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Green areas on highways and streets: a comprehensive study of the benefits and challenges of implementing vegetation on roadways

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Abstract. With the rapid expansion of urban areas, roadside green infrastructure has become a critical element of sustainable urban planning. While green areas along highways and streets occupy a relatively small share of the urban carbon sink, they provide disproportionate ecological and social benefits, including improved air quality, carbon sequestration, effective stormwater management, heat island mitigation, and support for biodiversity. This study employs a qualitative comparative case study approach, drawing on literature and policy analysis from Kyoto (Japan), Hangzhou (China), and Riyadh (Saudi Arabia), to evaluate how differing climatic and urban contexts shape the design, performance, and challenges of roadside vegetation. The findings highlight that canopy type, planting methodology, and policy frameworks have a strong influence on the effectiveness of RGI, particularly in regulating temperature, controlling pollution, and supporting ecological connectivity. However, the study also identifies common challenges across contexts, such as spatial constraints, high maintenance demands, and vulnerability to climate extremes. Addressing these issues requires integrated strategies that combine ecological design, long-term governance, and context-specific policies. The paper concludes by emphasizing that effective roadside greening can enhance urban resilience, provided it is supported by informed planning and sustained management.

Keywords: urban vegetation, street trees, roadside landscaping, carbon sequestration, urban tree management

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Introduction

Even the most diminutive natural elements may effectuate substantial transformation in the urban milieu. Trees serve as the city's "lungs" and reservoirs of "carbon stock", while landscaping approaches often reflect cultural significance, emotions, and symbolism. In addition to aesthetics, these aspects impact human psychology and bring movement and energy to otherwise boring urban landscapes [1]. The built environment is primarily influenced by transportation infrastructure, which has enduring impacts on mobility systems as well as the broader environmental, economic, and social framework [2, 3]. Highways are vital to national development initiatives, serving as crucial infrastructure that addresses social needs and supports economic progress.

Cities distinguished by their "green" character are increasingly imperiled by the deterioration of natural components, especially street trees. Landscapes are influenced by several human factors, including land use, urban design configurations (e.g., roadway layouts), vandalism, and stewardship [4]. Intense traffic volumes exacerbate the deterioration of roadside vegetation [5]. Consequently, roadside air quality has become a significant public health issue. In Europe, vehicular traffic was responsible for around 60% of particle number emissions in 2010, with concentrations in heavily trafficked urban areas reaching as high as 90% [6]. Vulnerable establishments, including educational institutions, healthcare facilities, and the residential regions situated within 150 meters of main thoroughfares, face heightened danger.

Urban habitats impose particularly severe circumstances on trees, characterized by thermal stress, suboptimal soils, drainage complications, and spatial constraints. Inadequate planting tactics may result in resource wastage and tree death. Meticulous consideration of species selection, planting timing, and ecological conditions is essential for ensuring survival [7].

Empirical research substantiates the ecological significance of roadside plantings. In Nagpur, India, avenue plantings and institutional landscapes featured a diverse array of trees, with roadside plants yielding the most biomass due to their larger tree diameters [6]. Mediterranean Cypress barriers in Istanbul lowered nanoparticle concentrations by as much as 37%, yielding direct health advantages for pedestrians [6]. These examples demonstrate that well-designed roadside vegetation promotes air quality, reduces surface temperatures, enhances thermal comfort for walkers, and reduces carbon footprints.

Nevertheless, obstacles persist. Restricted tree-pit dimensions, inadequate drainage, and soil compaction often impede sustained growth [8]. Although several studies emphasize the comfort of car occupants, surveys indicate that drivers usually underestimate the benefit of roadside plantings, despite their extensive ecological and public health importance [9]. This contradiction underscores the need for comprehensive strategies that integrate transportation, health, and environmental concerns.

Sustainable road-building approaches are increasingly being used. Green roads constructed using carbon-neutral or recycled materials can help reduce emissions, absorb excess heat, and decrease dependence on natural resources [10]. These strategies correspond with international climate objectives and provide an opportunity to integrate roadside green infrastructure (RGI) with sustainable engineering methodologies.

Conceptual background

Principles of RGI. RGI encompasses the integration of vegetation and ecological design into transport corridors to deliver multiple benefits, including pollution reduction, temperature regulation, and biodiversity enhancement. Vegetation can act as both a filter and a barrier, capturing fine particles on its leaves and thereby reducing human exposure. However, dense vegetation may also restrict airflow, potentially leading to localized pollutant buildup [11].

Airborne particulate matter (PM) and ultrafine particles (UFPs), primarily emitted by vehicles, pose a significant health hazard [12]. Roadside trees can reduce exposure for pedestrians, cyclists, and residents, though the effectiveness varies by canopy structure, density, and species-specific tolerance to air pollution [13, 14]. Highway vegetation acts as a porous medium, influencing airflow, pollutant dispersion, and deposition [15, 16]. In this way, roadside trees are not merely ornamental - they serve as living infrastructure, providing measurable ecological services [17].

Considerations for the selection of species. Species selection is a cornerstone of successful RGI. Criteria include growth rate, drought and pollution tolerance, canopy density, and lifespan [7]. Tree girth and canopy architecture are also critical: dense, broad canopies improve shading and particulate capture but may trap pollutants in narrow street canyons [12]. Optimal species, therefore, balance pollution removal capacity with site-specific spatial and climatic constraints [1,18].

Biodiversity considerations extend beyond trees to include associated insects, birds, and pollinators, which rely on roadside vegetation as habitat and movement corridors [19]. Tree selection should therefore favor species that support diverse ecological interactions, enhancing urban biodiversity resilience. However, trade-offs exist: long-lived species grow slowly, while fast-growing trees often have short lifespans [20]. Proactive planning must therefore combine functional, ecological, and aesthetic criteria in species choice.

Components of RGI. The efficacy of RGI is contingent upon both biological and structural elements. Essential elements include tree-pit dimensions, drainage conditions, pruning intensity, adjacent land use, sidewalk width, and the existence of bicycle paths or tree guards [4]. The urban environment influences the interaction of these components with pollution loads and human use.

Sustainable engineering approaches complement RGI by enhancing vegetation. Green roads built using recycled or carbon-neutral materials, such as fly ash, slag, rice husk ash, synthetic rubber, or plastic, decrease greenhouse gas emissions and improve road durability [10]. This integration converts roadways from carbon-intensive to environmentally beneficial infrastructure.

The nascent idea of green corridors - transport pathways aimed at enhancing fuel economy, minimizing CO_2 emissions, and fostering biodiversity - demonstrates the intersection of ecological design and transportation planning [21]. International instances, such as Denmark and Vatican City attaining carbon neutrality, illustrate how RGI and green roads may aid in accomplishing global sustainability objectives.

The methodology

This study employs a qualitative, comparative case study methodology, complemented by a critical literature review, to investigate the components, performance, and challenges of roadside green infrastructure (RGI) in urban environments. Three cities - Kyoto, Japan; Hangzhou, China; and Riyadh, Saudi Arabia were selected based on their contrasting climate zones, urbanization patterns, and distinctive green infrastructure practices. The research proceeded in three stages:

1) Document analysis - a review of peer-reviewed publications, policy reports, and case studies (2014–2023) with an emphasis on urban ecology, environmental engineering, and landscape planning.

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2) Comparative analysis – evaluation of key RGI parameters, including: tree species selection and canopy types, planting methodologies, temperature control, air pollution mitigation, and biodiversity value.

1-Table. Comparative overview of RGI practices in Kyoto, Hangzhou, and Riyadh.

Indicator	Kyoto, Japan	Hangzhou, China	Riyadh, Saudi Arabia
Urban context	Dense, historic city; compact urban form	Rapidly urbanizing megacity; mix of old/new districts	Low-density, car-dependent metropolis
Climate zone	Moderately humid climate, with a pronounced urban heat island effect	Humid subtropical climate, hot and humid summer	Arid climate, extremely high summer temperatures
Dominant canopy type	Mixed deciduous–evergreen (e.g., Zelkova, Ginkgo, Camphor trees)	Broadleaf deciduous and evergreen mix (e.g., Platanus, Cinnamomum, Osmanthus)	Drought-tolerant evergreen species (e.g., Date palm, Acacia, Conocarpus)
Planting methodology	Narrow tree pits with stone grates;emphasis on aesthetic alignment with streets	Large avenue plantations; integration with parkways and waterways	Spaced plantings along wide boulevards; irrigation-supported roadside plantations
Pollution control methods	Vegetation barriers near traffic corridors; emphasis on particulate capture	Green corridors with layered vegetation; integration of water bodies for cooling	Limited direct air filtration; emphasis on dust suppression and shading
Temperature regulation	Shading + evapotranspiration reduce the surface heat island	Combined shading + water cooling effects in summer	Shade provision primary; high evapotranspiration limited by aridity
Biodiversity value	Supports pollinators and native urban fauna	High tree diversity enhances bird and insect populations	Limited diversity; mostly monocultures adapted to arid soils
Unique challenges	Space constraints in historic districts; root	High urban growth pressures; risk of	Extreme heat, scarce water, soil salinity; high cost of irrigation maintenance

	confinement in narrow pits	monoculture disease outbreaks	
Tree survival rate factors	Soil compaction, limited pit volume	Competition for space with infrastructure; intensive maintenance needed	Dependence on artificial irrigation; vulnerability to drought and water scarcity
Policy/management focus	Strong emphasis on cultural landscape preservation	Integration of “eco-civilization” policies into urban greening	Strategic greening in line with Vision 2030 sustainability goals

3) Performance indicators – identification of measurable outcomes, such as: decline in the temperature of the air and the surface; Pollutant absorption efficacy (e.g., PM2.5, NOx); Spatial configurations and tree survival rates (e.g., the design of tree pits, the presence of grates); The influence of land use patterns on the sustainability of vegetation.

This comparative paradigm aims to provide context-specific insights on optimizing RGI to mitigate environmental stresses while improving urban resilience and livability.

Comparative case studies

Kyoto city, Japan

In Kyoto, Japan, a study highlights the relationship between local land use planning and the growth of street trees, which are considered essential ecological assets. These trees provide ecological connectivity, alleviate heat island effects, and support wildlife. Effective street tree planting involves careful design, selection of appropriate species, and measures to protect them from pedestrian damage. Local planners have enhanced tree conditions through detailed attention to planting strategies, reflecting the complex factors influencing urban success in developed regions [6].

Hangzhou city, Zhejiang province, China

Roadside trees are vital to urban forests, enhancing the environment by cooling and humidifying air during summer through solar radiation management. However, quantifying their impact on air temperatures is challenging due to their complex 3D structures and varying planting types. Research in China indicated that umbrella canopy designs yield the best cooling effects, while columnar shapes provide the least benefit. Canopy cover reduces the amount of solar energy reaching road surfaces, thereby helping to lower air temperatures. The cooling and humidification effects are closely linked to canopy shape, with species featuring pileate, spherical, or high pyramidal canopies recommended for plantings along highways. Two-sided plantings are also advocated for metropolitan areas [22].

Riyadh’s green highway

The thoughtful landscape strategy for highways in Saudi Arabia enhances not only aesthetics but also functionality, fostering increased tree cover and biodiversity, and creating urban ecological corridors. This design approach reflects the understanding of the past, rooted in the Elemental Heritage of Saudi Arabia, which influences the city's evolution through culture, ecology, history, architecture, and topography. By integrating these factors, the design preserves historical

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and cultural elements while ensuring development, emphasizing a balance of the core elements: Fire, Earth, Water, and Wind. To highlight the similarities and differences across the three contexts,

Table 1 presents a comparative overview of RGI practices, linking canopy types, planting methods,
and key challenges in Kyoto, Hangzhou, and Riyadh.

Challenges and future direction

Despite proven benefits, roadside plantations remain highly vulnerable in rapidly urbanizing regions. In Asia, mature trees are frequently removed to accommodate road widening, metro corridors, or subterranean infrastructure such as gas lines and sewage systems [3,7]. These pressures result in fragmented planting strips, reduced soil volumes, and higher mortality rates.

Future directions for RGI must address three interlinked challenges:

- *Spatial constraints* – ensuring adequate soil, drainage, and continuous planting strips rather than isolated pits;
- *Biodiversity protection* – integrating ecological restoration and corridor planning into roadside design [19];
- *Governance and perception* – overcoming the undervaluation of vegetation by motorists and ensuring long-term stewardship.

Findings/Discussion

Structural and biological factors influencing RGI performance. Efficient RGI depends on the harmonious integration of biological and structural elements. In the three case studies, several crucial elements were consistently recognized as vital for success: (i) the choice of pollution-resistant and rapidly growing species, (ii) regular maintenance practices including pruning and canopy management, and (iii) adequately sized and continuous tree pits to facilitate healthy root growth [1, 20]. Complementary infrastructure components - such as bike lanes, flowerbeds, and expansive sidewalks - are similarly significant in mitigating soil compaction and protecting root zones from trampling [23]. These approaches, when combined, promote resilient canopies, enhance pollution collection efficiency, and promote ecological stability in densely populated urban environments.

Climatic and ecological advantages. Unique meteorological and urban characteristics influenced the environmental benefits of RGI in each location.

- Kyoto, Japan: Low-canopied, terrestrial trees improved ecological connectedness and alleviated the urban heat island phenomenon. Meticulous species selection yielded elevated survival rates, especially in settings of space limitation [6].
- In Hangzhou, China, umbrella-shaped canopies lowered surface air temperatures by as much as 2.5 °C relative to asphalt, while dual-sided roadside plants enhanced shade and soil moisture retention [22].
- Riyadh, Kingdom of Saudi Arabia: In the dry environment, green roadway designs created ventilation corridors that enhanced microclimatic comfort. These techniques amalgamate ecological design with cultural legacy, underscoring the synergy between contemporary infrastructure and old environmental wisdom.

Comprehensive research indicates that canopy shape has a significant impact on air pollution deposition, ventilation, and temperature regulation. Porous vegetation may promote the dispersion of pollution, but thick foliage can entrap delicate particulate matter in urban street canyons, exacerbating near-road air quality. This highlights the importance of tailoring canopy design to individual sites. Socio-ecological issues. Notwithstanding their advantages, RGI initiatives encounter considerable limitations.

The fast urban growth in Asian megacities often results in the elimination of older trees, creating fragmented and narrow planting strips with reduced ecological efficacy [23]. Recently planted roadside trees have experienced elevated death rates due to vandalism, inadequate care, grazing pressures, and persistent exposure to automobile pollution [20]. In India, roadside plantings face significant biotic stressors, including encroachment, overcrowding, and fires, which compromise their long-term viability despite extensive planting initiatives [20].

The urban form also presents issues. Elevated roadway canyons impede ventilation and entrap pollutants, exacerbating exposure levels for pedestrians [23]. Although barriers, such as fences or plant belts, help mitigate traffic-related air pollution (TRAP), they may also raise societal concerns over accessibility, aesthetics, and fire hazards [26, 32]. Moreover, conflicts between root systems and urban infrastructure (e.g., sidewalks, drainage systems) hinder the long-term viability of RGI projects [20].

Innovative practices and future directions*.* Emerging strategies demonstrate how RGI can evolve beyond conventional street tree planting. Incorporating recycled materials, including fly ash, plastics, and steel slag, into pavement construction improves road durability while lowering CO_2 emissions [24]. Similarly, Low Impact Development (LID) practices, such as rainwater harvesting for irrigation in Taichung (Taiwan), integrate water-sensitive design into transportation infrastructure [27]. Bioengineering techniques, including slope stabilization with native vegetation, further enhance erosion control and reduce landslide risks [28, 29]. At the global level, advanced climate mitigation approaches, including direct air capture and peatland restoration, underscore the importance of integrating urban RGI with broader negative-emission strategies [24]. While resource-intensive, these technologies complement the immediate benefits of strategically placed vegetation, which captures pollutants most effectively when located near emission sources [30]. Policy implications for urban planners*.* The comparative evidence from Kyoto, Hangzhou, and Riyadh suggests several actionable insights:

- Structural design is decisive: Canopy shape, pit size, and planting layout influence pollutant control more strongly than species choice alone [11, 23].
- Context-specific approaches are essential: Cooling should be prioritized in humid regions (Hangzhou), ventilation in the arid areas (Riyadh), and ecological connectivity in dense historic districts (Kyoto) [6, 22].
- Socio-ecological resilience must be built in: Without adequate maintenance, protection from vandalism, and adaptation to local biotic pressures, even well-designed RGI projects suffer high mortality [20].
- Circular economy and eco-design add value: Recycled construction materials, water-sensitive designs, and ecosystem-based engineering practices improve both sustainability and cost-effectiveness [24, 27].

In sum, RGI has demonstrated strong potential to mitigate air pollution, reduce thermal stress, and enhance urban biodiversity. Yet, its long-term effectiveness depends on balancing ecological, structural, and socio-economic factors while adopting context-sensitive planning frameworks that align with both local and global sustainability goals.

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Conclusion

This comparative analysis of RGI in Kyoto, Hangzhou, and Riyadh highlights the commonalities and unique challenges of implementing urban vegetation policies in diverse climatic and cultural contexts. Kyoto exemplifies the significance of ecological connectedness in densely populated urban environments, Hangzhou showcases the cooling capabilities of umbrella-shaped canopies, and Riyadh highlights the need for ventilation corridors in desert regions.

The results validate that structural elements - such as canopy type, planting arrangement, and tree pit design - are crucial for reducing pollution and managing thermal conditions. Nonetheless, these advantages are often compromised by socio-ecological obstacles, such as insufficient maintenance, biotic stressors, and urban encroachment. Innovative strategies, such as the use of recycled materials, water-sensitive design, and bioengineering methods, offer promising avenues for enhancing resilience and sustainability.

The policy implications are evident: urban areas must implement context-specific, multi-faceted solutions that emphasize structural design, guarantee long-term maintenance, and integrate circular economy concepts. Consequently, roadside green infrastructure may transition from a decorative element to an essential aspect of climate-responsive and socially resilient urban development.

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No conflicts of interest.

The contribution of the authors.

Quratulain Saifullah – conceptualization, methodology, international case study review, manuscript writing (initial draft);

Muhammad Faisal Rehman – data analysis, literature review, visualization, editing;

L.A. Zhaksylykova – contextual adaptation, validation of conclusions, critical review of manuscript;

A.M. Saurbayeva – supervision, academic editing, structure development, final proofreading;

K.K. Arynov – scientific advising, overall project leadership.

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Автомагистральдер мен көшелердегі жасыл аймақтар: жол бойына өсімдіктер отырғызудың артықшылықтары мен қиындықтарына жан-жақты шолу

Аңдатпа. Қалалық аумақтардың қарқынды кеңеюімен бірге жол бойындағы жасыл инфрақұрылым орнықты қала жоспарлаудың маңызды элементіне айналуда. Дегенмен, автомагистральдар мен көшелер бойындағы жасыл аймақтар қалалық көміртек сіңіргішінің салыстырмалы түрде шағын үлесін алатын болса да, олар экологиялық және әлеуметтік тұрғыдан айтарлықтай пайда әкеледі. Олардың қатарында ауаның сапасын жақсарту, көмірқышқылды сіңіру, нөсер суларын тиімді басқару, «қалалық жылу аралы» әсерін төмендету және биоалуантүрлілікті қолдау бар. Бұл зерттеуде Киото (Жапония), Ханчжоу (Қытай) және Эр-Рияд (Сауд Арабиясы) қалаларындағы әдебиеттер мен саясаттық талдауға негізделген сапалық салыстырмалы кейс-стади әдісі қолданылып, әртүрлі климаттық және урбанистік жағдайлардың жол бойындағы көгалдандырудың жобалануына, тиімділігіне және қиындықтарына қалай әсер ететіні бағаланады. Зерттеу нәтижелері тәждің түрі, отырғызу әдістері және саяси шеңберлер жасыл инфрақұрылымның тиімділігіне, әсіресе температураны реттеу, ластануды бақылау және экологиялық байланыстылықты қамтамасыз етуге айтарлықтай ықпал ететінін көрсетті. Сонымен қатар, барлық контекстер үшін ортақ мәселелер анықталды: кеңістіктің шектеулілігі, жоғары күтім шығындары және климаттық төтенше жағдайларға осалдық. Бұл мәселелерді шешу үшін экологиялық жобалау, ұзақ мерзімді басқару және контекстке сәйкес саясатты үйлестіретін кешенді стратегиялар қажет. Қорытындылай келе, тиімді жол бойы көгалдандыру қалалардың тұрақтылығын арттыра алады, егер ол сауатты жоспарлау және жүйелі басқарумен қамтамасыз етілсе.

Түйін сөздер: қалалық өсімдіктер, дала ағаштары, жол жиегін көгалдандыру, көміртекті сіңіру, қалалық ағаштарды басқару.

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Зелёные зоны вдоль автомагистралей и улиц: комплексный взгляд на преимущества и вызовы внедрения растительности в дорожную инфраструктуру

Аннотация. С быстрым расширением городских территорий придорожная зеленая инфраструктура становится важнейшим элементом устойчивого городского планирования. Несмотря на то что зеленые зоны вдоль автомагистралей и улиц занимают относительно небольшую долю городского углеродного поглотителя, они обеспечивают несоразмерно большие экологические и социальные преимущества, включая улучшение качества воздуха, секвестрацию углерода, эффективное управление ливневыми водами, снижение эффекта городского теплового острова и поддержку биоразнообразия. В данном исследовании используется качественный сравнительный метод кейс-стади, основанный на анализе литературы и политических стратегий в Киото (Япония), Ханчжоу (Китай) и Эр-Рияде (Саудовская Аравия), для оценки того, как различные климатические и урбанистические контексты влияют на проектирование, эффективность и проблемы придорожной растительности. Результаты показывают, что тип кроны, методы посадки и политические рамки оказывают значительное влияние на эффективность зеленой инфраструктуры, особенно в регулировании температуры, контроле загрязнения и поддержке экологической связанности. Однако исследование также выявило общие проблемы для всех контекстов, такие как пространственные ограничения, высокая потребность в уходе и уязвимость к климатическим экстремумам. Решение этих вопросов требует интегрированных стратегий, сочетающих экологический дизайн, долгосрочное управление и контекстно-специфическую политику. В заключение подчеркивается, что эффективное озеленение дорожных территорий может повысить устойчивость городов при условии его поддержки грамотным планированием и постоянным управлением.

Ключевые слова: городская растительность, уличные деревья, озеленение вдоль дорог, углеродный баланс, управление городскими деревьями.

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