ecological and Urban Impact Projection

Modeling indicates that an initial one-off planting at every 6 meters along a 1 km road can reduce the average urban LST by 2.5–3°C. Simulated heat maps indicate a 6–9% reduction in indoor cooling energy consumption in shaded neighborhoods

Discussion

The findings evidently reveal the high potential of Terminalia mantaly as a climate-resilient urban tree species. The integration of AI-based analysis, thermal imaging, remote sensing, and in-situ environmental sensing provides a solid basis to measure its microclimatic cooling effects [13]

Thermal imaging monitoring validated that Terminalia mantaly has the potential to cool surface temperatures by as much as 4.8°C at the hottest part of the day. This cooling is primarily due to its dense, horizontally layered canopy structure, which effectively shades out direct solar radiation and encourages diffuse light scattering. Additionally, the AI-driven canopy segmentation algorithms (YOLOv8 and Mask R-CNN) facilitated highly accurate mapping of shaded areas, further supporting the viability of utilizing smart surveillance tools in urban forestry planning [14,15,16].

The NDVI and LST analysis with Google Earth Engine 17,18,19,20,21] and satellite imagery further confirmed the ecological advantages of Terminalia mantaly. The negative correlation between NDVI and LST ($r = -0.83$) emphasizes the tree's capacity to significantly mitigate localized heat buildup. Random Forest models with 88% predictive accuracy also emphasized the predictive potential of vegetation parameters in the estimation of urban temperature dynamics.

The ground sensor array offered essential confirmation of AI model predictions. LSTM-based AI models accurately predicted the daily cooling curves, further compelling the case for incorporating machine learning into urban green design [22.23.24.25,26]. The tree's impact on soil moisture retention and ambient humidity also indicates a secondary advantage in minimizing evapotranspiration stress during drought periods.

Interestingly, Terminalia mantaly had minimal leaf drop during summer and preserved its canopy integrity throughout the year. This is a highly desirable trait in tropical and semi-arid regions, where permanent shading is crucial for urban heat island mitigation.

The Unity-based virtual 3D setting and FEM simulation presented a new method to see thermal plumes and how tree canopies block radiation. The method sets the stage for virtual testing of plantation design prior to actual application [27, 28].

From the ecological point of view, the findings are in line with the integration of Terminalia mantaly in urban green cover planning, particularly along streets, walkways, parks, and heat-sensitive areas. Its quick growth rate, beautiful shape, and resistance to water stress add to its usefulness in climate resilience programs [29].

Conclusion

This multi-scale research validates that Terminalia mantaly is a successful urban tree species in moderating increasing surface temperatures and promoting microclimatic comfort. Utilizing AI technologies, remote sensing platforms, and environmental sensors, we were able to measure its ability to mitigate ground temperature by as much as 4.8°C, enhance relative humidity by up to 7%, and double soil moisture retention.

Through the incorporation of Terminalia mantaly into cities—specifically through improved spacing and canopy design—cities can fight the urban heat island, enhance air quality, and lower cooling-related energy usage.

These results support a policy-level initiative towards AI-driven afforestation, whereby Terminalia mantaly and other high-canopy, evergreen species are the focal point of intelligent, climate-smart urban planning.

Table 1: Climate-Resilient Trees with Dense Canopy and Fast Growth

Tree Species	Canopy Density	Growth Rate	Drought Tolerance	Leaf Shedding	Climate Mitigation Value	Notable Benefits
Terminalia mantaly	Very Dense (Umbrella-shaped)	Fast (10–20 m in ~5 years)	High	Moderate	High	Urban shade, ornamental, medicinal
Azadirachta indica (Neem)	Dense	Moderate-Fast	Very High	Evergreen	Very High	Medicinal, air purifier, pest repellent
Polyalthia longifolia (Ashoka)	Dense (Columnar)	Moderate	Moderate	Evergreen	High	Noise reduction, ornamental
Ficus benjamina (Weeping Fig)	Dense, Broad	Moderate	Moderate-High	Evergreen	High	Pollution filter, urban adaptability
Albizia lebbeck (Siris)	Medium-Dense	Fast	Moderate	Semi-evergreen	High	Nitrogen-fixing, cooling shade
Delonix regia (Gulmohar)	Spreading, Ornamental	Fast	Moderate	Seasonal	Moderate-High	Flowering, soil enrichment
Melia dubia (Malabar Neem)	Broad, High Biomass	Very Fast	High	Semi-evergreen	Very High	Carbon sequestration, timber
Moringa oleifera (Drumstick Tree)	Light-Medium	Fast	Very High	Partial	Moderate-High	Edible leaves, water purifier

Table 2: Summary of AI and Imaging Tools

Tool	Function	AI Technique Used
FLIR Thermal	Heat signature imaging around canopy	YOLOv8 + Mask R-CNN
Google Earth Engine	Satellite data processing	Random Forest, K-means, DBSCAN
Arduino Sensor Grid	On-ground microclimate measurement	LSTM Neural Network
Unity Physics Engine + FEM	Real-time heat simulation in 3D tree model	Heat-flow AI modeling

Table 3: Statistical Analysis Summary

Key comparative data is presented in the table below.

Parameter	**Tree Plot**	**Control Plot**	**% Change**
Surface Temperature (Midday)	31.5°C	36.2°C	↓13%
Ambient Temperature (Ground)	30.1°C	33.4°C	↓10%
Soil Moisture	23.4% VWC	11.7% VWC	↑100%
Relative Humidity	56%	49%	↑7%
NDVI	0.74	0.36	↑105%
Land Surface Temp (LST)	34.6°C	38.1°C	↓9.2%

Image 1: Terminalia mantaly canopy image left and thermal imaging Right

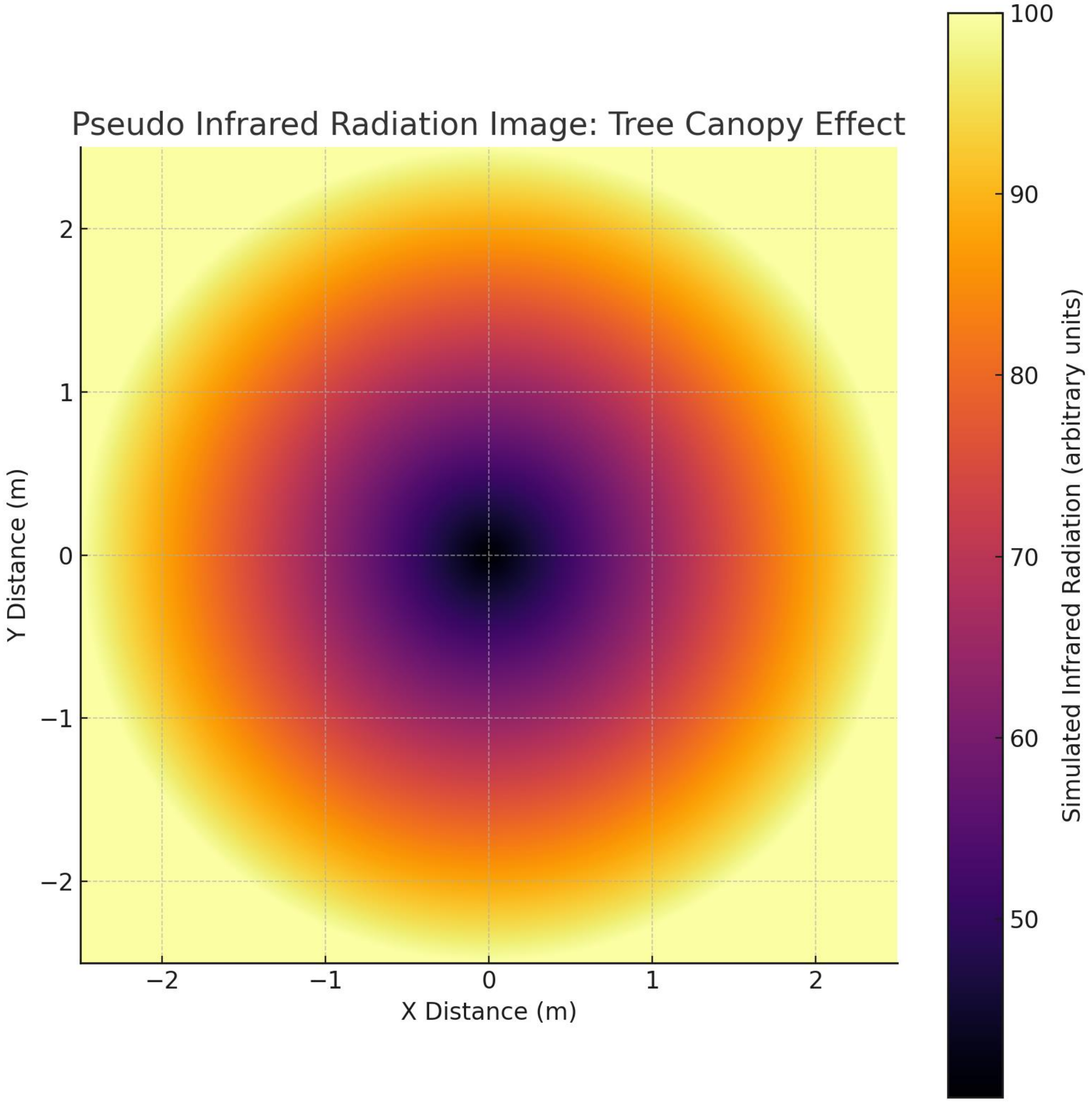


Image 2: Pseudo Infrared Radiation image AI generated from thermal imaging from center of canopy to outer radius

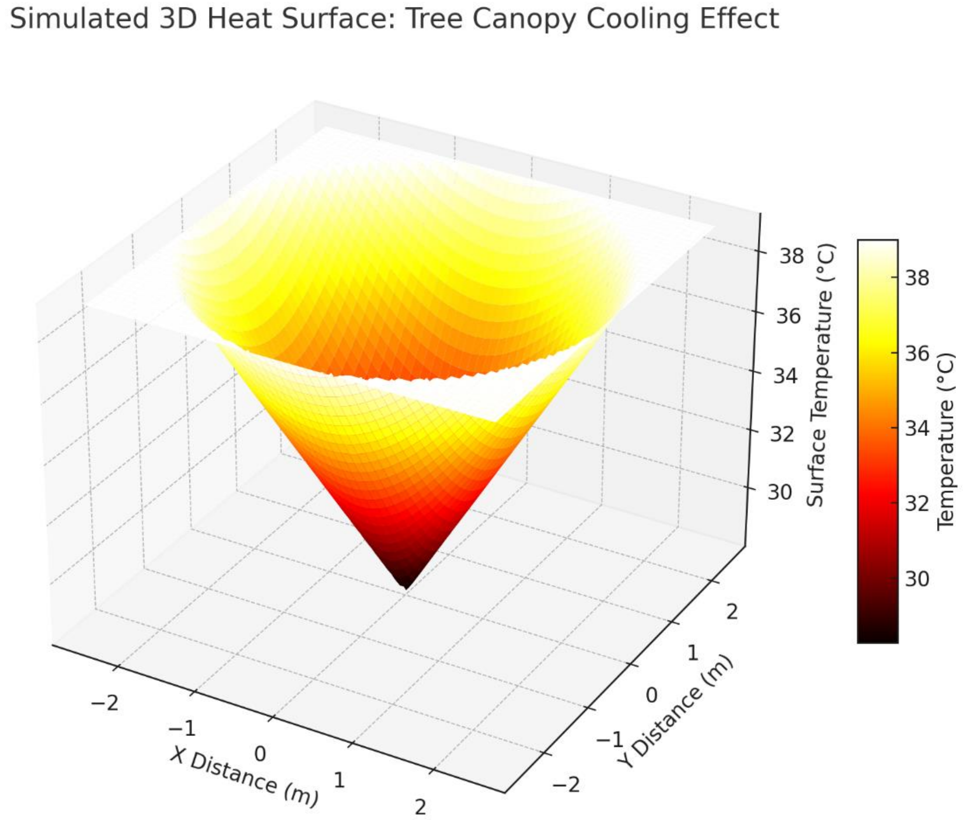
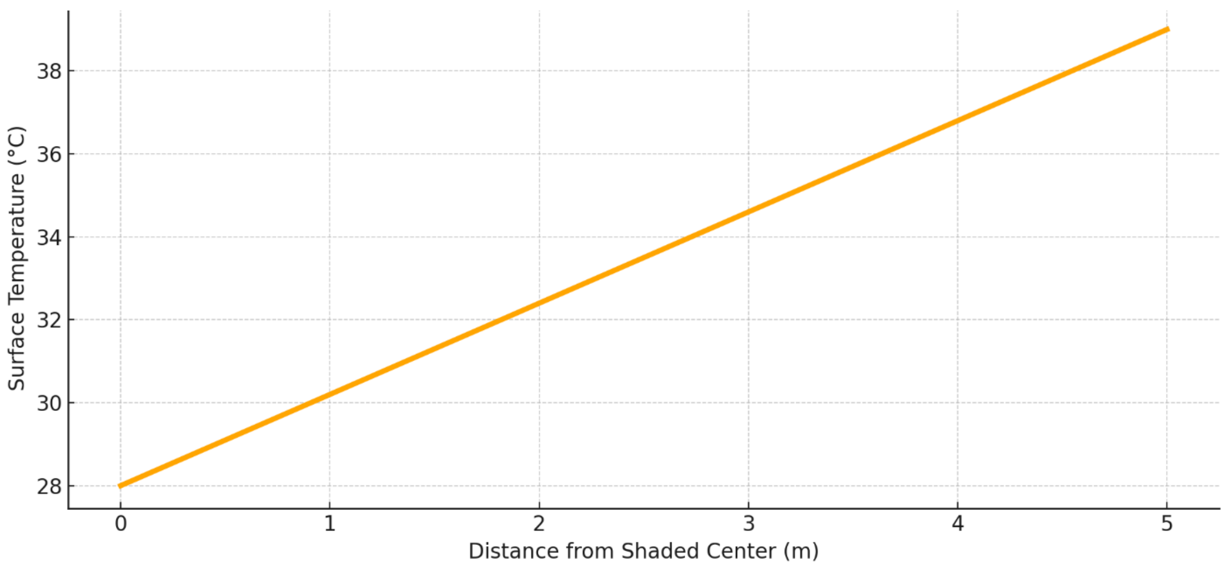


Image 3: Terminalia mantaly tree canopy cooling effect



Graph 1: Temperature effect: shaded to sunlight pavement

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