Review Paper:

Assessment of tools and methods for urban green infrastructure with Emphasis on carbon storage in India

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Abstract

Urban Green Infrastructure (UGI) has become a pivotal framework for addressing the interwoven challenges of rapid urbanization, climate change and environmental degradation, thereby ensuring sustainable urban development. This study presents a comprehensive review of diverse methodologies, planning tools including the Green Infrastructure Gauge (GIG) and Urban Green Space Index (UGSI) and compelling case studies that underscore UGI's role in fostering resilient and liveable urban environments. This study highlights the multifaceted benefits of UGI, notably in climate change mitigation, urban heat island reduction, biodiversity conservation, enhanced human well-being, addressing socio-economic disparities and air pollution. Despite these significant advantages, the review acknowledges persistent challenges in UGI implementation, such as limited stakeholder awareness, financial constraints, inadequate inter-agency collaboration and policy integration hurdles.

Furthermore, the study explores UGI's potential for carbon sequestration and biomass management, reinforcing the necessity of holistic urban planning frameworks to optimize ecological and social advantages. The findings firmly establish UGI as not merely an environmental necessity but a strategic imperative for sustainable urban development. This study asks for future research focused on refining UGI assessment tools and methodologies, exploring innovative financing mechanisms and strategic approaches and fostering enhanced stakeholder engagement. Ultimately, prioritizing investment and research in UGI is crucial for cities to enhance their resilience, to improve residents' quality of life and to contribute substantively to global sustainability goals, building truly resilient and liveable urban futures.

Keywords: Urban Green Infrastructure, Sustainable Urban Development, Climate Resilience, Ecosystem Services, Nature-Based Solutions, Urban Planning, Smart Growth.

Introduction

Climate change impacts are intensifying globally, necessitating adaption strategies increasingly crucial in environmental sciences. Simultaneously, rapid urbanization is driving to densification and expansion of cities, often resulting in the reduction of urban green spaces. This trend is particularly concerning given that human health and well-being remain fundamentally linked to access to nature[64]. The integration of natural environment within urban setting has become increasingly evident. These spaces should be designed to seamlessly integrate public use, to promote healthy lifestyles through sustainable food systems, mitigating the climate change impacts and preserving biodiversity[98].

A critical need exists to meticulously study and strategic plan for the expansion of existing towns and development of new towns and communities. This necessity encompasses comprehensive planning from conceptualization and design to implementation and management, to ensure the creation of sustainable, resilient and livable communities. Contemporary urban development strategies, particularly smart growth principles, offer evidence-based frameworks for reshaping urban spaces, representing an evolution in urbanization approaches supported by quantifiable outcomes.

Urban Green Infrastructure (UGI) has emerged as a key framework for advancing sustainable urban development[52]. UGI refers to interconnected networks of green spaces, encompassing both natural elements such as waterways and woodlands and constructed features, including parks and community gardens. UGI is recognized across disciplines from planning and design to science and engineering for its capacity to deliver a wide range of ecosystem services that benefit both human well-being and environmental health[16].

Urban Green Infrastructure (UGI) serves as a comprehensive framework for delivering ecosystem services in urban environments, offering evidence-based strategies for long-term resource management.

As illustrated in Figure 1, UGI contributes significantly to urban sustainability by providing a confluence of environmental, economic and social benefits. Figure 2 presents a comparative analysis between conventional and green infrastructure systems, highlighting their distinct characteristics and operational differences. UGI provides numerous documented benefits, including urban heat island mitigation, crime reduction, enhanced property values, improved air quality and human well-being, aesthetic enhancement, biodiversity conservation and carbon sequestration[92]. Furthermore, UGI aligns seamlessly with landscape and regional planning frameworks, making it a highly integrative tool for sustainable urban development[102].

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UGI plays a critical role in mitigating the impacts of climate change in urban and peri-urban areas. This crucial role is consistently underscored in both scientific discourse and the development of urban strategies and frameworks[21]. The ecological, social and economic benefits of UGI have established it as a key instrument in city management and policymaking, contributing to urban resilience and sustainable development. UGI functionality is fundamentally shaped by its temporal and spatial scales, which directly influence the benefits it provides[10] and introduce variability across different policy levels[8].

In recent decades, the increasing integration of UGI in urban areas and its promotion within planning and policy frameworks have elevated its importance as a research focus. This is particularly evident in studies focusing on the provisioning of ecosystem services that enhance quality of life and contribute to the sustainability of urban development[9]. Numerous studies have focused on defining Green Infrastructure (GI) as an evolving concept shaped by diverse approaches and scopes[29]. In contrast, research dedicated to the classification of GI is notably scarce[11]. Expanding this area of research is essential for enhancing our understanding of GI's role in urban planning and its implementation in sustainable development practices.

Researchers have developed various urban planning models including the smart city, compact city, green city and livable city, to address critical challenges in urban areas. However, determining the most sustainable urban planning and management paradigm remains an unresolved and crucial question[22]. A holistic understanding of sustainability is essential for achieving sustainable urban development, encompassing various concepts, approaches, methods, tools and evaluation techniques[43]. This review aims to address critical gaps by investigating the following:

1. The methods, principles, approaches, parameters and tools employed in urban Green Infrastructure (GI) planning;
2. Case studies of Urban Green Infrastructure (UGI) implementation across diverse urban contexts;
3. Frameworks developed for UGI planning specific to carbon sequestration and stormwater/flood management;
4. Typological classifications and terminologies applicable to these case studies and methodologies and
5. Potential approaches for translating these findings into a comprehensive conceptual framework for future UGI planning.

Review of Literature

Relevant research on Green Infrastructure (GI) planning in urban areas was developed by Ferrari et al[18] as a systematic methodology for identifying and expanding priority areas for GI implementation.

The approach utilized Urban Atlas classifications to map existing GI within a municipality and employed Morphological Spatial Pattern Analysis (MSPA), implemented via the free software toolbox GUIDOS, to identify essential GI components such as hubs (core areas) and links (bridges).

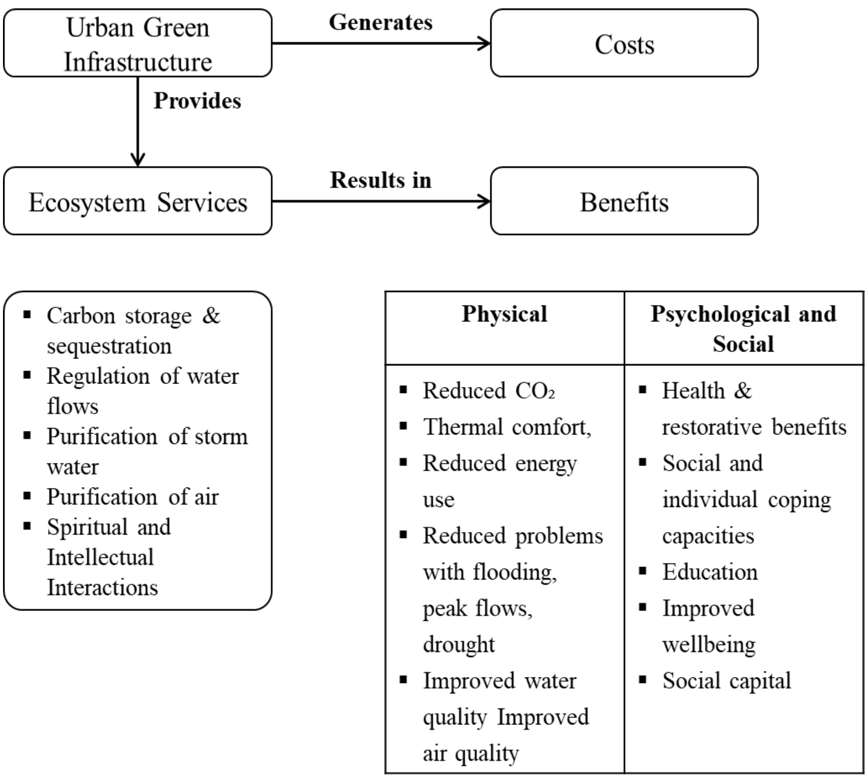

Figure 1: Framework for ecosystem services delivery by Urban Green Infrastructure

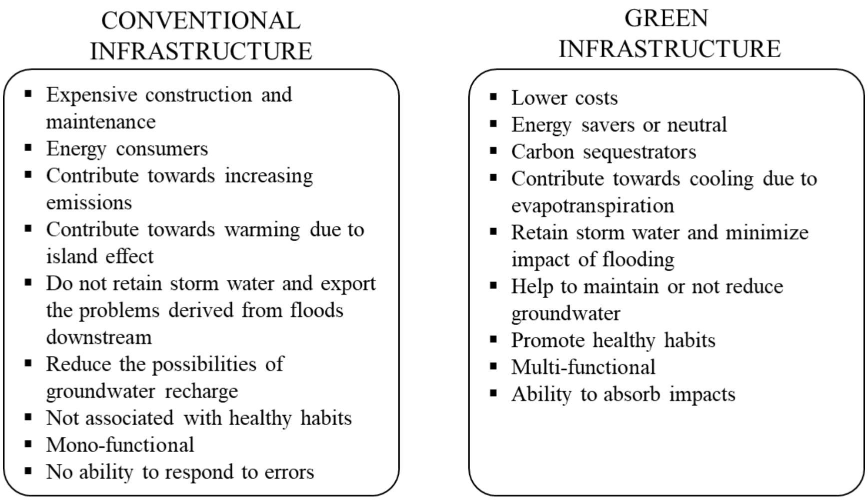

Figure 2: Differences between conventional infrastructures and green infrastructures

The researchers then conducted scenario modelling that incorporated existing GI and agricultural lands within a 300-meter buffer zone from developed areas. Their analysis demonstrated that converting approximately 8,000 hectares of agricultural land to GI elements could significantly improve connectivity while limiting urban sprawl. This methodology aimed to assist decision-makers in integrating Nature-Based Solutions (NBS) into urban planning and enhance overall GI connectivity.

Huang et al[32] employed a multi-method approach to construct integrated ecological and cultural landscape networks as key components of Green Infrastructure (GI). Their methodology combined landscape connectivity analysis, minimum cumulative resistance modelling, gravity modelling, kernel density analysis and circuit theory. These techniques were systematically integrated to develop a composite GI network, achieved through the organic coupling of node selection, landscape corridor construction and corridor integration. The findings highlighted the effectiveness of landscape connectivity analysis in quantitatively assessing patch importance and identifying key ecological nodes. Additionally, the study applied minimum cumulative resistance analysis and gravity modeling to evaluate and prioritize GI corridors, ultimately establishing a robust ecological landscape framework.

Mohsen et al[60] conducted a comprehensive review of climate change impacts on urban environments in the Middle East, with a focus on infrastructure vulnerability and adaptation strategies. Their study emphasized the necessity of proactive climate adaptation planning to enhance urban resilience against both gradual and extreme climate events. The authors highlighted that effective adaptation measures are critical for maintaining socioeconomic stability and ensuring sustainable urban development in the face of evolving climatic conditions. Masoud et al[58] developed stochastic programming models to optimize Green Infrastructure (GI) placement across watershed candidate locations, aiming to minimize expected runoff under medium-term precipitation uncertainties. Their study introduced a two-stage stochastic programming model, later reformulated with perturbed parameters to enhance computational efficiency and to reduce processing time. This approach was subsequently extended to a multi-stage framework. To validate their methodology, they conducted a case study in an urban watershed within a mid-sized U.S. city, performing sensitivity analyses to assess constraint significance and derive practical insights for GI planning.

Terkenli et al[88] conducted a cross-cultural comparative study examining urban tourists' perceptions in eight European cities. The findings reinforced established international tourism patterns, specifically that neighbouring countries constitute the primary tourist markets for urban destinations. This finding corroborated the well-documented travel patterns of Northern and Central Europeans seeking tourism experiences in Mediterranean destinations. The study revealed limited tourist familiarity with the term "Green Infrastructure" (GI) and specific UGI features within the visited cities, the importance of GI was generally acknowledged and viewed positively. The findings provided valuable insights for local and regional authorities in planning, managing and promoting UGI as an integral component of urban tourism offerings.

Girma et al[23] conducted a case study to assess the integration of urban green infrastructure planning principles within the green space planning practices of an urban center in Ethiopia, focusing on the emerging towns of the Oromia Special Zone surrounding Finfinne (Addis Ababa). Through document analysis, supplemented by interviews and field observations, the researchers identified several key limitations in existing green space implementation. Existing green spaces primarily offered mono-functional services and demonstrated limited integration with urban infrastructure (grey structures).

Furthermore, the analysis demonstrated a significant gap between UGI principles and current planning practices, particularly regarding the provision of ecological connectivity through green corridors and greenways. The study identified four primary barriers to UGI integration in urban development: insufficient awareness among stakeholders, financial limitations, lack of inter-agency collaboration and inadequate public participation.

Radhakrishnan et al[72] developed "CgreenSoup," a framework for evaluating the sustainability of Green Infrastructure (GI) in urban precincts, considering social, environmental, economic and engineering aspects. The framework's applicability was validated through an assessment of green infrastructure plant composition implemented under Singapore's Active, Beautiful and Clean Waters Features (ABC Waters) program. These findings informed the selection of plant species for "sponge city" projects, emphasizing the importance of avoiding negative ecological impacts. The study concluded that utilizing a comprehensive set of selection criteria that collectively support ecological health, is essential for sustainable green infrastructure outcomes in urban landscapes.

Rafael et al[73] demonstrated that Urban Ecosystem Services (UES) enhance urban resilience through their direct dependence on the quantity, quality and diversity of Green Infrastructure (GI). To investigate this, the study focused on the western boundaries of Mexico City, employing a methodology that classified different GI settings as Service Providing Units (SPUs). Utilizing remote sensing techniques, specifically the Normalized Difference Vegetation Index (NDVI) combined with ground-truth data, the study assessed UES provision at both local and regional scales. The findings revealed that the majority of GI in the study area is of low quality, significantly limiting its capacity to provide the UES necessary for enhancing Mexico City’s resilience.

Table 1
Methodological Approaches in Urban Green Infrastructure Research: A Comparative Analysis

Methodological Framework and Key Findings
Developed a three-stage methodological framework comprising: (1) Morphological Spatial Pattern Analysis (MSPA) for comparing urban GI patterns across residential districts, (2) GI-adapted Gini coefficient analysis for spatial equity assessment and (3) correlation analysis between spatial patterns and equity distribution across residential typologies.[98]
Conducted comparative analysis of valuation approaches for nature-based solutions alongside conventional infrastructure, integrating both green and grey interventions within a comprehensive infrastructure framework. The study established foundational directions for future research in this emerging field.[101]
Developed and validated a typological framework incorporating political, economic and ecological forces to assess GI development levels. The framework was tested through comparative case studies of metropolitan areas (San Antonio, Texas; Auckland, New Zealand; and New York City), identifying opportunities for mainstreaming GI implementation.[105]
Established a framework for Adaptive Co-Management (ACM) of UGI, validated through the Livada LAB case study in Ljubljana, Slovenia. Results demonstrated enhanced stakeholder engagement, strengthened network connections and broader integration of sustainable development objectives in stakeholder practices.[35]
Employed qualitative stakeholder-based assessment of multifunctionality in peri-urban farmland UGI development. The resulting strategic framework highlighted the significance of stakeholder involvement in defining functional synergies across scales, addressing non-linear relationships between multiple functions.[78]
Investigated correlations between heat-related diagnoses among elderly populations (75+) and monthly air temperatures in Oslo, examining the role of tree canopy cover in reducing extreme land surface temperatures. Findings supported the ecosystem service value of urban tree cover in heat reduction and informed municipal climate adaptation policies.[96]
Developed an ecosystem services-based UGI planning methodology, utilizing a 32-ecosystem service assessment matrix against various land-use types. The approach enabled identification of priority protection areas and strategic development zones for UGI implementation.[106]
Developed and validated the Qatar Sustainability Assessment System-Neighborhood Development (QSAS-ND) using the Waterfall Process method. The model’s application in Lusail city demonstrated superior sustainable neighborhood design performance while identifying areas for transportation and diversity improvements.[19]

Gupta[27] conducted a case study examining Urban Green Spaces (UGS) in Chandigarh, India, where the city faced challenges of traffic congestion, air pollution and environmental degradation. The study highlighted the multifaceted challenges and benefits of UGS, emphasizing the need for innovative and efficient management strategies. The researchers employed an integrated approach combining geospatial technologies with Information and Communication Technology (ICT) tools.

This methodology enabled urban planners to quantify, assess and evaluate UGS distribution and accessibility, while identifying vulnerable areas requiring intervention. This study effectively demonstrated the potential of advanced geospatial and ICT applications for the systematic evaluation and monitoring of urban green spaces.

Pauleit et al[70] developed the GREEN SURGE project to strengthen the conceptual foundation of Green Infrastructure (GI) planning and governance. The project identified opportunities to better integrate top-down, Government-led planning with bottom-up, community-driven initiatives for creating and managing urban green infrastructure (UGI). The project's findings emphasized the need for context-sensitive UGI development that considers the diverse needs and cultural practices of urban residents in their interactions with nature.

Rall et al[74] investigated the value of Public Participation GIS (PPGIS) in assessing and planning for urban green infrastructure (UGI) in Berlin. Their study compared the results of a PPGIS survey conducted in Berlin with real-life assessment tools for cultural ecosystem services (CES) used in the city. At the site level, PPGIS helped to identify conflict zones and undervalued areas requiring redesign or management intervention, while also highlighting valued park features meriting preservation. At the district and city levels, PPGIS enhanced the representativeness and accuracy of expert-based assessments, identified cold spots and challenging-to-map functions, corrected assessment deficits and improved understanding of functional synergies within UGI planning. At district and city scales, the method enhanced the accuracy and representativeness of expert assessments, identified functional cold spots, addressed mapping deficiencies and improved understanding of functional synergies.

Shekhar et al[83] developed an urban green space index (UGSI) to assess and visualize green space density in Kalaburagi city, India. The study employed a two-tiered analysis: a meso-level analysis at the ward level and a micro-level analysis at a 200m x 200m grid cell level. The UGSI extraction demonstrated high accuracy (>90%), underscoring its reliability. The findings highlighted critical deficiencies in urban green spaces: 22 out of 55 administrative wards had less than 10% urban green space (UGS) and 25 wards had a per capita green space (PCGS) below 9 m². These findings underscore the critical need for prioritizing green infrastructure development in these areas to enhance urban liveability and environmental quality.

Anejionu et al[3] developed the Spatial Urban Data System (SUDS), a comprehensive spatial big data infrastructure supporting nationwide urban analytics across UK cities and city-regions. SUDS leverages geospatial technology, synthetic small area urban metrics and cloud computing to enable the analysis and visualization of social and economic aspects of cities and city-regions. Initial validation using housing, transportation and employment metrics demonstrated the system's capability, while ongoing development aims to incorporate Internet of Things (IoT) data and user-generated content to enable predictive urban analytics.

Bartesaghi-Koc et al[11] developed a streamlined framework for automated mapping, classification and thermal evaluation of Green Infrastructure (GI) using remote sensing data. The framework was tested at multiple spatial scales, enabling rapid analysis of extensive urban areas with high spatial accuracy.

The study demonstrated the framework's ability to evaluate and compare intra- and inter-typology variability in land surface temperatures (LSTs), highlighting its potential for assessing other ecosystem service categories.

Carbon storage and sequestration in biomass and soil are widely recognized as critical ecosystem services provided by green infrastructure (GI). While numerous tools exist for assessing carbon cycling across diverse ecosystems, most rely on land use and land cover (LULC) classifications, often adjusted for geographic, climatic and land management factors. However, the development of specific assessment models for carbon sequestration and biomass within urban green infrastructure (UGI) remains limited and requires further refinement. Addressing this gap is essential for accurately quantifying the role of UGI in climate change mitigation and enhancing its integration into urban planning and policy frameworks.

Kim et al[45] developed a typology to enhance the ecological and social potential of urban vacant land. This study systematically surveyed vacant land conditions and introduced a matrix framework to guide city policies for effective use and reuse. The proposed urban vacant land matrix serves as a strategic tool for planners and city managers, facilitating the optimization of vacant parcels to maximize ecological and social benefits.

By redefining vacant land as a valuable resource, this typology promotes innovative approaches to urban open space and landscape design. Moreover, it has significant policy implications, enabling a more informed and adaptive use of underutilized urban areas.

Table 2
Synthesis of Methodological Approaches and Tools for Urban Green Infrastructure Assessment

Objective and Methodology	Key Findings
Developed integrated techniques to prioritize restoration of coal mining subsidence areas using green infrastructure (GI) in Xuzhou, China.[31]	Restoration priorities were categorized into five grades. High-priority areas (Classes 4 and 5) were strongly recommended for GI integration and targeted restoration efforts.
Designed the HARMONISE toolkit to enhance resilience and security in large-scale urban developments against attacks and disruptions.[33]	The toolkit improved situational awareness across building collections, optimizing responses to various situations.
Explored water-sensitive urban design (WSUD) for green urban water infrastructure.[48]	Provided Planning Support System (PSS) developers with critical insights to enhance PSS utility and expedite GI implementation.
Used artificial neural networks (ANN) and adaptive network-based fuzzy inference systems (ANFIS) to predict GI transformation likelihoods in Manchester's derelict and waterway corridor (WWC) sites.[49]	ANFIS models demonstrated higher predictive accuracy (72%) than logistic models (65%). WWC sites exhibited an 80% likelihood of transformation versus 60% for derelict sites.
Developed a spatial multi-criteria tool to prioritize green roof implementation and optimize ecosystem service provision in Barcelona.[50]	The tool offered flexible, adaptable guidance for municipal policies in leveraging GI for ecosystem services.
Proposed a method to identify spatial priorities for multifunctional GI planning by assessing diverse functions.[28]	Highlighted the need for policy shifts from generic assumptions to localized, evidence-based design strategies.
Applied remote sensing and census data to model urban flood reduction services through GI.[55]	Uneven distribution of flood reduction capacities was observed, with varying contributions from public and private surfaces.
Assessed GI's mitigation of the Urban Heat Island (UHI) effect in Rome, Italy.[56]	GI effectively reduced urban heat during summer, with outcomes influenced by GI type and local environmental constraints.
Investigated the impact of street-level GI interventions on subjective well-being (SWB) using photo simulation.[61]	All GI interventions significantly enhanced perceived happiness and reduced stress during short-term exposure, with varying effect sizes depending on intervention type and scale.
Developed a hierarchical framework to prioritize UGI arrangements for temperature cooling in urban canyons.[63]	Provided actionable insights for local governments to optimize UGI for temperature mitigation.

Kim et al[46] quantified the ecosystem services and economic value of vacant land in Roanoke, Virginia. Using aerial photo interpretation and ground-truthing, they identified and mapped vacant parcels within city limits. The analysis, conducted with i-Tree Canopy and i-Tree Eco models, classified land cover and quantified ecosystem structure and services. Findings revealed that Roanoke's vacant land supported approximately 210,000 trees, covering 30.6% of the area. These trees provided substantial ecosystem services, including:

- Carbon sequestration: 97,500 t, valued at $7.6 million
- Carbon dioxide removal: 2,090 t annually, valued at $164,000
- Air pollutant removal: 83 t annually, valued at $916,000
- Energy cost reduction: $211,000 annually for 97,000 residents
- Structural tree value: $169 million

The study underscores the critical role of urban forests on vacant land, advocating for their integration into urban planning and green infrastructure management strategies.

M'Ikiugu et al[52] developed the Green Infrastructure Gauge (GIG), a tool designed to optimize the integration of green infrastructure (GI) elements, functioning into urban master plans and evaluate their status in existing urban areas. Through a survey of public workers across 41 Japanese municipalities, the GIG identified and prioritized key GI functions and elements essential for future urban development. The tool aims to enhance ecosystem services and promote environmental well-being, contributing to the creation of sustainable communities. This innovative approach provides a practical framework for urban planners and policymakers to systematically incorporate GI

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into urban development strategies, ensuring long-term ecological and social benefits.

Romero-Duque et al[79] proposed a conceptual framework highlighting the critical role of ecosystem services within urban ecological infrastructure. Their analysis, focused on Brazil, Mexico, Chile and Argentina, revealed a strong emphasis on green, blue and grey-hybrid infrastructure solutions as key components of urban sustainability. While the supply of ecosystem services and their intermediate beneficiaries were extensively examined, the study identified a significant gap in the literature: most research lacked comprehensive biophysical, socio-cultural, or economic assessments, relying instead on proxy variables. These findings underscore the need for a more integrated and holistic approach in incorporating ecosystem services into urban planning policies across the region, ensuring that ecological, social and economic dimensions are adequately addressed.

McPhearson et al[59] developed a methodology for assessing ecosystem services (ES) within urban green spaces, integrating these assessments with the social conditions of urban neighborhoods. Focusing on vacant land in New York City, their analysis provided strategic insights into urban ecosystem management. The study identified clusters of vacant lots in areas characterized by low ecological value but high social need for ecosystem services, particularly in East Harlem, the South Bronx and Central Brooklyn. These findings highlight the critical importance of targeting interventions in areas where social needs and ecological opportunities converge, offering a pathway to maximize urban sustainability outcomes. This approach underscores the potential for aligning ecological restoration with social equity goals in urban planning.

García et al[20] proposed a holistic spatial planning methodology for green infrastructure (GI), emphasizing its capacity to deliver comprehensive ecosystem services (ESS). The approach involved delineating buffer zones and multifunctional zones at the landscape scale, using a structured procedure tailored to each zone type. By integrating ESS assessments into multifunctional GI design, the methodology streamlined land-use planning and management, ensuring the sustained provision of diverse ESS.

The study also presented a shortlist of valuation toolkits (Table 3), highlighting their objectives and contributions in quantifying the economic value of GI elements. These findings underscore the wide-ranging benefits of GI, providing a robust framework for optimizing ecosystem service delivery and supporting sustainable urban and landscape planning.

Sirkku[85] employed the green factor tool to assess and enhance the effectiveness of urban green areas in Helsinki. The study found that while the tool demonstrated efficacy in promoting green space planning, its implementation could be strengthened through improved monitoring mechanisms. Furthermore, the ambitious targets integrated into the tool were shown to incentivize developers to prioritize green space planning and construction. However, the study also identified challenges posed by existing regulatory frameworks which may hinder the tool's full implementation. These findings underscore the importance of aligning policy instruments with practical implementation strategies to maximize the potential of urban green infrastructure in fostering sustainable urban development.

Wang et al[99] introduced an instrumental framework called the UIEC model to evaluate the economic capacity of urban infrastructure. This integrated model incorporates the Coupling-Coordination Degree Model, Mean-Variance Analysis Method, Support-Pressure Model and Super-efficiency Slack-based-measure Window model. By employing the UIEC model, the economic capacity of urban infrastructure was appreciated by investigating the economic carrying efficiency of urban infrastructures. A case study in China from 2008 to 2017 demonstrated the applicability of this framework. Key findings revealed that: 1) Economic location and self-governance authority significantly influence UIEC, 2) The overall economic carrying efficiency of urban infrastructure in the studied cities exhibited a declining trend and 3) A strong exponential relationship exists between economic carrying efficiency and GDP value. The study underscored that high utilization efficiency of urban infrastructure is a critical pre-requisite for sustaining robust urban economic development.

Parisa et al[68] conducted a systematic analysis of tools, methods and applications for evaluating the carbon performance of green infrastructure (GI) in Australia. The study examined existing tools, highlighting variations in scale, components and input methodologies for assessing GI sustainability.

It categorized these tools based on their relevance in quantifying carbon sequestration services and other GI features. The primary objective was to assist policymakers, environmental groups and researchers in selecting the most appropriate tools for context-specific carbon footprint assessments, thereby enhancing the accuracy and reliability of GI evaluation methods.

Wendy[100] conducted a nationwide study assessing the role of urban green infrastructure (UGI) in the carbon balance of 35 major Chinese cities. By 2010, urban green spaces, the primary UGI components, covered 6.38% of the total land area in these cities, representing 51.7% of the total urban green spaces across all 657 Chinese cities. The study estimated that UGI vegetation in these 35 cities stored 18.7 million tons of carbon, with a mean carbon density of 21.34 t/ha.

Table 3
Shortlist of valuation toolkits

Tool Name	Objective	Developer and Version	Type
Nature Value Explorer (NVE)[38]	Demonstrates the impact of various land-use scenarios on ecosystem service value and generation	VITO, BE (2018)	Web tool
i-Tree Eco[39]	Quantifies environmental effects and societal value using tree, pollution and meteorological data	USDA Forest Service, US (2019)	Computer program
Green Infrastructure Valuation Toolkit (GIVal)[36]	Establishes the value of green assets or proposed investments using calculator tools	The Mersey Forest, UK (2015)	Spreadsheet
A Guide to Valuing Green Infrastructure	Informs decision-makers and planners on green infrastructure benefits and valuation methods	Centre for Neighbourhood Technology, US (2011)	Textual guide
Toolkit for Ecosystem Service Site-based Assessment (TESSA)[84]	Provides guidance for evaluating benefits from natural sites to support decision-making	BirdLife International, UK (2015)	Textual guide
Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST)[4,66]	Quantifies trade-offs of management choices and identifies areas for natural capital investments	Natural Capital Project, UK (2018)	Computer program
EcoPLAN Scenario Evaluator (SE)[53]	Evaluates ecosystem service supply in alternative spatial development scenarios	University of Antwerp, BE (2017)	Computer program
Green Infrastructure Benefits Valuation Tool[91]	Provides quick assessments of costs and benefits of green infrastructure investments	Earth Economics, US (2018)	Spreadsheet
Capital Asset Value of Amenity Trees (CAVAT)[66]	Assigns monetary value to tree stocks or individual trees for strategic decision-making	London Tree Officers Association, UK (2018)	Spreadsheet
Benefits Estimation Tool (B£ST)[7]	Monetizes economic, social and environmental benefits of blue-green infrastructure to guide investments	CIRIA, UK (2019)	Spreadsheet

In 2010, annual carbon sequestration by UGI in these cities totalled 1.90 million tons, with an average sequestration rate of 2.16 t/ha/year. However, this sequestration offset only 0.33% of fossil fuel emissions, with city-level offsets ranging from 0.01% in Hohhot to 22.45% in Haikou. The study emphasized that young vegetation stands to dominate China's urban green infrastructure, indicating a significant potential for enhanced carbon sequestration. Realizing this potential, however, requires targeted policies and management strategies that optimize UGI for climate change mitigation and adaptation.

Andrew et al[2] integrated high-resolution tree canopy and biomass data with local tree growth measurements in Boston, Massachusetts, to estimate the magnitude and distribution of annual biomass carbon (C) uptake. The analysis revealed that 85% of the city's tree canopy was within 10 meters of an edge, indicating predominantly open-growing conditions. By incorporating growth models that account for canopy edge effects and urban growth dynamics, the study estimated Boston's biomass C uptake at approximately double that of rural forests (median: 10.9 GgC yr^{-1}, 0.5 MgC ha^{-1} yr^{-1}), with a significant portion occurring in high-density residential areas. However, the total annual C sequestration in long-term biomass storage accounted for less than 1% of the city's annual fossil CO_2 emissions. The findings underscore the necessity of incorporating altered ecosystem structure and function in urban carbon assessments to evaluate ecosystem services accurately.

Li et al[51] reviewed advancements in municipal biomass resource estimation, classifying urban biomass into three categories: municipal solid waste, municipal sewage and urban wood biomass. Their analysis examined the proximate composition, ultimate properties and calorific values of these biomass types, identifying distinct energy potential variations. Reported calorific values ranged from 7.10–19.90 MJ/kg for municipal solid waste, 8.73–19.10 MJ/kg for municipal sewage and 16.96–21.59 MJ/kg for urban wood biomass. The study also evaluated biomass resource estimation models, emphasizing artificial neural networks (ANNs) and multiple linear regression. Among these, ANNs emerged as the most promising approach, demonstrating high accuracy in predicting municipal biomass quantities. Feng et al[17] conceptualized Urban Ecological Infrastructure (UEI) as an integrated framework that enhances ecosystem services and supports sustainable urban systems amid changing landscapes and climate conditions. UEI is the synergistic integration of blue (water-based), green (vegetated) and grey (built) infrastructures, interconnected through exits (outflows, treatment, recycling) and arteries (corridors) at an ecosystem scale. This framework envisions UEI as a dynamic network that facilitates biotic and abiotic interactions, linking natural and artificial systems to strengthen urban resilience.

Table 4
Representative selection of different tools for evaluating UGI

Tool	Link	Developer	Primary Function	Complexity Level	Technical Requirements	Data Inputs and Outputs
Green LTC EZ Template	https://www.epa.gov/green-infrastructure/epas-green-long-term-control-ez-template	EPA	Presumptive planning approach	Low	Non-technical, web-based	Minimal data requirements, no GIS needed
National Stormwater Calculator	https://www.epa.gov/water-research/national-stormwater-calculator	EPA	Desktop modelling application	Moderate	Non-technical, online interface	Site-specific inputs, moderate data needs
Green Values National Calculator	http://greenvalues.cnt.org/national/calculator.php	Centre for Neighbourhood Technology	Curve number-based planning tool	Moderate	Non-technical, spreadsheet-based	Site-specific inputs, lifecycle cost analysis
L-THIA LID	https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.php	Purdue University	Curve number analysis	Moderate	Technical, online interface	Land use areas, pollutant data
LIDRA Low Impact Development Rapid Assessment	http://www.lidratool.net/	University of Utah	Decision support system with rainfall-runoff modelling	Moderate	Technical, online interface	GIS preferred, land use data, cost analysis capabilities
RECARGA Model for Infiltration Basins and Bioretention Design	https://dnr.wi.gov/topic/stormwater/standards/recarga.html	University of Wisconsin	Water balance model for infiltration designs	High	Technical, standalone software	Rainfall data, design specifications, evaporation rates
MUSIC Model for Urban Stormwater Improvement	https://ewater.org.au/products/music/	e-Water	Decision support system with routing and water balance	High	Technical, standalone software	GIS integration, land use areas, pollutant tracking
SWMM-5 dynamic rainfall-runoff model	https://www.epa.gov/water-research/storm-water-management-model-swmm	EPA	Dynamic rainfall-runoff simulation	High	Technical, standalone software	GIS for large areas, comprehensive hydrological modelling
SUSTAIN System for Urban Stormwater Treatment and Analysis Integration	https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain	EPA	ArcGIS-linked decision support system	Moderate	Technical, no longer supported	GIS integration, cost optimization features
WMOST Watershed Management Optimization Support Tool	https://www.epa.gov/ceam/wmost-10-download-page	EPA	Watershed optimization with curve number analysis	Moderate	Technical, standalone software	Requires runoff input, land use data, cost optimization

Table 5
Reviewed modelling tools

Tool	Developer	Primary Function	Key Features
P8 Urban Catchment Model	IEP, Inc.	Predicts pollutant transport in urban runoff	TSS reduction modeling, GI effectiveness assessment
WERF BMP/LID Cost Model	Water Environment Research Foundation	Life cycle cost evaluation	Comprehensive economic assessment of GI practices
GI Valuation Toolkit	Mersey Forest	Environmental-economic benefit analysis	Monetary valuation of GI environmental services
WinSLAMM	PV & Associates	Urban runoff quality analysis	Specialized in GI impact on runoff quality improvement

Table 6
List of methods and tools for calculating carbon storage in urban trees in India.

Method/Tool	Description
Allometric Equations[86]	Utilizes species-specific models to estimate biomass based on measurable parameters such as diameter at breast height (DBH).
Biomass Estimation[54]	Calculates above-ground biomass (AGB) and below-ground biomass (BGB) to determine total carbon storage in trees.
Remote Sensing[76]	Uses satellite imagery and aerial photography to assess tree cover and estimate biomass and carbon sequestration.
InVEST Model[82]	Assesses carbon storage as part of ecosystem services by modelling land-use changes and their impact on carbon dynamics.
Carbon Default Values[90]	Uses standardized conversion factors (e.g., 0.5 for carbon content in biomass) to estimate carbon stocks.
Tree Inventory Systems[1]	Systematic data collection catalogues tree species, sizes and locations for carbon storage assessment.
Field Measurements[104]	Direct measurement of tree height, girth and other parameters using tools like clinometers and measuring tapes.
i-Tree Eco*	Widely used tool incorporating species-specific wood density and field data to quantify urban tree carbon storage.
Allometric Models (with Terrestrial Laser Scanning)[95]	Enhances accuracy in biomass estimation by capturing detailed 3D structural data of trees.
Field-Based Inventory[104]	Involves direct sampling and measurement of urban trees to gather empirical data on species, size and health.
Carbon Sequestration Worksheets[104]	Structured worksheets calculate annual carbon sequestration based on tree species, age and growth rates.

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By integrating these infrastructures, UEI optimizes resource circulation, enhances ecosystem functions and fosters adaptive urban development. This comprehensive approach provides a strategic foundation for rational urban planning, advancing regional sustainability and climate adaptability.

Inostroza[34] analyzed the spatial evolution of livestock activity and urban development in Southern Patagonia, Chile, framing it as a metabolic relationship between the steppe ecosystem and the urban environment of Punta Arenas. This dynamic interaction left lasting imprints on the city's-built environment where architectural grandeur emerged as a tangible expression of ecosystem appropriation. The stratified architectural layers of Punta Arenas reflect the progressive depletion of the Steppe's ecological resources, illustrating a direct link between environmental exploitation and urban transformation. The conversion of Patagonian pasturelands into bourgeois architecture represents a metabolic chain, transforming biomass into techno-mass, encapsulating the intertwined processes of resource extraction and urbanization.

A comprehensive literature review was conducted for each tool, drawing from user guides, design manuals, fact sheets, case studies, journal articles, conference proceedings and book chapters. Key details of the selected modeling tools including model descriptions, ownership, availability and intended applications, are summarized in table 4 and table 5[36]. Each tool was evaluated against five criteria: (1) represented Urban Green Infrastructure (UGI) practices, (2) applicable spatial scales, (3) modeling algorithms, (4) required inputs and generated outputs and (5) user interface and operational complexity. Table 3 presents the various tools for UGI evaluation, while table 4 details the modeling tools and their specific UGI applications. In table 3, DSS denotes decision support systems, # indicates applicability limited to regions outside the Midwest US and GIS refers to geographical information systems.

The review underscores the necessity of integrating multiple methodologies to enhance the accuracy and reliability of urban tree carbon storage assessments. The combination of remote sensing, field-based inventories and advanced computational models such as InVEST and i-Tree Eco provides robust insights into urban carbon sequestration dynamics. These tools and methodologies serve as essential resources for urban planners and researchers aiming to develop sustainable, climate-resilient urban environments in India.

Conclusion

Urban Green Infrastructure (UGI) has emerged as a crucial framework for promoting sustainable urban development and enhancing urban resilience against climate change. This study underscores the importance of integrating UGI into urban planning and policy frameworks to deliver a wide range of ecosystem services, including carbon sequestration, stormwater management, biodiversity conservation and improved human well-being. Through a comprehensive review of existing literature, methodologies and case studies, this study highlights the role of UGI in addressing contemporary urban challenges, such as heat island effects, air pollution and socio-environmental disparities.

Collectively, these conclusions underscore the paramount importance of UGI as a strategic framework for fostering sustainable and resilient urban environments amidst rapid urbanization and escalating climate change. The integration of UGI into urban planning and development is not merely an aspirational goal but a critical imperative for addressing multifaceted challenges, delivering a wide spectrum of ecosystem services that span environmental, social and economic dimensions.

These benefits range from climate change mitigation and urban heat island reduction to biodiversity conservation, enhanced human well-being and improved urban resilience against environmental stressors. While the reviewed case studies and methodologies highlight the significant potential of UGI, they also reveal varying degrees of implementation success and persistent challenges. Context-sensitive approaches are essential, necessitating robust frameworks, advanced planning tools like the Green Infrastructure Gauge (GIG) and Urban Green Space Index (UGSI) and multidisciplinary strategies that incorporate spatial planning, landscape ecology and socio-economic considerations. Furthermore, realizing the full potential of UGI requires addressing existing limitations in valuation toolkits, promoting cross-sectoral integration, fostering stakeholder engagement and leveraging technological advancements such as GIS and big data, to optimize planning and assessment.

Future research should focus on refining UGI assessment methodologies, developing standardized classification frameworks, exploring innovative financing mechanisms and filling data gaps concerning urban ecosystems and the long-term impacts of UGI. By actively pursuing these advancements and embracing a paradigm shift towards nature-based solutions, urban planners, policymakers and researchers can collaboratively unlock the transformative potential of UGI, paving the way for ecologically balanced, livable and resilient cities. This comprehensive understanding reinforces the call to action: prioritizing and investing in UGI is not just an environmentally sound decision but a strategic imperative for building sustainable and thriving urban futures.

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