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Urban Heat Island Effects on Roadside Plant Physiology: A Comparative Study of *Bougainvillea spectabilis* and *Polyalthia longifolia* in Warangal city, Telangana, India

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Abstract

Rapid urbanization and global warming has intensified the Urban Heat Island (UHI) effect, resulting in elevated temperatures and increased environmental stress on urban vegetation. Roadside plants are an essential component of urban green infrastructure, are continuously exposed to high temperature, vehicular emissions, particulate matter, and limited water availability, making them particularly vulnerable to UHI stress. The present study was undertaken to evaluate the impact of Urban Heat Island stress on roadside plant physiology through a comparative assessment of *Bougainvillea spectabilis* and *Polyalthia longifolia* growing under roadside and control conditions in Warangal urban area, Telangana, India.

The study integrated physiological, biochemical and anatomical analyses to assess plant responses to urban heat stress. Physiological parameters such as leaf temperature, relative water content, and total chlorophyll content were estimated. Biochemical parameters including proline content, malondialdehyde concentration, and antioxidant enzyme activity were analyzed to assess osmotic adjustment and oxidative stress. Anatomical adaptations were examined through stomatal density measurements. The results revealed that roadside plants experienced significantly higher leaf temperatures and reduced relative water content compared to control plants, indicating pronounced thermal and dehydration stress under Urban Heat Island conditions. A significant reduction in chlorophyll content was observed in roadside plants, suggesting impairment of photosynthetic efficiency. Biochemical analysis showed increased proline accumulation and enhanced antioxidant enzyme activity in roadside plants, reflecting activation of stress defense mechanisms. Elevated malondialdehyde levels indicated increased oxidative damage, particularly in

Polyalthia longifolia. Anatomical observations revealed reduced stomatal density in roadside plants, representing an adaptive response to minimize water loss under high temperature conditions. This comparative study analysis revealed that *Bougainvillea spectabilis* exhibited greater tolerance to Urban Heat Island stress than the *Polyalthia longifolia*, as evidenced by higher relative water content, better chlorophyll retention, greater proline accumulation, lower lipid peroxidation, stronger antioxidant responses, and effective anatomical adaptations. Hence, the study concludes that *Bougainvillea spectabilis* is a suitable species for roadside and urban landscaping in hot semi-arid cities like Warangal. The findings provide valuable scientific evidence to support climate-resilient urban greening strategies and sustainable management of urban ecosystems under increasing Urban Heat Island conditions.

Keywords: Urban Heat Island; Urbanization; Green infrastructure; Plant physiological parameters

Introduction

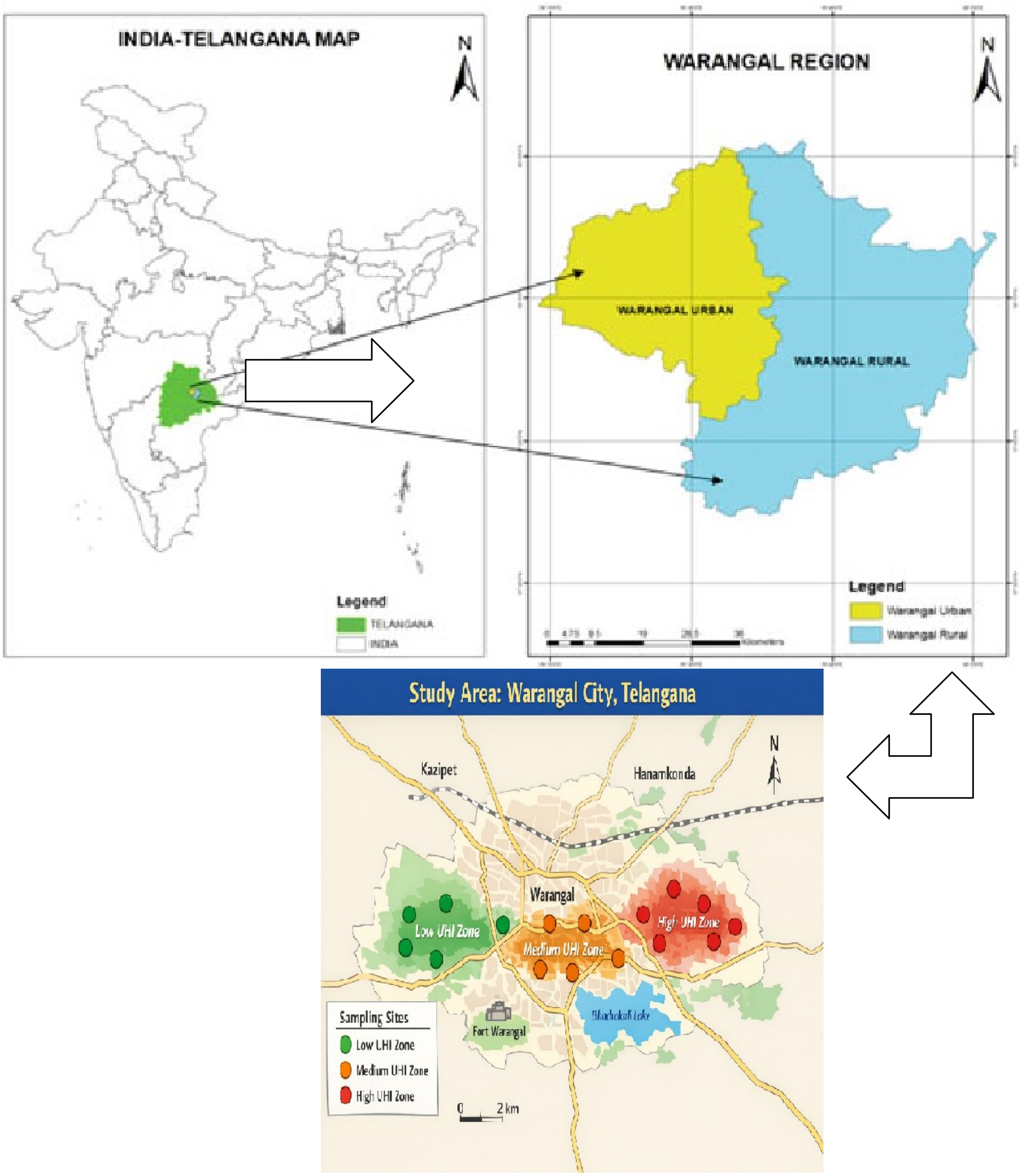
Urbanization is one of the most profound anthropogenic processes influencing the natural environment in the modern era. Rapid expansion of cities leads to an extensive modification of land use patterns, leading to the replacement of natural vegetation, urbanization and other impervious surfaces (Verma et al.,2020). These transformations significantly alter the urban ecosystems and disrupt the natural energy balance, resulting in the development of the Urban Heat Island (UHI) effect, wherein urban areas experience higher temperatures than surrounding rural regions due to anthropogenic heat emissions from vehicles, industries, and air-conditioning systems further intensify urban warming (Manoli et al., 2020; Santamouris, 2020). Impervious surfaces such as asphalt and concrete absorb and retain large amounts of solar radiation during the daytime and release heat slowly during the night, causing sustained elevation of ambient temperature (Arnfield & Mills, 2020). Altered airflow patterns caused by dense infrastructure also limit heat dissipation, contributing to the persistence of high temperatures in urban areas. Elevated urban temperatures have serious implications for human health, energy demand, air quality, and ecological stability (IPCC, 2021). Beyond human systems, Urban Heat Island conditions exert significant stress on urban vegetation by altering plant microclimates and imposing chronic thermal stress, which can affect plant survival, growth, and ecosystem services (Tripathi et al.,2014; Chen et al., 2021).

Urban vegetation plays a crucial role in mitigating the Urban Heat Island effect by providing shade, reducing surface temperatures, enhancing evapotranspiration, and improving air quality (Jenerette et al., 2021; Gupta et al., 2015). Roadside vegetation contributes to temperature regulation, dust trapping, carbon sequestration, and aesthetic improvement of urban landscapes (Kumar et al., 2012). However, roadside plants are continuously exposed to extreme environmental conditions, making them one of the most stressed components of urban ecosystems (Chen et al., 2021; Liu et al., 2022). Urban green spaces and roadside vegetation have been found to reduce ambient temperatures locally, but their effectiveness is moderated by species selection, canopy architecture, and health status of individual plants (Bharathi et al., 2016; Rahman et al., 2021). This study highlights the need to understand species-specific responses to UHI conditions, especially in the context of climate-resilient urban landscaping.

Recent research emphasizes the species-specific nature of UHI responses. Some species with efficient water-use strategies, robust antioxidant systems, and structural adaptations perform relatively better under urban heat stress, while others exhibit pronounced stress symptoms including chlorophyll loss, reduced RWC, and higher levels of lipid peroxidation (Liu et al., 2022; Rahman et al., 2021). This suggests that urban greening and roadside plantation programs must prioritize species with demonstrated adaptive traits to ensure long-term survival and ecosystem function.

Study area:

The study was conducted in Warangal city, located in the northern region of Telangana state, India. It is the second-largest city in Telangana. Warangal experiences a semi-arid tropical climate characterized by high summer temperatures, intense solar radiation, and limited rainfall. During the summer season, ambient temperatures frequently exceed 45°C in summer and heavy monsoons, making the city highly suitable for Urban Heat Island studies.



Materials and Methods

The present investigation was carried out during 2024 to 2025 to evaluate the impact of Urban Heat Island stress on roadside plant physiology using selected ornamental and avenue plant species in Warangal city, Telangana. The study was designed to compare physiological, biochemical and anatomical parameters of plants growing under roadside conditions with those growing under relatively less stressful control environments. The samples were collected from last two consecutive year in different time intervals and standard experimental and analytical procedures were adopted to ensure reliability and reproducibility of the results.

Selection of Plant Species: Two commonly planted roadside plant species were selected for the present study based on their abundance, ecological relevance and contrasting growth habits. *Bougainvillea spectabilis* is an ornamental shrub widely used in urban landscaping and roadside plantations due to its drought tolerance, vibrant floral bracts, and minimal maintenance requirements. It is known to survive under limited water availability and high temperature conditions, making it a suitable model species for studying heat stress tolerance. *Polyalthia longifolia* is a tall, evergreen avenue tree frequently planted along roadsides and medians for its slender growth habit and aesthetic value. Despite its widespread use, limited information is available regarding its physiological response to extreme urban heat stress.

The selection of these two species allowed for a comparative assessment of shrub and tree responses to Urban Heat Island conditions.

1. Sampling Design and Collection of Plant Material: Sampling was carried out during peak summer months (April–May) to capture maximum Urban Heat Island stress effects. Healthy, fully expanded, sun-exposed leaves of similar age and size were collected from roadside and control plants. For each species, leaves were collected from at least five individual plants at each site to ensure representative sampling. Leaf samples were collected during morning hours to minimize diurnal variation in physiological parameters. Immediately after collection, samples were placed in clean polyethylene bags, transported to the laboratory in an ice box, and processed without delay for physiological and biochemical analysis.

2. Measurement of Microclimatic Parameters: Leaf temperature was measured at the sampling sites using a handheld infrared thermometer. Measurements were taken directly from the leaf surface to assess the thermal load experienced by plants under roadside and control conditions. Ambient air temperature was also recorded at each site to correlate plant responses with surrounding microclimatic conditions.

3. Physiological Parameters

3.1 Relative Water Content (RWC): Relative water content was estimated to assess the water status of plant leaves. Fresh weight of leaf samples was recorded immediately after collection. The leaves were then immersed in distilled water for 4-6 hours to obtain turgid weight. Subsequently, the leaves were dried in a hot air oven at 80°C until constant weight was achieved to determine dry weight. Relative water content was calculated using the standard formula:

3.2 Estimation of Chlorophyll Content: Total chlorophyll content was estimated using the Arnon method. Fresh leaf samples were homogenized in 80% acetone and centrifuged to obtain a clear supernatant. Absorbance of the extract was measured at 645 nm and 663 nm using a UV–Visible spectrophotometer. Chlorophyll a, chlorophyll b, and total chlorophyll content were calculated using standard equations and expressed as mg g^{-1} fresh weight.

4. Biochemical Parameters

4.1 Estimation of Proline Content: Proline content was estimated following the method described by Bates et al. Fresh leaf tissue was homogenized in sulfosalicylic acid and centrifuged. The supernatant was reacted with acid ninhydrin and glacial acetic acid, followed by heating in a water bath. The chromophore formed was extracted with toluene, and absorbance was measured at 520 nm. Proline concentration was calculated using a standard curve and expressed as µmol g^{-1} fresh weight.

4.2 Estimation of Malondialdehyde (MDA): Malondialdehyde content, an indicator of lipid peroxidation, was estimated using the thiobarbituric acid (TBA) reaction method. Leaf tissue was homogenized in trichloroacetic acid and centrifuged. The supernatant was mixed with TBA reagent and heated in a water bath. After cooling, absorbance was measured at 532 nm and corrected for nonspecific turbidity at 600 nm. MDA concentration was expressed as nmol g^{-1} fresh weight.

4.3 Antioxidant Enzyme Assays: Catalase activity was estimated by measuring the decomposition rate of hydrogen peroxide spectrophotometrically at 240 nm. Superoxide dismutase activity was determined based on its ability to inhibit the photochemical reduction of nitroblue tetrazolium. Enzyme activities were expressed as units mg^{-1} protein. These assays provided insight into the antioxidant defense mechanisms activated under Urban Heat Island stress.

5. Anatomical Studies: Leaf anatomical studies were conducted to assess structural adaptations under Urban Heat Island conditions. Epidermal peels were obtained using the nail polish impression technique. The peels were mounted on glass slides and observed under a light microscope. Stomatal density was calculated by counting the number of stomata per unit leaf area. Leaf thickness was measured using transverse sections prepared with a sharp blade and observed under a microscope fitted with an ocular micrometer.

The overall experimental design involved a comparative analysis of two plant species grown at roadside and control conditions. Physiological, biochemical, and anatomical parameters were measured using standard protocols to evaluate the impact of Urban Heat Island stress. This integrated approach ensured comprehensive assessment of plant responses and facilitated identification of stress tolerance mechanisms.

Results and Discussion

The present study investigated the impact of Urban Heat Island stress on physiological, biochemical and anatomical parameters of *Bougainvillea spectabilis* and *Polyalthia longifolia* growing under roadside and control conditions in Warangal city. Urban Heat Island conditions significantly influenced the physiological and biochemical performance of both the plant species. Roadside plants exhibited clear symptoms of thermal stress compared with plants growing under relatively less stressful conditions. Leaf temperature increased in roadside plants (38.9 ± 0.54^0C and 41.6 ± 0.73^0C), indicating exposure to elevated urban thermal loads. Such temperature elevation is commonly associated with heat absorption by impervious surfaces and reduced evaporative cooling in urban environments (Singh et al.,2010). Relative water content decreased in plants growing under roadside conditions (71.3 ± 1.15 and 64.5 ± 1.18), reflecting dehydration stress caused by high temperature and limited moisture availability. Maintenance of relatively higher water status in *Bougainvillea spectabilis* suggests greater physiological adaptability.

Table 1. Comparative physiological, biochemical and anatomical responses of *Bougainvillea spectabilis* and *Polyalthia longifolia* growing under control and roadside UHI

Parameter	***Bougainvillea* (C)**	***Bougainvillea* (R)**	***Polyalthia* (C)**	***Polyalthia* (R)**
Leaf Temperature (°C)	32.4 ± 0.48	38.9 ± 0.54	31.8 ± 0.55	41.6 ± 0.73
Relative Water Content (%)	84.6 ± 1.07	71.3 ± 1.15	82.1 ± 0.91	64.5 ± 1.18
Total Chlorophyll (mg g^{-1} FW)	2.40 ± 0.03	1.82 ± 0.05	2.31 ± 0.03	1.48 ± 0.04
Proline Content (µmol g^{-1} FW)	2.12 ± 0.11	6.78 ± 0.39	1.90 ± 0.16	4.90 ± 0.32
Malondialdehyde (nmol g^{-1} FW)	3.24 ± 0.21	5.58 ± 0.24	3.40 ± 0.16	8.10 ± 0.30
Catalase Activity (Units mg^{-1}	18.36 ± 0.61	34.20 ± 0.64	17.88 ± 0.47	26.80 ± 0.70
Stomatal Density (no. mm^{-2})	182.0 ± 5.4	145.4 ± 3.4	215.0 ± 4.0	175.8 ± 3.6

(*Note: V*alues represent mean ± SD (n = 5 replicates) C=Control; R=Replicate)

Chlorophyll content declined in roadside plants, indicating disruption of photosynthetic pigments under heat stress conditions. Similar trends have been reported in urban vegetation exposed to high temperature and pollution stress (1.82 ± 0.05 and 1.48 ± 0.04). Proline accumulation increased in roadside plants, indicating osmotic adjustment and protective metabolic responses to environmental stress. Proline is known to stabilize proteins and cellular membranes under stress conditions. Lipid peroxidation increased in roadside plants, reflecting oxidative damage caused by reactive oxygen species. However, oxidative damage was more pronounced in *Polyalthia longifolia*, indicating greater susceptibility to heat stress. Antioxidant enzyme activity increased in roadside plants, suggesting activation of defense mechanisms that help neutralize reactive oxygen species and protect cellular components. Anatomical analysis revealed reduced stomatal density in roadside plants (145.4 ± 3.4 and 175.8 ± 3.6). Such structural changes may represent adaptive strategies to reduce water loss under high temperature conditions. Overall, *Bougainvillea spectabilis* demonstrated better physiological stability and stress tolerance compared with *Polyalthia longifolia*, indicating its suitability for roadside plantations in hot semi-arid urban environments.

Conclusion

The results clearly demonstrate that elevated urban temperatures significantly alter plant physiological balance, induce oxidative stress, and trigger adaptive responses at biochemical and anatomical levels. The findings of this study are consistent with recent global research emphasizing that plant responses to Urban Heat Island stress are highly species-specific and dependent on physiological plasticity and adaptive capacity (Rahman et al., 2021; Zhang et al., 2022). The superior performance of *Bougainvillea spectabilis* suggests that drought-tolerant and stress-resilient species are better suited for roadside plantations in hot semi-arid cities. In conclusion, the study highlights the critical importance of scientific evaluation of plant species for urban greening programs. Selection of heat-tolerant species such as *Bougainvillea spectabilis* can enhance survival, reduce maintenance costs, and improve ecosystem services in cities experiencing increasing Urban Heat Island effects.

Future Scope

Future research should focus on long-term monitoring of urban vegetation to better understand seasonal and spatial variations in plant responses to UHI stress. Integration of remote sensing and Geographic Information System (GIS) techniques can also help map UHI intensity and evaluate vegetation performance across urban landscapes (Rahman et al., 2021; Zhang et al., 2022). Additionally, comparative studies involving a wider range of native and exotic plant species are necessary to identify climate-resilient species suitable for sustainable urban greening and heat mitigation in rapidly urbanizing tropical cities.

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Conflict of interest: The authors declare that there is no conflict of interest in publication of the present article.

Ethical issues: None

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