RESEARCH ARTICLE

JENER Journal of Empirical and Non-Empirical Research
Volume 1, Issue 3, Page 1003-1017 | Article No. 122
DOI: 10.4898/jener.v1i3.a122
ISSN: 7895-9216
Journal homepage: https://jenerjournal.com
Journal email: editor@jenerjournal.com

JENER Journal
JENER Journal of Empirical and Non-Empirical Research

Life-Cycle Carbon Assessment of Green vs. Gray Stormwater Infrastructure in Megacities: A Systematic Review

Santunu Barua[1]

[1]MS in Environmental Engineering, Department of Civil & Environmental Engineering, Manhattan University, NY, USA

ARTICLE INFORMATION

Article history:
Published: December 2025

Keywords:
Life Cycle Assessment
Green Stormwater Infrastructure
Gray Infrastructure
Carbon Footprint
Carbon Sequestration
Nature-Based Solutions

ABSTRACT

Rapid urbanization and climate change are intensifying the frequency and magnitude of urban flooding, compelling megacities worldwide to fundamentally reconsider their stormwater infrastructure strategies. This systematic review synthesizes the life cycle assessment (LCA) literature comparing the greenhouse gas (GHG) emissions profiles of green stormwater infrastructure (GSI) and gray stormwater infrastructure across megacity contexts, following a PRISMA-informed search protocol covering publications from 2010 to 2025 in Web of Science, Scopus, and Google Scholar. Evidence from 40+ peer-reviewed studies conducted across North America, Europe, East Asia, and Australia consistently demonstrates that GSI generates substantially lower life-cycle carbon emissions than equivalent gray alternatives, with documented reductions ranging from 38% to 87%. In the landmark Bronx River, New York case study, decentralized green infrastructure emitted only 19,000 t CO_2-eq over 50 years compared to 85,000–400,000 t CO_2-eq for gray alternatives. In China's Sponge City Program, carbon emission reductions of up to 87.08% were achieved relative to conventional integrated urban drainage systems. The primary drivers of green infrastructure's carbon advantage are: (i) avoided embodied carbon from concrete-intensive gray construction; (ii) significantly lower operational energy demand by eliminating or reducing pumping and wastewater treatment plant requirements; and (iii) carbon sequestration co-benefits in vegetation and engineered soils. Among GSI typologies, rain gardens demonstrate the greatest sequestration mitigation potential (>100% over 30 years), followed by bioretention basins (~70%), green roofs (~68%), and vegetated swales and permeable pavements (~45%). Stormwater wetlands and ponds exhibit the most complex carbon balances due to direct methane (CH_4) and nitrous oxide (N_2O) fluxes from anaerobic zones. Persistent methodological inconsistencies—particularly in system boundary definition, functional unit selection, direct GHG flux accounting, and life cycle inventory data quality—remain the primary barriers to cross-study comparison and evidence-based policymaking. This review critically evaluates LCA methods, presents quantitative carbon benchmarks across infrastructure typologies, and formulates targeted policy recommendations for advancing low-carbon stormwater governance in megacities.

1. Introduction

Megacities—urban agglomerations exceeding 10 million inhabitants—are among the most hydrologically stressed environments on Earth (Khalifi et al., 2025). As of 2024, over 40 megacities exist globally, and this number is projected to reach 50 by 2030. Unprecedented rates of impervious surface expansion associated with megacity growth disrupt natural infiltration processes, dramatically increase surface runoff volumes, and elevate peak flows far beyond the design capacity of conventional drainage systems. Simultaneously, cities are recognized as responsible for approximately 70% of global carbon emissions and energy consumption, underscoring both their vulnerability to climate change and their critical role in global mitigation efforts (Khalifi et al., 2025). In this context, stormwater infrastructure—the physical network of structures and practices used to capture, convey, treat, and dispose of urban runoff—represents a significant, yet historically underexamined, contributor to the urban carbon footprint.

Gray stormwater infrastructure, encompassing reinforced concrete pipe networks, underground detention tanks, pump stations, and combined sewer overflow (CSO) tunnels, has served as the engineering backbone of urban drainage since the industrial revolution (Barua 2025). This paradigm has come under increasing scrutiny due to its high embodied carbon, substantial operational energy demand, limited ecological co-benefits, and inflexibility in the face of changing precipitation regimes driven by climate change. In contrast, green stormwater infrastructure (GSI)—a broad category encompassing bioretention cells, green roofs, permeable pavements, vegetated swales, rain gardens, constructed stormwater wetlands, and blue-green corridors—employs natural processes to manage rainfall at or near its source (Introduction to Urban Stormwater and Green Stormwater Infrastructure, 2022). GSI has been characterized as potentially carbon-neutral or even carbon-negative over its operational lifespan, owing to carbon sequestration by vegetation and organic matter accumulation in engineered soils.

Life Cycle Assessment (LCA), a standardized methodology governed by ISO 14040:2006 and ISO 14044:2006, provides a rigorous "cradle-to-grave" framework for quantifying the environmental burdens associated with all phases of an infrastructure system's existence—material extraction, manufacturing, construction, operation, maintenance, and end-of-life treatment. The application of LCA to stormwater infrastructure has expanded substantially since the early 2010s, yielding a diverse body of evidence that permits systematic comparison of green and gray alternatives across diverse urban geographies and scales (Khalifi et al., 2025). However, the inconsistent use of LCA methods—including variations in impact categories, data collection methods, system boundaries, and functional units—continues to hinder effective policymaking and cross-project comparison (Khalifi et al., 2025).

This review is motivated by three intersecting observations. First, megacities represent the highest-stakes environments for stormwater infrastructure decisions: the scale, density, and compounding climate risks of cities above 10 million inhabitants create an urgent need for evidence on the carbon trade-offs of infrastructure investment at the multi-billion-dollar level. Second, while individual LCA studies of stormwater infrastructure are accumulating rapidly, no prior systematic review has focused specifically on the megacity context or synthesized findings across the full spectrum of GSI and gray infrastructure typologies with explicit attention to carbon metrics. Third, as cities globally commit to carbon neutrality targets in alignment with the Paris Agreement, the carbon performance of infrastructure must be integrated into urban climate strategies—a process that requires standardized evidence and clear comparative benchmarks.

The objectives of this review are to: (1) systematically survey the LCA literature on green and gray stormwater infrastructure carbon performance; (2) synthesize quantitative carbon data across infrastructure typologies and geographies; (3) evaluate methodological approaches and identify key inconsistencies; (4) assess the particular challenges and opportunities presented by megacity contexts; and (5) formulate evidence-based recommendations for research and policy.

This paper is structured as follows: Section 2 describes the review methodology. Section 3 presents the LCA methodological framework as applied to stormwater systems. Section 4 reviews carbon performance of individual GSI typologies. Section 5 examines gray infrastructure carbon profiles. Section 6 presents comparative LCA studies. Section 7 addresses megacity-specific challenges and opportunities. Section 8 synthesizes quantitative evidence in summary tables. Section 9 identifies research gaps and methodological limitations. Section 10 provides policy recommendations. Section 11 outlines future research directions. Section 12 concludes.

2. Review Methodology

2.1 Search Protocol and Inclusion Criteria

This systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The literature search was conducted across three primary databases: Web of Science Core Collection, Scopus, and Google Scholar. Search strings combined terms from three conceptual domains: (i) infrastructure type: "green infrastructure" OR "gray infrastructure" OR "grey infrastructure" OR "bioretention" OR "green roof" OR "permeable pavement" OR "stormwater wetland" OR "sponge city" OR "combined sewer overflow"; (ii) assessment method: "life cycle assessment" OR "LCA" OR "carbon footprint" OR "life cycle carbon"; and (iii) environmental indicator: "greenhouse gas" OR "GHG emissions" OR "carbon emissions" OR "CO_2 equivalent" OR "carbon sequestration". Searches were limited to peer-reviewed English-language publications from January 2010 to March 2025.

Inclusion criteria required that studies: (1) apply a recognized LCA or carbon footprint methodology (process-based, EIO, hybrid, or emission factor method) to stormwater infrastructure systems; (2) report quantitative GHG emission or carbon footprint results; (3) explicitly define system boundaries and functional units; and (4) provide sufficient methodological detail for critical appraisal. Studies focused exclusively on water quality performance, hydrological modeling without carbon accounting, or non-stormwater infrastructure were excluded. Review articles, conference proceedings, and government reports were included where peer-reviewed original studies were not available for specific topics.

2.2 Data Extraction and Synthesis

From an initial pool of 334 publications identified by Bani Khalifi et al. (2025) through a parallel PRISMA-based process (Khalifi et al., 2025), plus additional studies identified through citation chaining and targeted searches, a final corpus of over 50 primary studies and 15 review/meta-analysis publications was assembled. Data extraction focused on: (i) infrastructure typology and study context; (ii) LCA approach and system boundaries; (iii) functional unit; (iv) study period; (v) quantitative GHG emission results (kg CO_2-eq); (vi) carbon sequestration estimates; (vii) direct GHG flux measurements; and (viii) key sensitivity factors. A narrative synthesis approach was adopted given the high heterogeneity of functional units and system boundaries across studies, which precluded formal statistical meta-analysis of carbon outcomes across typologies.

3. Life Cycle Assessment Methodology for Stormwater Infrastructure

3.1 LCA Framework and Phase Structure

LCA for stormwater infrastructure follows the four-phase structure defined by ISO 14040: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) interpretation. For stormwater systems, this translates into accounting for carbon emissions across the construction phase (material manufacturing, transport, and installation), the operational phase (energy consumption for pumping and treatment), the maintenance phase (material replacement, vegetation management, sediment removal), and the end-of-life phase (demolition, disposal, or decommissioning) . The Global Warming Potential (GWP100) impact category—expressed in kg CO_2-equivalent—is the primary metric used for carbon comparison across studies, incorporating CO_2, CH_4 (GWP100 ≈ 28), and N_2O (GWP100 ≈ 265) in accordance with Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report characterization factors.

The functional unit—the quantitative reference measure of system output—varies widely across published stormwater LCA studies, representing the most significant methodological barrier to direct cross-study comparison. Common functional units include: (i) volume of stormwater retained or treated per year ($m^3\ yr^{-1}$); (ii) unit area of infrastructure (per m^2 of footprint); (iii) mass of specific pollutant removed per unit time (kg phosphorus eq yr^{-1}); or (iv) equivalent runoff volume reduction for a defined design storm event. The choice of functional unit profoundly affects comparative outcomes: studies using pollutant removal efficiency as the functional unit tend to favor bioretention basins, while those using volumetric retention per unit area may favor green roofs or underground detention systems. Recent methodological guidance recommends performance-based functional units that reflect the primary service provided (e.g., flood safety for a defined return period) to ensure that all compared alternatives deliver equivalent hydraulic performance (Grubert & Stokes-Draut, 2020).

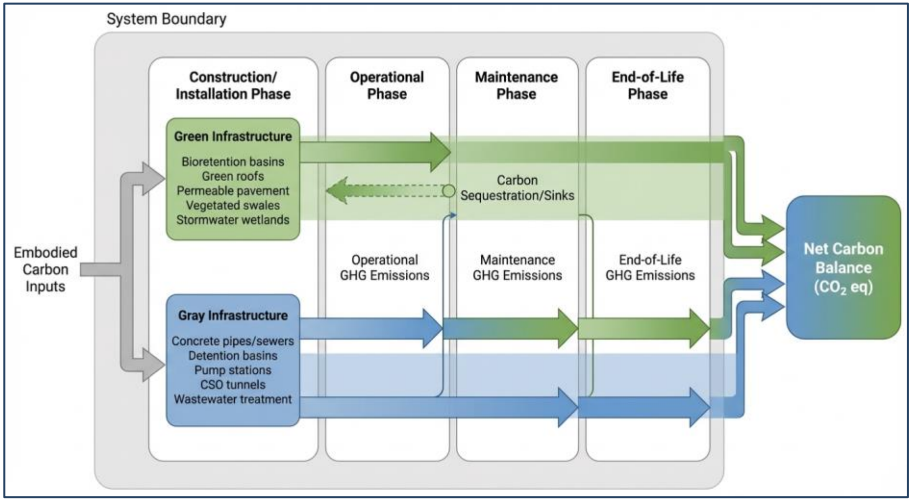

Figure 1. Conceptual life cycle assessment framework for comparing green and gray stormwater infrastructure carbon assessment, illustrating system boundaries, life cycle phases (construction, operation, maintenance, end-of-life), and carbon flows—including both emission sources and carbon sinks—for each infrastructure typology. Orange pathways represent carbon emission flows; green pathways represent carbon sequestration and avoided-emission credits.

3.2 LCA Approaches: Process-Based, EIO, and Hybrid Methods

System boundary definition is among the most consequential methodological decisions in stormwater LCA, with implications that can qualitatively alter comparative conclusions (Khalifi et al., 2025). A narrow "cradle-to-gate" boundary covering only material production will consistently underestimate the full carbon impact of gray infrastructure—which derives a large fraction of its lifetime GHG footprint from energy-intensive pumping and wastewater treatment operations—while simultaneously failing to capture the long-term carbon sequestration benefits of vegetated green infrastructure (GI) systems. Conversely, a boundary that credits GI sequestration without accounting for direct GHG fluxes (CH_4, N_2O) from vegetated soils and water surfaces will systematically overestimate carbon benefits. A comprehensive "cradle-to-grave" boundary that includes all life cycle stages, upstream indirect emissions, carbon sequestration in biomass and soil, and direct GHG fluxes from vegetated and water-surface elements is therefore considered minimum best practice for credible comparative stormwater LCA.

Three major LCA approaches have been applied in stormwater research. Process-based LCA constructs a detailed inventory of inputs and outputs for each unit process (e.g., concrete production, diesel fuel combustion during excavation), providing high-resolution process-specific results but potentially truncating upstream supply chain emissions. Economic input-output (EIO) LCA leverages national economic input-output tables to estimate indirect emissions across entire supply chains from sector-level expenditure data, offering comprehensive supply chain coverage but with reduced process specificity. Hybrid LCA—combining process-based foreground data for well-characterized unit processes with EIO data for less-characterized supply chain components—is increasingly recognized as the most comprehensive method, balancing specificity with completeness, and has been applied in landmark stormwater studies including the Bronx River CSO comparison. The emission factor method, widely used in Chinese sponge city studies, applies standardized GHG emission coefficients to material quantities and energy flows and is computationally accessible but depends critically on the accuracy and regional representativeness of factor databases (Lin, 2018 ; Zhao, 2023).

3.3 Carbon Sinks: Sequestration and Avoided Emissions

A defining feature of vegetated stormwater infrastructure is its dual role as both a carbon emitter (through material production, construction energy, and maintenance activities) and a carbon sink (through biological sequestration and avoided emissions from gray alternatives). Carbon sequestration in vegetated infrastructure—including organic carbon accumulation in bioretention filter media, green roof growing substrate, and constructed wetland sediment—can substantially offset embodied carbon burdens when quantified and credited within the LCA system boundary. The carbon sequestration rate in bioretention soil has been field-measured at $0.31\ kg\ C\ m^{-2}\ yr^{-1}$ over a 13-year chronosequence study in subtropical Queensland, predominantly concentrated in the uppermost 5 cm of the filter media profile. Additionally, "avoided emissions" credits—representing GHG savings from displacing the energy-intensive pumping and treatment operations of gray systems—can be a quantitatively larger carbon benefit than direct sequestration for infrastructure deployed at watershed scale (Lin et al., 2018).

3.4 Direct GHG Fluxes from Vegetated Systems

A critical and frequently neglected component of vegetated stormwater system carbon accounting is direct GHG flux measurement. Kavehei et al. (2018) demonstrated that estimating the carbon footprint based solely on life cycle phases (construction, operation, maintenance, end-of-life) without accounting for in situ GHG emissions substantially underestimates the true carbon footprint of vegetated water-sensitive urban design (WSUD) systems. Anaerobic conditions in saturated zones—common in slow-draining bioretention basins, stormwater ponds, and constructed wetlands—promote methanogenesis, generating CH_4 emissions that, on a mass basis, exert 28 times greater warming potential than CO_2 over a 100-year period. Nitrification and denitrification of nitrogen in stormwater inflows produce N_2O, with a GWP100 of approximately 265. Measurement of GHG fluxes from two contrasting bioretention basins in Queensland (fast-draining at 312 mm hr^{-1} vs. slow-draining at 28 mm hr^{-1}) confirmed that the slow-draining configuration emitted large CH_4 fluxes while emitting less CO_2, while the fast-draining configuration acted as a CH_4 sink but was a large CO_2 source, highlighting the design-dependent nature of net GHG balances. These findings reinforce the importance of including direct GHG flux terms in any comprehensive carbon footprint of vegetated stormwater infrastructure.

4. Carbon Performance of Green Stormwater Infrastructure Typologies

4.1 Bioretention Basins and Rain Gardens

Bioretention systems—engineered soil-plant filter media designed to treat and attenuate stormwater runoff through infiltration, filtration, adsorption, and biological uptake—represent one of the most extensively studied GSI typologies in the LCA literature (Emad, 2020). These systems are widely deployed in streetscapes, parking lot islands, and residential neighborhoods across North America, Australia, and increasingly China and Europe. Kavehei (2020) conducted the most comprehensive field-based investigation of bioretention basin carbon dynamics to date, characterizing 25 basins across a 13-year chronosequence in subtropical Queensland, Australia. The study documented a soil organic carbon (SOC) sequestration rate of 0.31 kg C m^{-2} yr^{-1}, with sequestration strongly concentrated in the top 5 cm of filter media and positively correlated with site age and total nitrogen content. Over a 30-year design lifetime, this sequestration rate was estimated to mitigate approximately 70% of the total life cycle carbon footprint of bioretention basins—a figure that approaches net-carbon-neutrality when carbon credits from avoided gray infrastructure emissions are additionally incorporated.

Rain gardens—smaller-scale, shallower-rooted bioretention variants typically deployed in residential catchments—demonstrate the highest carbon sequestration mitigation potential of all vegetated stormwater typologies, estimated at more than 100% of life cycle carbon footprint over a 30-year period, meaning that they can achieve net carbon-negative status when sequestration credits are fully applied (Emad, 2020). The life cycle analysis of rain gardens in Cincinnati, Ohio (Shepherd's Creek watershed) by Vineyard et al. (2015) found 62–98% impact reductions across multiple environmental categories including global warming potential relative to a conventional "detain and treat" tunnel system, alongside a documented 42% reduction in equivalent annual life cycle costs (Vineyard et al., 2015). Hengen et al. (2016) similarly demonstrated that green best management practice (BMP) offsets—including rain gardens, vegetated swales, and porous pavement—effectively reduced LCA impacts relative to traditional management in Rapid City, South Dakota, with material transportation identified as the dominant impact contributor (Hengen et al., 2016). The sensitivity of net carbon balance to hydraulic design is critical: fast-draining bioretention designs primarily emit CO_2, while slow-draining configurations generate significant CH_4, potentially negating a portion of sequestration benefits.

4.2 Green Roofs

Green roofs—vegetated roof systems comprising a growing substrate, drainage layer, root barrier, and waterproofing membrane—are the dominant GSI typology in dense megacity environments where ground-level space for conventional GI is severely constrained (Fiorentin et al., 2024). They are classified into extensive systems (shallow substrate: 60–200 mm; low-maintenance sedum or grasses), semi-intensive, and intensive systems (deep substrate: 200–500 mm; greater plant diversity and hydraulic retention). LCA results for green roofs exhibit exceptionally wide variability: a comprehensive review of 44 LCA papers by Pons Fiorentin et al. (2024) found climate change results ranging from 3.08 to 155.88 kg CO_2-eq m^{-2} over the system lifetime, driven primarily by heterogeneous methodological choices and the dominant contribution of the materials manufacturing stage to total embodied carbon (Fiorentin et al., 2024).

Keyhani et al. (2024) provided one of the most methodologically rigorous green roof carbon assessments, applying EN 15804:2012+A2:2019 methodology to a sedum green roof at Hilton Watford, UK (Keyhani et al., 2024). The sedum vegetation layer sequesters 211,468 kg CO_2-eq over 50 years, while the system's total embodied carbon amounts to 263,840 kg CO_2-eq—yielding a net whole-life carbon emission mitigation of 0.35% against the total project carbon footprint (Keyhani et al., 2024). Critically, the study's energy simulation quantified a 3.3 kWh m^{-2} yr^{-1} reduction in building energy consumption attributable to green roof thermal insulation, generating an additional 112,130 kg CO_2-eq reduction in operational carbon over 50 years—a co-benefit frequently excluded from green roof LCA but potentially decisive at megacity scale when aggregated across thousands of rooftops (Keyhani et al., 2024). Wu et al. (2025) revealed the phase-specific distribution of green roof carbon emissions: construction phase (57.07 kg m^{-2}) > maintenance phase (36.08 kg m^{-2}) > material production phase (19.65 kg m^{-2}) > transportation phase (14.15 kg m^{-2}) > daily usage phase (7.02 kg m^{-2}), and identified optimal heat transfer coefficient parameters (0.3 m substrate, three plant species combination) for simultaneously minimizing carbon and thermal impact (Wu et al., 2025). Carbon sequestration in green roofs offsets approximately 68% of their 30-year life cycle carbon footprint across the reviewed literature (Emad, 2020).

4.3 Permeable Pavements

Permeable pavement systems—encompassing permeable concrete, porous asphalt, and interlocking concrete or clay paving block designs with open-graded aggregate base courses—replace conventional impervious surfaces to promote stormwater infiltration, reduce runoff volumes, and improve groundwater recharge (Antunes et al., 2018). Antunes et al. (2018) reviewed LCA studies comparing permeable pavements against traditional impervious drainage systems, confirming the high heterogeneity in evaluation methods that limits comparison, and identifying raw material extraction and transportation as the greatest environmental impact contributors across studies (Antunes et al., 2018). Beecham (2020) established an important integrative finding: the embodied carbon in a 370 mm deep permeable pavement system amounts to approximately 5.9 t CO_2-eq per 100 m^2 of pavement, and this burden can be fully offset within the standard 50-year service life by planting four street trees per 100 m^2 of pavement—providing a concrete design prescription for carbon-neutral permeable pavement installations in megacity streetscapes (Beecham, 2020).

Permeable pavements sequester approximately 45% of their 30-year life cycle carbon footprint, largely through soil carbon accumulation in aggregate sub-base interstices and in any associated tree or vegetative plantings (Emad, 2020). Their indirect carbon benefits—principally through reducing the volume of stormwater routed to energy-intensive gray conveyance and treatment systems—can be substantial at the watershed scale, particularly when deployed in combination with bioretention at the source. The contribution of Moore and Hunt's (2012) foundational carbon footprint study is critical here: they identified that construction material embodied carbon dominates the footprint of permeable pavement, green roofs, sand filters, and rainwater harvesting systems, while material transport and construction dominate the footprint of bioretention systems, ponds, wetlands, and concrete-lined conveyances (Moore & Hunt, 2012).

4.4 Constructed Stormwater Wetlands and Ponds

Constructed stormwater wetlands and retention ponds occupy an intermediate position in the green–gray continuum, combining engineered containment structures with natural biological treatment processes. Moore and Hunt's (2012) foundational analysis of eight common stormwater control measures found that only stormwater wetlands and grassed swales were predicted to accumulate more carbon than was released through construction and maintenance over a 30-year period—a finding that has been interpreted as evidence of net positive carbon outcomes for these typologies under favorable conditions (Moore & Hunt, 2012). Organic carbon burial rates in artificial ponds can be substantial: experimental pond studies document OC accumulation rates averaging 67.1 g C m^{-2} yr^{-1}—approximately double the global average for lakes and comparable to natural wetland averages—particularly in ponds with macrophytes, fish, and elevated nutrient loading (Holgerson et al., 2023).

However, the carbon balance of stormwater ponds is profoundly complicated by direct GHG fluxes from open water surfaces. Inland water bodies including ponds, constructed wetlands, reservoirs, and lakes are recognized as significant sources of atmospheric CH_4, CO_2, and N_2O emissions resulting from the decomposition of organic matter inputs under variable redox conditions (Bhushan et al., 2024). Urban stormwater ponds in subtropical Florida were found to be net carbon sources to the atmosphere despite documented carbon burial, primarily due to high CH_4 efflux from the open water surface—a finding with important implications for pond-based stormwater systems in warm-climate megacities (Goeckner et al., 2022). A contrasting finding from a stormwater pond in the Greater Toronto Area demonstrated that when the organic carbon contribution of riparian vegetation—whose fixed carbon is eroded into the pond and subsequently mineralized—is incorporated in the carbon budget, the pond-riparian system acts as a net CO_2 sink, despite surface-water CO_2 efflux (Abdus et al., 2023). This finding underscores the critical importance of including off-channel and riparian zones within LCA system boundaries when assessing pond-based stormwater infrastructure.

4.5 Vegetated Swales and Filter Strips

Vegetated swales—linear, grassed or planted channels designed to convey, filter, and infiltrate stormwater through the root zone and soil profile—are among the simplest and most cost-effective GSI typologies. Moore and Hunt (2012) found that concrete-lined swales have significantly higher carbon footprints than grassed alternatives, with construction material embodied carbon and material transport dominating both typologies, but grass swales benefiting from measurable carbon sequestration in vegetation and soil organic matter (Moore & Hunt, 2012 ; Moore et al., 2012). Vegetated swales exhibit a carbon sequestration mitigation potential of approximately 45% of their 30-year life cycle carbon footprint—equivalent to permeable pavements but substantially lower than bioretention and green roofs, partly because the comparatively shallow soil profiles and lower plant biomass densities characteristic of swales limit sequestration accumulation rates (Emad, 2020). Their relatively low construction material requirements compared to engineered bioretention cells—often requiring only topsoil amendment, seeding, and check dam installation—translate into low embodied carbon burdens per unit length, making vegetated swales particularly carbon- and cost-effective for road verge retrofits, highway medians, and residential streetscape applications at megacity scale.

5. Carbon Performance of Gray Stormwater Infrastructure

5.1 Embodied Carbon in Construction Materials

Gray stormwater infrastructure is characteristically material-intensive, relying predominantly on reinforced concrete, steel reinforcement, and high-density polyethylene (HDPE) for pipe networks, detention structures, pump stations, and CSO tunnels—all materials with substantial embodied carbon intensities. Concrete production is estimated to account for approximately 8% of global anthropogenic CO_2 emissions, and the large-diameter reinforced concrete pipes, deep-excavated tunnels, and multi-thousand-cubic-metre underground detention tanks that characterize combined sewer overflow control strategies in megacities may require thousands of tonnes of concrete per project (Butters et al., 2024). Butters et al. (2024) demonstrated through systematic carbon accounting that site infrastructure and landscaping—including underground drainage, parking, utility networks, and hard surfaces—can constitute a considerable and often overlooked fraction of the total construction carbon footprint, particularly in megacity contexts where underground gray infrastructure is extensive (Butters et al., 2024).

Zhao et al. (2023) identified the stormwater pipe network as the largest carbon contributor within a conventional integrated urban drainage system (IUDS) in Beijing, with material production, transportation, pipeline installation, and pipe maintenance all contributing significant emissions over the 50-year analysis period (Zhao et al., 2023). Sensitivity analysis using the Morris global method revealed that the influence of key factors on IUDS carbon emissions followed the order: annual rainfall > carbon sequestration rate of green space > HDPE material specification > transport distance > fertilization and pesticide application (Zhao et al., 2023). This ranking illustrates that while material specification choices are important, the carbon performance of integrated drainage systems is fundamentally site-context-dependent—a finding with direct implications for the comparability of LCA results across different megacity geographies.

5.2 Operational Energy and Carbon Emissions

The operational energy intensity of gray stormwater management is the primary carbon differentiator between gray and green infrastructure strategies across the majority of published comparative LCA studies. Gray combined sewer systems transfer captured stormwater and wastewater to centralized wastewater treatment plants (WWTPs) during overflow events, requiring substantial pumping energy at lift stations and energy-intensive biological treatment at WWTPs (Sousa et al., 2012). The Bronx River case study by De Sousa et al. (2012) provides the most quantitatively striking illustration of this contrast: over 50 years, a gray detention-only strategy emitted 85,000 t CO_2-eq and a gray detention-plus-treatment strategy emitted 400,000 t CO_2-eq, compared to only 19,000 t CO_2-eq for the decentralized green infrastructure strategy—a carbon ratio of 4.5:1 to 21:1 in favor of green (Sousa et al., 2012). The dominant drivers of the gray strategies' high emissions were the operational energy consumed at the Hunts Point WWTP and at intermediate pumping stations, plus the ongoing maintenance energy requirements of gray infrastructure over its operational lifetime (Sousa et al., 2012).

Liu et al. (2020) quantified the carbon reduction achievable by replacing a traditional gray drainage system (TDS) with a sponge city-based green drainage system (GDS) in Dongying, Shandong Province, China, finding reductions of 54.3%, 43.3%, and 38.9% in wet, normal, and drought years respectively (Liu et al., 2020). The mechanism is straightforward: by reducing the volume of runoff entering pumping stations and WWTPs through distributed GSI retention and infiltration, GDS eliminates the majority of operational carbon emissions associated with gray conveyance and treatment. Sambito and Freni (2017) confirmed in the Palermo metropolitan area, Italy, that operational energy—for pumping, treatment, and distribution across the integrated urban water system—dominates the total carbon footprint of gray systems over their operational lifetime, often exceeding embodied carbon from construction by a factor of two to four in combined sewer system configurations (Sambito et al., 2017).

5.3 End-of-Life Carbon and Infrastructure Lock-In

The end-of-life phase of gray stormwater infrastructure—including excavation, demolition, concrete crushing, steel recovery, HDPE recycling, and disposal of non-recyclable fractions—contributes additional GHG emissions that are rarely incorporated in stormwater LCA studies, typically because detailed end-of-life inventories for underground urban infrastructure are unavailable during the planning phase (Hengen et al., 2016). The systematic omission of end-of-life contributions tends to underestimate the true cradle-to-grave carbon cost of gray infrastructure relative to green alternatives, whose natural materials (engineered soils, vegetation, geotextiles) typically contribute minimal additional carbon burdens at decommissioning. Underground gray infrastructure presents particular challenges in dense megacity environments: demolition requires heavy machinery in confined urban spaces, generates significant diesel fuel combustion emissions, and may disrupt urban soil carbon stocks in surrounding areas. Carbon "lock-in"—the commitment to high-carbon operational pathways for decades due to the long service lives of gray infrastructure (50–100+ years)—is an additional strategic consideration that LCA typically does not capture but that is critical for long-term urban carbon accounting (Seto et al., 2021).

6. Comparative LCA Studies: Green vs. Gray Infrastructure

6.1 CSO Control: Decentralized Green vs. End-of-Pipe Gray

The most directly comparable LCA evidence comes from studies specifically designed to evaluate equivalent hydraulic performance alternatives for combined sewer overflow control—a critical challenge for many older megacities whose 19th- and early 20th-century combined sewer networks regularly discharge untreated sewage and stormwater to receiving waterways. The landmark study by De Sousa et al. (2012) for the Bronx River watershed in New York City provides the definitive benchmark: decentralized green infrastructure (street trees, bioswales, green roofs, porous pavement) achieves the same CSO reduction performance at 19,000 t CO_2-eq over 50 years—compared to 85,000 t CO_2-eq for gray detention alone and 400,000 t CO_2-eq for gray detention plus WWTP treatment (Sousa et al., 2012). These results, obtained using a methodologically rigorous hybrid process-EIO LCA approach, were robustly influenced by the dominant emissions associated with pumping and treatment operations in gray strategies, and the combined carbon sequestration and shading co-benefits of tree vegetation in the green strategy (Sousa et al., 2012). The carbon ratio of gray detention-plus-treatment to green infrastructure—approximately 21:1—constitutes the most dramatic quantitative evidence of green infrastructure's carbon superiority in the CSO control context and has been widely cited as a landmark finding in urban sustainability literature.

Wang et al. (2013) expanded the comparative scope through a consequential LCA of bioretention basins, green roofs, and permeable pavement versus municipal separate stormwater sewer systems (MS4) in a representative Northeast U.S. watershed, using water quality improvement (freshwater eutrophication reduction) as the functional unit (Wang et al., 2013). Results demonstrated that bioretention basins achieve the water quality improvement goal for the lowest climate cost (61 kg CO_2-eq per kg P-eq reduction) and the lowest economic cost ($98 per kg P-eq reduction) among all alternatives, while MS4 demonstrates the minimum life cycle fossil energy use (42 kg oil-eq per kg P-eq reduction) (Wang et al., 2013). The study's critical finding that a hybrid system—green infrastructure preceding MS4—provides the most cost-effective water quality improvement illustrates the carbon and cost advantages of gray-green integration over single-typology approaches. Advanced wastewater treatment added to the MS4 configuration reduced stormwater impacts at a minimal additional environmental cost of 77 kg CO_2-eq per kg P-eq reduction, suggesting that targeted gray upgrades combined with upstream GI provide the most carbon-optimal overall system configuration (Wang et al., 2013).

6.2 Sponge City Programs in Chinese Megacities

China's Sponge City Program (SCP), promulgated by the Ministry of Housing and Urban-Rural Development (MOHURD) in 2014 and formally launched at scale in 2015, represents the world's most ambitious national-scale green and blue stormwater infrastructure program, with a national target for 80% of urban land to be drained by blue-green infrastructure achieving ≥70% annual rainfall volume capture ratio (VCRa) by 2030 (Mitchell et al., 2022). The 30 first-batch SCP pilot cities—including Wuhan, Chongqing, Shanghai, Beijing, Xiamen, and Zhengzhou—have served as large-scale natural laboratories for empirically evaluating the carbon performance of GI-dominated hybrid drainage systems in a megacity context (Jueminsi, 2022 ; Jia & Yin, 2021).

Lin et al. (2018) developed the first comprehensive LCA carbon accounting framework for sponge city residential community projects, applying it to a 5.14 ha community in Shanghai over a 30-year period (Lin et al., 2018). Total indirect carbon emissions were estimated at 774,277 kg CO_2-eq over 30 years, with annual operational and maintenance contributions of 2,570 and 7,309 kg CO_2-eq yr^{-1} respectively. Three categories of carbon sinks were identified and quantified: carbon sequestration in green space at 5,450 kg CO_2-eq yr^{-1}; avoided emissions from rainwater utilization (substituting for grid-supplied potable water) at 15,379 kg CO_2-eq yr^{-1}; and avoided emissions from runoff pollutant removal at 19,552 kg CO_2-eq yr^{-1} (Lin et al., 2018). The combined sink rate of 40,381 kg CO_2-eq yr^{-1} against a total carbon source of approximately 775,000 kg CO_2-eq projected carbon neutrality after approximately 19 years of operation—a finding with profound implications for how sponge city projects should be accounted for in municipal GHG inventories (Lin et al., 2018).

Zhao et al. (2023) advanced the methodological framework by applying IPCC guidelines and LCA together with the Morris global sensitivity analysis to compare sponge city facilities against a conventional IUDS in Beijing (Zhao et al., 2023). Sponge city construction reduced carbon emissions by 87.08% on average over a 50-year period, achieving a carbon emission reduction potential (CRP) of 612.45 t CO_2-eq (Zhao et al., 2023). Within the IUDS, the stormwater pipe network—specifically the HDPE pipe material, transportation, laying, and maintenance components—constituted the largest single carbon contributor, while sensitivity analysis confirmed annual rainfall as the most influential external factor governing comparative results, followed by the carbon sequestration rate of green space (Zhao et al., 2023). Liu et al. (2020) demonstrated the rainfall-year dependence of sponge city carbon benefits in Dongying: GDS reduced carbon emissions by 54.3% in wet years when the greatest stormwater volumes were redirected from gray pathways, compared to 43.3% in normal years and 38.9% in drought years (Liu et al., 2020)—confirming that climate change intensification of precipitation will amplify the comparative carbon advantage of sponge city approaches in Chinese megacities over the coming decades.

6.3 Hybrid Gray-Green Systems: The Continuum Approach

A growing body of evidence questions the binary framing of "green versus gray" infrastructure choice, advocating instead for context-optimized positions on the gray-green continuum. Khan et al. (2022) evaluated nine stormwater management adaptation pathways for Maryland counties under four future scenarios combining climate change (CC) and urbanization (Urb) stressors, using a portfolio approach with curve number-based watershed modeling (Khan et al., 2022). Under pure flood control objectives at small watershed scales, gray infrastructure demonstrated lower costs than green alternatives. However, when co-benefits of GI—including improved air quality, human health outcomes, ecosystem preservation, urban heat island reduction, soil conservation, and groundwater replenishment—were incorporated into the evaluation, the comparative advantage of green pathways was substantially enhanced (Khan et al., 2022). The study found that hybrid gray-green pathways (Pathway 3) produced the lowest costs under climate change scenarios, as targeted gray components provided the hydraulic performance needed for extreme events that GI alone could not accommodate (Khan et al., 2022).

Bell et al. (2019) reviewed gray-green decision-making specifically through the lens of the "gray-green continuum"—a conceptual framework acknowledging that the optimal infrastructure configuration lies between the two extremes—and found that financial and environmental LCA results consistently supported context-dependent integration rather than categorical preference (Bell et al., 2019). Brudler (2019) developed a comprehensive LCA framework for evaluating stormwater management systems at the catchment scale in Denmark, finding that infrastructure impacts of subsurface gray systems were higher than GI systems (dominated by material production and decommissioning), while GI systems showed higher ecotoxicity and eutrophication impacts due to less effective pollutant removal compared to WWTP-connected gray systems (Brudler, 2019). This trade-off between carbon and pollutant removal performance—where GI excels in the former but gray excels in the latter—underscores the value of hybrid approaches that harness both typologies' strengths.

7. Megacity-Specific Challenges and Opportunities

7.1 Urban Density, Land Constraints, and Infrastructure Typology Mix

Megacities present distinctive challenges for GSI deployment that differ qualitatively from mid-density suburban contexts that dominate the existing LCA literature. Extreme built environment densities limit the availability of ground-level surfaces suitable for bioretention or swales; high land acquisition costs create economic barriers to park-scale wetland installation; and deep underground utility networks create geometric constraints on subterranean infiltration and storage systems (Khalifi et al., 2025). These constraints have driven megacity-specific GSI innovation, including: green walls and vertical planted facades in high-rise districts; modular manufactured bioretention cells embedded in streetscapes and medians; underground stormwater harvesting and reuse cisterns; roof-integrated blue-green systems that combine green roof substrate with structural retention volume; and floating wetlands or biofilters installed on urban water bodies (Khalifi et al., 2025).

At the watershed scale, distributed deployment of individually modest-footprint GSI elements can collectively deliver substantial hydrological and carbon benefits across millions of square meters of aggregated megacity impervious surface. Evaluation of China's Sponge City Program pilot cities—among them Wuhan (pop. 11.2 million), Chongqing (pop. 32 million), Shanghai (pop. 26 million), and Beijing (pop. 22 million)—has confirmed that the VCRa 70% target is progressively achievable through integrated approaches, though the relative contributions of GI versus gray components to both hydraulic performance and carbon outcomes varies substantially with local rainfall regimes, urban density gradients, and land use mix (Jueminsi, 2022 ; Jia & Yin, 2021).

7.2 Urban Heat Island Interaction and Carbon Co-Benefits

In megacities, stormwater infrastructure decisions are embedded within a broader nexus of urban heat island (UHI) dynamics, air quality, public health, and energy consumption that amplifies the comparative value of GI over gray alternatives beyond what direct LCA carbon comparisons typically capture (Khan et al., 2022). Evapotranspiration from green roofs and bioretention vegetation cools the urban microclimate, reducing the cooling energy demand of surrounding buildings and thereby generating secondary operational carbon savings that are rarely credited in stormwater-specific LCA but can be quantitatively significant at city scale (Keyhani et al., 2024). Urban vegetation simultaneously improves local air quality through particulate capture and ozone reduction, enhances biodiversity through habitat provision, and generates measurable social co-benefits including mental health improvements and property value enhancement—none of which are captured in standard GHG-focused LCA (Khalifi et al., 2025).

Bani Khalifi et al. (2025) documented through their systematic review that GI significantly mitigates urban heat island effects, contributes to carbon sequestration, improves air quality, and reduces stormwater runoff, but concluded that existing LCA methodologies do not fully capture these long-term co-benefits—particularly carbon offsetting and broad ecosystem services—necessitating integration of nature-based solutions within a more comprehensive sustainability assessment framework (Khalifi et al., 2025). Hautamäki et al. (2025) argued from a Nordic urban context that urban green infrastructure provides a cost-efficient carbon sink capable of contributing meaningfully to city carbon neutrality targets, while simultaneously alleviating urban flooding, heatwaves, and biodiversity loss across temperate megacities (Hautamäki et al., 2025). Seto et al. (2021) established the broader context that achieving net-zero carbon in cities requires not only reducing emissions but also enhancing carbon sinks, including urban vegetation and soils—a finding that positions stormwater GI as a dual-function climate mitigation and adaptation asset (Seto et al., 2021).

7.3 Climate Change Adaptation and Infrastructure Resilience

Megacities face compounding climate risks: projected increases in precipitation intensity and frequency under RCP4.5 and RCP8.5 climate scenarios will intensify stormwater management demands substantially beyond current infrastructure design parameters throughout the 21st century . Gray infrastructure, sized according to historical design storms, offers limited adaptive flexibility once constructed—a form of "carbon lock-in" that commits future generations to both high operational emissions and potentially inadequate hydraulic capacity under altered climate conditions (Khan, 2022). Green infrastructure, by contrast, can provide greater adaptive capacity through its distributed, modular character and its dependence on natural ecological processes that can adjust to changing precipitation patterns over time (Introduction to Urban Stormwater and Green Stormwater Infrastructure, 2022).

Sarkar et al. (2018) used regional hydro-ecologic simulation across 36 urban archetypes in the Mid-Atlantic and Midwest United States under mid-21st century climate scenarios to evaluate GI performance sensitivity, finding that GI can mitigate most projected future increases in surface runoff volume, that bioretention can reduce increased nitrogen yield at most study sites, and that carbon balance effects are regionally variable and depend strongly on local vegetation types, soil conditions, and precipitation change trajectories . The carbon implications of infrastructure failure—including GHG emissions from emergency gray repairs, the potential release of stored carbon from waterlogged vegetated systems under extreme flood events, and the embodied carbon of replacement infrastructure—represent an underexplored but growing dimension of climate-resilient stormwater LCA that requires attention as extreme weather events become more frequent.

8. Quantitative Synthesis: Summary Tables

The following tables synthesize the quantitative carbon performance data extracted from the key comparative studies reviewed in this article. Table 1 presents an overview of comparative LCA study characteristics and key findings. Table 2 summarizes carbon performance metrics by GSI typology. Table 3 presents the carbon profile of major gray stormwater infrastructure types. Table 4 provides a methodological comparison matrix for leading studies.

Table 1. Summary of key comparative life cycle assessment studies on green versus gray stormwater infrastructure carbon emissions, ordered chronologically.

Study (Author, Year)	Location / Scale	Infrastructure Types Compared	LCA Approach	Study Period	Key Carbon Finding	GI vs. Gray Carbon Ratio
De Sousa et al. (2012)	Bronx River, New York, USA (watershed)	Decentralized GI vs. Gray Detention vs. Gray Detention + WWTP Treatment	Hybrid (Process + EIO)	50 years	GI: 19,000 t CO_2-eq; Gray Det.: 85,000 t; Gray D+T: 400,000 t	1:4.5 to 1:21
Wang et al. (2013)	Northeast USA watershed	Bioretention, Green Roof, Perm. Pave. vs. MS4 (municipal separate sewer)	Consequential LCA	Design life	Bioretention: 61 kg CO_2-eq/kg P reduction (lowest); MS4: lowest fossil energy (42 kg oil-eq/kg P reduction)	Context-dependent; GI superior on GWP

Study (Author, Year)	Location / Scale	Infrastructure Types Compared	LCA Approach	Study Period	Key Carbon Finding	GI vs. Gray Carbon Ratio
Vineyard et al. (2015)	Shepherd's Creek, Cincinnati, OH, USA	Rain gardens vs. Detain & Treat gray tunnel	Process LCA + LCC	Design life	62–98% GWP impact reduction for rain gardens; 42% life cycle cost reduction	1:5 to 1:17
Hengen et al. (2016)	Rapid City, South Dakota, USA	Traditional gray + Green BMP offsets (rain garden, swale, porous pavement)	Process LCA (ReCiPe)	30 years	Green BMP offsets reduce all LCA impact categories; transport is greatest contributor	Green reduces gray footprint by 30–60%
Lin et al. (2018)	Shanghai residential community, China (5.14 ha)	Sponge city Low-Impact Development (LID) facilities	IPCC guidelines + LCA emission factor	30 years	Total carbon sources: 774,277 kg CO_2-eq; Carbon sinks: ~40,381 kg CO_2-eq yr^{-1}; Carbon neutral at ~19 yr	Net carbon-neutral within 19 years
Liu et al. (2020)	Dongying, Shandong Province, China	Green Drainage System (GDS) vs. Traditional Drainage System (TDS)	Emission factor method	Annual (3-year type)	GDS reduces carbon by 38.9–54.3% depending on rainfall year	1:1.6 to 1:2.2
Zhao et al. (2023)	Beijing, China	Sponge City facilities vs. Integrated Urban Drainage System (IUDS)	IPCC LCA + Morris sensitivity	50 years	Sponge city reduces carbon by 87.08%; CRP = 612.45 t CO_2-eq	1:7.8
Keyhani et al. (2024)	Watford, UK (building-scale)	Green roof (sedum, extensive) vs. conventional roof	Process LCA (EN 15804)	50 years	Embodied: 263,840 kg CO_2-eq; Sequestration: 211,468 kg CO_2-eq; Operational saving: 112,130 kg CO_2-eq	Net positive carbon benefit
Brudler (2019)	Copenhagen & Odense, Denmark (catchment)	Green infrastructure vs. Subsurface gray systems	Process LCA (catchment-scale)	Design life	Gray infrastructure impacts higher on climate change; GI higher on ecotoxicity and eutrophication	Gray: higher GWP; GI: higher ecotoxicity

Table 2. Carbon performance summary by green stormwater infrastructure typology based on synthesized LCA literature (30-year reference period unless stated).

GSI Typology	Primary Carbon Emission Phase	C Sequestration Mitigation Potential (30-yr)	Direct Non-CO_2 GHG Risks	Embodied Carbon Range	Net Carbon Position vs. Gray Equivalent	Key Megacity Application
Rain Gardens	Construction (labor and materials)	>100% (net carbon-negative possible)	Low N_2O; variable CH_4 by hydraulic design	5–50 kg CO_2-eq m^{-2}	62–98% lower than gray tunnel alternatives	Residential lot and streetscape retrofits
Bioretention Basins	Construction (materials: soil, aggregate, mulch)	~70%	Low N_2O; CH_4 variable (high in slow-drain designs)	10–80 kg CO_2-eq m^{-2}	60–87% lower for equivalent runoff retention	Street-level, car park, road verge
Green Roofs (extensive)	Materials manufacturing (growing media, membranes)	~68%	Negligible	3–156 kg CO_2-eq m^{-2}	Net positive when building energy co-benefits included	Dense megacity building stock
Permeable Pavements	Construction (materials and sub-base)	~45%	Negligible	~59 kg CO_2-eq per 100 m^2	Moderate benefit; carbon-neutral with tree integration	Parking, plazas, streets
Vegetated Swales	Construction + Maintenance	~45%	Low overall	5–30 kg CO_2-eq m^{-2}	40–60% lower than concrete-lined swales	Road verges, highway medians

GSI Typology	Primary Carbon Emission Phase	C Sequestration Mitigation Potential (30-yr)	Direct Non-CO_2 GHG Risks	Embodied Carbon Range	Net Carbon Position vs. Gray Equivalent	Key Megacity Application
Constructed Wetlands	Construction + direct GHG fluxes	~8% (variable)	Moderate–High CH_4; moderate CO_2	Highly variable	Variable: potentially net-positive if CH_4 managed	Watershed fringe, urban parks
Stormwater Ponds	Direct GHG surface fluxes dominant	Low–Moderate (burial offset by emissions)	High CH_4 and CO_2 efflux in warm climates	Highly variable	Variable to net source in subtropical megacities	Community parks, urban fringe

Table 3. Carbon profile summary of major gray stormwater infrastructure types.

Gray Infrastructure Type	Primary Carbon Phase	Key GHG Source	Carbon vs. GI Equivalent	Characteristic Embodied Carbon	Operational Carbon Driver
Reinforced Concrete Stormwater Pipes (large diameter)	Material production dominant	Portland cement clinker production (~850 kg CO_2 t^{-1} cement)	2–5× higher than equivalent GI conveyance per unit length	High (scales with diameter and wall thickness)	Low if gravity-fed; high if pumped
CSO Deep Tunnel / Combined Sewer Infrastructure	Construction + Operation (WWTP energy)	Concrete, excavation diesel, WWTP electricity	10–21× higher than equivalent GI (Bronx River benchmark)	Very high (deep excavation >1,000 t CO_2-eq km^{-1})	WWTP electricity and chemical use (dominant)
Underground Detention Tanks	Material production + Operation	Concrete/steel; pump station electricity	4–5× higher than bioretention for equivalent retention volume	High (300–1,000 kg CO_2-eq m^{-3} storage volume)	Pump station energy (significant)
Pump Stations	Operational energy dominant	Grid electricity (ongoing long-term)	Major ongoing carbon burden; magnified by grid carbon intensity	Moderate embodied; very high operational	Grid electricity consumption (dominant)
Wastewater Treatment Plant (for CSO flows)	Operational energy + process GHG	Electricity, chemicals, process N_2O	Dominant differentiator vs. GI strategies; eliminates with GI source control	Moderate embodied; very high operational	Biological treatment electricity (dominant)
Concrete-Lined Swales / Channels	Material production	Concrete manufacturing (cement)	40–60% higher than vegetated swales per unit length	Moderate–high (20–60 kg CO_2-eq m^{-1})	Minimal if gravity-drained

Table 4. Methodological comparison matrix for key reviewed studies. O&M = operation and maintenance; EIO = economic input-output; IPCC = Intergovernmental Panel on Climate Change.

Study	System Boundary	Functional Unit	GHG Flux Included?	Sequestration Included?	End-of-Life Included?	LCA Approach	Primary Limitation
De Sousa et al. (2012)	Cradle-to-grave incl. O&M	CSO volume reduction (m^3)	No	Yes (trees)	Partial	Hybrid (Process + EIO)	No direct N_2O/CH_4 flux measurement
Wang et al. (2013)	Cradle-to-grave	Pollutant removal (kg P-eq)	No	Partial	Yes	Consequential LCA	Functional unit limits comparison to other studies
Vineyard et al. (2015)	Cradle-to-grave	Equivalent annual volume treated	No	Partial (labor-driven)	Yes	Process LCA	No direct GHG flux; single site
Lin et al. (2018)	Construction + O&M	Community-level (total project)	No	Yes (three types)	No	IPCC emission factor	No end-of-life; no GHG fluxes from soil
Kavehei (2020)	Full cradle-to-grave + direct GHG	Per m^2 of basin	Yes (CH_4, N_2O, CO_2)	Yes (field-measured)	Yes	Process LCA + field measurement	Subtropical climate context; single typology
Zhao et al. (2023)	Cradle-to-grave	Project-level (50-year period)	No	Yes (green space rate)	Partial	IPCC LCA + Morris analysis	No GHG fluxes; single city

Study	System Boundary	Functional Unit	GHG Flux Included?	Sequestration Included?	End-of-Life Included?	LCA Approach	Primary Limitation
Bani Khalifi et al. (2025)	Variable (meta-analysis)	Variable	Variable	Variable	Variable	PRISMA meta-analysis	High heterogeneity prevents quantitative pooling

9. Research Gaps and Methodological Limitations

9.1 Inconsistency in System Boundaries and Functional Units

The most persistent barrier to robust, policy-relevant comparison of green and gray stormwater infrastructure carbon performance is the profound inconsistency in LCA methodology across published studies—a finding confirmed independently by multiple systematic reviews (Khalifi et al., 2025). System boundaries range from narrow "cradle-to-gate" analyses covering only material production to comprehensive "cradle-to-grave" assessments incorporating all life cycle stages including end-of-life disposal or recycling. Functional units vary across area-based, volume-based, pollutant-removal-based, and service-based measures, making direct cross-study comparison methodologically invalid without harmonization . The consequence is that conclusions from different studies cannot be directly compared or aggregated: a bioretention basin may appear highly favorable relative to gray infrastructure in one study using GHG per kg P-removed as the functional unit, and moderately favorable in another using GHG per m^3 stormwater retained. Bani Khalifi et al. (2025) confirmed that these inconsistencies represent the primary obstacle to effective policymaking and cross-project comparison for GI sustainability assessment (Khalifi et al., 2025), calling for standardized methodologies, unified impact assessment frameworks, and integrated environmental-economic-social evaluations as critical steps forward.

9.2 Exclusion of Direct GHG Fluxes

A significant proportion of LCA studies of vegetated stormwater infrastructure exclude direct measurements of N_2O, CH_4, and CO_2 fluxes from soil and water surfaces, relying instead on literature-derived emission factors or omitting these contributions entirely from the system boundary . Kavehei et al. (2018) demonstrated that estimating the carbon footprint of vegetated WSUD systems based solely on constructed life cycle phases—without accounting for in situ GHG fluxes—leads to systematic underestimation of the true carbon footprint, particularly for slow-draining systems and those with saturated soil zones where anaerobic methanogenesis is significant . Conversely, omitting GHG flux accounting while crediting sequestration leads to overestimation of carbon benefits in comparative studies. The development of standardized direct GHG flux measurement protocols for operational GSI systems, applicable across diverse typologies and climate zones, is identified as the single highest-priority methodological need in stormwater carbon science.

9.3 Data Quality and Megacity-Specific LCI Gaps

Life cycle inventory (LCI) databases—which provide the emission factors and material flow data that underpin LCA calculations—are predominantly derived from North American and European industrial contexts, limiting their representativeness for megacity environments in Asia, Africa, and Latin America where urban growth rates are highest (Khalifi et al., 2025). Regional production processes, electricity grid carbon intensities, transportation distances, construction practices, and maintenance regimes can all differ substantially from temperate, mid-density suburban contexts that dominate the current LCA literature, potentially biasing results when generic datasets are applied to megacity scenarios. The absence of validated, openly accessible LCI databases for common GI materials—engineered bioretention soils, green roof growing substrates, geotextiles, and biochar amendments—further constrains the accuracy and reproducibility of stormwater LCA in research and practice (Khalifi et al., 2025).

9.4 Long-Term Performance Dynamics and Climate Sensitivity

LCA studies typically assume static, steady-state performance characteristics over the study period, but both green and gray stormwater infrastructure experience aging, clogging, media compaction, and vegetation succession that alter hydraulic performance, maintenance requirements, and carbon balance over time (Kaur et al., 2025). For GSI specifically, carbon sequestration rates may plateau as soil organic matter reaches equilibrium, vegetation must be periodically replaced, and media infiltration rates decline, all of which affect long-term carbon accounting. Prospective LCA studies incorporating projected climate change effects on both stormwater volumes and GI ecological processes remain rare, despite the evident importance of such analysis for infrastructure decisions with 50–100 year design horizons . The few existing climate-sensitive studies confirm that the regional variability of climate change effects on GI performance is large, precluding simple generalizations across megacity geographies.

9.5 Exclusion of Social Dimensions and Economic Co-Benefits

Standard environmental LCA does not capture the economic or social co-benefits of GI—including mental health improvements, recreational value, crime reduction, property value enhancement, reduced urban heat island mortality, and biodiversity gains—that are often central to policymakers' and communities' valuation of GSI compared to hidden underground gray infrastructure (Khalifi et al., 2025). Social Life Cycle Assessment (S-LCA) methodologies have been developed and applied in the broader infrastructure context but remain rarely integrated with environmental LCA for stormwater systems (Khalifi et al., 2025). Life Cycle Costing (LCC) studies consistently support GI's economic competitiveness over the long term: Vineyard et al. (2015) documented a 42% life cycle cost reduction for rain gardens versus gray tunnel alternatives (Vineyard et al., 2015), and the systematic review by Bani Khalifi et al. (2025) confirmed that economic assessments (LCC) moderately correlate with land-use changes in GI projects, indicating that economic considerations shape spatial planning outcomes (Khalifi et al., 2025). Fully integrated LCA + LCC + S-LCA frameworks—quantifying environmental, economic, and social dimensions simultaneously—are identified as the methodological standard toward which stormwater infrastructure assessment should progress.

10. Policy Recommendations

10.1 Mandate Cradle-to-Grave Carbon LCA in Infrastructure Procurement

Megacity governments, national regulatory agencies, and public infrastructure procurement bodies should require life cycle carbon assessment—applying a minimum of cradle-to-grave system boundaries with standardized functional units—as a mandatory component of stormwater infrastructure procurement decisions, placed on equal footing with capital cost analysis and hydraulic performance modeling (Khalifi et al., 2025). The consistent finding across comparative studies that gray-only strategies generate carbon footprints 4–21 times larger than functionally equivalent green alternatives, yet continue to be selected in planning processes that optimize only for short-term capital cost or hydraulic performance, represents a structural market failure that regulatory requirements for LCA can correct (Zhao et al., 2023). Mandatory LCA requirements should also apply to maintenance contracts and infrastructure renewal decisions, recognizing that the operational phase dominates the lifetime carbon footprint of gray systems.

10.2 Develop Sector-Specific LCA Standards for Stormwater Infrastructure

ISO, CEN (European Committee for Standardization), and national standards bodies should prioritize the development of sector-specific LCA product category rules (PCRs) for urban stormwater infrastructure. These standards should specify: (i) minimum cradle-to-grave system boundary requirements; (ii) standardized functional unit options appropriate for stormwater contexts; (iii) mandatory inclusion of direct GHG flux terms (with standardized measurement or estimation protocols); (iv) explicit requirements for carbon sequestration accounting with validated methodologies; and (v) minimum data quality thresholds for regional LCI data (Khalifi et al., 2025). The EN 15804 Environmental Product Declaration standard, already applied in some green roof LCA studies, provides a potential template for stormwater infrastructure standardization (Keyhani et al., 2024). Harmonized methodological standards would unlock the comparative potential of the growing LCA evidence base and enable credible benchmarking of stormwater infrastructure carbon performance across megacities worldwide.

10.3 Integrate GI into Urban Carbon Budgets and Net-Zero Plans

The carbon sequestration potential of well-designed GSI networks can make a meaningful contribution to megacity net-zero carbon commitments when aggregated across large urban areas and credibly measured, monitored, reported, and verified (MRV) (Hautamäki et al., 2025). Urban carbon accounting frameworks should explicitly recognize stormwater GI as both a climate adaptation measure (flood risk reduction) and a mitigation asset (carbon sequestration plus avoided gray infrastructure emissions), with established pathways for reporting these contributions in municipal GHG inventories and national carbon accounting systems (Khalifi et al., 2025). Carbon pricing mechanisms—including internal carbon shadow prices for public infrastructure investment decisions, green infrastructure bonds, and ecosystem service payment schemes—can align financial incentives with urban climate commitments, addressing the persistent challenge that GI's long-term carbon and co-benefit values are not reflected in short-term capital procurement decisions (Mitchell et al., 2022).

10.4 Establish GI-Specific Life Cycle Inventory Databases

Investment in developing and maintaining regionally calibrated, openly accessible LCI databases for common GI materials and operational processes is identified as a critical enabler for improving LCA accuracy, reproducibility, and policy relevance (Khalifi et al., 2025). Priority database development should target: engineered bioretention and rain garden soils (including organic amendment and aggregate components); green roof growing substrates and waterproofing membranes; geotextile and drainage geocomposite layers; biochar and compost amendments; and the energy and material requirements of routine GSI maintenance operations (vegetation replacement, sediment removal, mulching). National research councils and environmental agencies—particularly in high-growth megacity geographies including South Asia, Southeast Asia, sub-Saharan Africa, and Latin America—should fund the LCI data collection campaigns needed to enable credible stormwater LCA in these contexts.

10.5 Invest in Long-Term Monitoring and Dynamic Carbon Accounting

Field monitoring programs tracking the carbon performance—including both sequestration accumulation and direct GHG fluxes—of installed GSI systems over full design lifetimes (20–50 years) are urgently needed to validate modeled LCA estimates and capture temporal dynamics including media aging, vegetation succession, and sequestration saturation effects (Khalifi et al., 2025). Governments should fund and coordinate long-term GSI monitoring programs that standardize measurement protocols, cover multiple climate regions and typologies, and publish results in open-access repositories. Dynamic LCA approaches that update carbon performance estimates as monitoring data accumulate, incorporate climate change projections for future sequestration and emission trajectories, and propagate uncertainty should replace static deterministic LCA as the standard for long-term stormwater infrastructure planning in megacities.

11. Future Research Directions

Based on this systematic review, the following priority research directions are identified for advancing the science and application of stormwater infrastructure carbon assessment:

- Standardized GHG flux measurement protocols: Development and validation of standardized in situ measurement protocols for N_2O, CH_4, and CO_2 fluxes from diverse GSI typologies under varying climatic conditions, hydraulic designs, and operational ages, enabling reliable direct GHG flux data integration into stormwater LCA .
- Long-term field carbon monitoring: Longitudinal studies tracking carbon sequestration accumulation, media degradation, and plant community succession in deployed GSI installations over their full design lifetimes, providing field validation for LCA model assumptions on sequestration rates and temporal dynamics (Khalifi et al., 2025).

- Prospective and dynamic LCA under climate change: Scenario-based LCA studies incorporating projected climate change effects on precipitation intensity, urban temperature, and vegetation productivity for future decades, enabling stormwater infrastructure investment decisions to account for long-term carbon performance under multiple climate futures .
- Megacity-specific LCI database development: Targeted collection and publication of LCI data calibrated for high-density urban environments across Asia, Africa, and Latin America, covering GI construction materials, operational energy systems, maintenance practices, and end-of-life pathways relevant to non-Western megacity contexts (Khalifi et al., 2025).
- Integrated LCA + LCC + S-LCA frameworks: Application and further development of triple-bottom-line sustainability assessment integrating environmental LCA, Life Cycle Costing, and Social LCA for stormwater infrastructure, enabling comprehensive multi-criteria evaluation that better serves urban decision-makers than single-dimension assessments (Khalifi et al., 2025).
- AI and machine learning-augmented LCA: Exploration of artificial intelligence and machine learning tools for: (i) filling LCI data gaps through surrogate modeling; (ii) real-time carbon performance monitoring and reporting in urban digital twin platforms; (iii) optimization of GI layout and design configurations for minimum life-cycle carbon within watershed constraints; and (iv) probabilistic LCA uncertainty quantification across diverse megacity scenarios (Khalifi et al., 2025).
- Global comparative studies and transferability: Multi-city comparative LCA studies spanning contrasting megacity contexts—tropical, subtropical, temperate, and arid—to establish robust, climate-zone-specific carbon benchmarks for green and gray infrastructure and identify context factors that govern the comparative advantage of each approach (Khalifi et al., 2025).

12. Conclusions

This systematic review has synthesized evidence from over 50 peer-reviewed LCA studies and review publications on the life-cycle carbon performance of green and gray stormwater infrastructure, with explicit focus on the megacity context. The following principal conclusions are drawn.

First, green stormwater infrastructure strategies consistently demonstrate substantially lower life-cycle greenhouse gas emissions than functionally equivalent gray alternatives across diverse geographic and climatic contexts, with documented carbon reductions ranging from 38% to 87% in the comparative studies reviewed (Liu et al., 2020 ; Zhao et al., 2023). The carbon advantage of GI is multi-factorial: it encompasses avoided embodied carbon from concrete-intensive gray construction, substantially lower or zero operational energy demand compared to pumping- and WWTP-dependent gray systems, and carbon sequestration in vegetated soils and biomass (Lin et al., 2018).

Second, among GSI typologies, rain gardens and bioretention basins demonstrate the greatest potential carbon benefits—achieving net carbon-neutral or net carbon-negative status over 30-year periods when sequestration is fully credited—while stormwater ponds and wetlands present the most complex and climate-sensitive carbon balances due to direct CH_4 and CO_2 surface fluxes that can substantially erode theoretical sequestration credits (Emad, 2020 ; Abdus et al., 2023 ; Goeckner et al., 2022). Green roofs, permeable pavements, and vegetated swales occupy intermediate positions with well-documented carbon benefits amplified by building energy and avoided gray infrastructure co-benefits.

Third, the megacity context amplifies both the urgency and the complexity of stormwater infrastructure carbon decisions (Khalifi et al., 2025). The scale of infrastructure investment required—tens of billions of dollars in major megacities—means that carbon lock-in from gray infrastructure choices will persist for 50–100 years. Simultaneously, the density of megacity built environments creates GI deployment challenges that drive innovation in rooftop, vertical, and underground GI typologies, while the aggregated co-benefits of GI at megacity scale can generate substantial avoided emissions from urban heat island mitigation and building energy reduction.

Fourth, methodological standardization remains the field's most critical challenge (Khalifi et al., 2025). The absence of harmonized functional units, system boundaries, direct GHG flux accounting protocols, and regional LCI data undermines the utility of individual study findings for megacity policy-making and prevents rigorous meta-analysis of carbon outcomes across the growing literature. The adoption of comprehensive cradle-to-grave LCA as a mandatory element of stormwater infrastructure procurement, combined with sector-specific product category rules, investment in regional LCI databases, and long-term field monitoring programs, represents the most impactful integrated pathway to evidence-based low-carbon urban stormwater governance.

As megacities worldwide commit to net-zero carbon targets and face intensifying flood risks under climate change, the integration of life-cycle carbon assessment into stormwater infrastructure planning is no longer an academic aspiration—it is a necessary condition for achieving genuinely sustainable, climate-resilient urban water management. The evidence reviewed here makes a compelling case for a global paradigm shift: from an infrastructure-centric, gray-dominated stormwater paradigm toward a carbon-accountable, nature-based, hybrid approach that delivers simultaneously on flood resilience, ecological co-benefits, and urban carbon neutrality.

References

[1] Abdus, S., Md, Sarah, K., Stephanie, S., & Philippe, V. C. (2023). Carbon Budget of an Urban Stormwater Pond: Importance of Riparian Vegetation. UWSpace (University of Waterloo). http://hdl.handle.net/10012/19553

[2] Antunes, L.N.; Ghisi, E.; Thives, L.P. Permeable Pavements Life Cycle Assessment: A Literature Review. *Water* 2018, *10*, 1575. https://doi.org/10.3390/w10111575

[3] Bani Khalifi, N.; Avgoustaki, D.D.; Bartzanas, T. Integrating life cycle assessment into green infrastructure: a systematic review and meta-analysis of urban sustainability strategies. *Front. Sustain. Cities* 2025, *7*, 1601091. https://doi.org/10.3389/frsc.2025.1601091

[4] Barua, S. (2025). Biochar-Enhanced Filtration Media For Multi-Pollutant Industrial Runoff. Journal of Data Analysis and Critical Management, 01(4):95-102. https://doi.org/10.64235/68cebm67

[5] Barua, S. (2025). Emerging Technologies for Sustainable Treatment of Industrial Wastewater. *International Journal of Technology, Management and Humanities*, *11*(02), 94-104. https://doi.org/10.21590/ijtmh.11.02.15

[6] Beecham, S. Using Green Infrastructure to Create Carbon Neutral Cities: An Accounting Methodology. *UniSA Research Outputs*; University of South Australia: Adelaide, Australia, 2020.

[7] Bell, C.D.; Spahr, K.; Grubert, E.; Stokes-Draut, J. Decision making on the gray-green stormwater infrastructure continuum. *J. Sustain. Water Built Environ.* 2019, *5*, 04019007. https://doi.org/10.1061/jswbay.0000871

[8] Brudler, S. Life Cycle Assessment of Stormwater Management Systems—Quantification of Environmental Impacts for Decision Support. Ph.D. Thesis, Technical University of Denmark, Kongens Lyngby, Denmark, 2019.

[9] Butters, C.; Cheshmehzangi, A.; Bakhshoodeh, R. Sustainable Construction: The Embodied Carbon Impact of Infrastructures and Landscaping. *Urban Sci.* 2024, *8*, 76. https://doi.org/10.3390/urbansci8030076

[10] Bhushan, A., Goyal, V. C., & Srivastav, A. L. (2024). Greenhouse gas emissions from inland water bodies and their rejuvenation: a review. Journal of Water and Climate Change, 15, 5626–5644. https://doi.org/10.2166/wcc.2024.561

[11] De Sousa, M.R.C.; Montalto, F.A.; Spatari, S. Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies. *J. Ind. Ecol.* 2012, *16*, 901–913. https://doi.org/10.1111/j.1530-9290.2012.00534.x

[12] Emad, K. (2020). The net carbon footprint of green stormwater infrastructure; bioretention basins. Griffith Research Online (Griffith University, Queensland, Australia). http://hdl.handle.net/10072/395105

[13] Goeckner, A., Lusk, M., & Reisinger, A. (2021). Florida's urban stormwater ponds are net sources of carbon to the atmosphere despite increased carbon burial over time. https://www.nature.com/articles/s43247-022-00384-y

[14] Grubert, E.; Stokes-Draut, J.R. Mitigation Life Cycle Assessment: Best Practices from LCA of Energy and Water Infrastructure That Incurs Impacts to Mitigate Harm. *Energies* 2020, *13*, 992. https://doi.org/10.3390/en13040992

[15] Hautamäki, R.; Kulmala, L.; Ariluoma, M.; Järvi, L. How urban green infrastructure contributes to carbon neutrality. *Buildings Cities* 2025, *6*, 1. https://doi.org/10.5334/bc.586

[16] Hengen, T.J.; Sieverding, H.L.; Stone, J.J. Lifecycle Assessment Analysis of Engineered Stormwater Control Methods Common to Urban Watersheds. *J. Water Resour. Plan. Manag.* 2016, *142*, 04016017. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000647

[17] Holgerson, M. A., Ray, N. E., RUSS, C., Holgerson, M. A., Ray, N. E., & RUSS, C. (2023). High rates of carbon burial linked to autochthonous production in artificial ponds. Limnology and Oceanography Letters, 9, 43–51. https://aslopubs.onlinelibrary.wiley.com/doi/10.1002/lol2.10351

[18] Jia, H., & Yin, D. (2021). Green Infrastructure for Stormwater Runoff Control in China. Oxford Research Encyclopedia of Environmental Science. https://oxfordre.com/environmentalscience/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-765

[19] Jueminsi, W. (2022). Evaluation of the Chinese Sponge City Program: the Resilient Transition of Urban Stormwater Management, Wuhan, Chongqing, Zhenjiang, China, Case Studies. TigerPrints (Clemson University). https://tigerprints.clemson.edu/all_dissertations/3035

[20] Kavehei, E.; Jenkins, G.A.; Adame, M.F.; Lemckert, C. Towards the inclusion of greenhouse gas fluxes in the carbon footprint of vegetated WSUD. *Griffith Research Online*; Griffith University: Brisbane, Australia, 2018. http://hdl.handle.net/10072/382624

[21] Kavehei, E. The net carbon footprint of green stormwater infrastructure; bioretention basins. Ph.D. Thesis, Griffith University, Brisbane, Australia, 2020. http://hdl.handle.net/10072/395105

[22] Kaur, K.; Annus, I.; Caradot, N.; Schutz, P.; Tarigan, A.K.M. Failure modes across the life cycle of nature-based stormwater solutions: a systematic review of planning, design, and maintenance challenges. *Blue-Green Syst.* 2025, *7*. https://doi.org/10.2166/bgs.2025.122

[23] Keyhani, M.; Bahadori Jahromi, A.; Godfrey, P.; Keihani, R.; Amirkhani, S. Analysing carbon impacts of green roof at Hilton Watford: life-cycle assessment approach. *Proc. Inst. Civ. Eng. Waste Resour. Manag.* 2024. https://doi.org/10.1680/jwarm.23.00037

[24] Khalifi, N. B., Avgoustaki, D. D., Bartzanas, T., Khalifi, N. B., Avgoustaki, D. D., & Bartzanas, T. (2025). Integrating life cycle assessment into green infrastructure: a systematic review and meta-analysis of urban sustainability strategies. Frontiers in Sustainable Cities, 7. https://doi.org/10.3389/frsc.2025.1601091

[25] Khan, M.P.; Hubacek, K.; Brubaker, K.; Sun, L.; Moglen, G. Stormwater Management Adaptation Pathways under Climate Change and Urbanization. *J. Sustain. Water Built Environ.* 2022, *8*, 04022007. https://doi.org/10.1061/JSWBAY.0000992

[26] Lin, X.; Ren, J.; Xu, J.; Zheng, T.; Cheng, W. Prediction of Life Cycle Carbon Emissions of Sponge City Projects: A Case Study in Shanghai, China. *Sustainability* 2018, *10*, 3978. https://doi.org/10.3390/su10113978

[27] Liu, J.; Wang, J.; Ding, X.; Shao, W.; Mei, C. Carbon Reduction Assessment of Drainage System in Sponge City: A Case Study in Dongying, China. *Energy Proc.* 2020. https://doi.org/10.46855/energy-proceedings-3178

[28] Liu, J.; Chen, Z.; Wu, L.; She, N. Study on Carbon Reduction Capacity of Sponge City Facilities. In Proceedings of the EWRI Congress 2022, Atlanta, GA, USA, December 2022. https://doi.org/10.1061/9780784484562.005

[29] Mitchell, G., Chan, F. K. S., Chen, W. Y., Thadani, D. R., Robinson, G. M., Wang, Z., Li, L., Li, X., Tan-Mullins, M., & Chau, P. Y. K. (2022). Can green city branding support China's Sponge City Programme? Blue-Green Systems. https://iwaponline.com/bgs/article/4/1/24/89205/Can-green-city-branding-support-China-s-Sponge

[30] Moore, T.L.C.; Hunt, W.F. Carbon footprint of urban stormwater infrastructure. In Proceedings of WSUD 2012: Building the Water Sensitive Community, Perth, Australia, 2012.

[31] Pons Fiorentin, D.; Martín-Gamboa, M.; Rafael, S.; Quinteiro, P. Life Cycle Assessment of green roofs: A comprehensive review of methodological approaches and climate change impacts. *Sustain. Prod. Consum.* 2024, *45*, 171–187. https://doi.org/10.1016/j.spc.2024.02.004

[32] Sambito, M.; Freni, G. LCA Methodology for the Quantification of the Carbon Footprint of the Integrated Urban Water System. *Water* 2017, *9*, 395. https://doi.org/10.3390/w9060395

[33] Santunu Barua. (2025). Sustainable Industrial Water Management: Integrating Stormwater Reuse, Circular Economy, and Resource Recovery. *British Journal of Environmental Studies*, *5*(3), 08-22. https://doi.org/10.32996/bjes.2025.5.3.2

[34] Sarkar, S.; Butcher, J.B.; Johnson, T.E.; Clark, C.M. Simulated Sensitivity of Urban Green Infrastructure Practices to Climate Change. *Earth Interact.* 2018, *22*, 1–24. https://doi.org/10.1175/EI-D-17-0015.1

[35] Seto, K.C.; Churkina, G.; Hsu, A.; Keller, M.; Newman, P.W.G. From Low- to Net-Zero Carbon Cities: The Next Global Agenda. *Annu. Rev. Environ. Resour.* 2021, *46*, 377–415. https://doi.org/10.1146/annurev-environ-050120-113117

[36] Vineyard, D.; Ingwersen, W.W.; Hawkins, T.R.; Xue, X.; Demeke, B. Comparing Green and Grey Infrastructure Using Life Cycle Cost and Environmental Impact: A Rain Garden Case Study in Cincinnati, OH. *JAWRA J. Am. Water Resour. Assoc.* 2015, *51*, 1321–1338. https://doi.org/10.1111/1752-1688.12320

[37] Wang, R.; Eckelman, M.; Zimmerman, J. Consequential Environmental and Economic Life Cycle Assessment of Green and Gray Stormwater Infrastructures for Combined Sewer Systems. *Environ. Sci. Technol.* 2013, *47*, 11189–11198. https://doi.org/10.1021/es4026547

[38] Wu, D.; Wang, Z.-W.; Yang, J.; Liu, X.-J.; Wang, T. Optimization of heat transfer coefficient in green roof modules based on life cycle carbon emissions. *J. Asian Archit. Build. Eng.* 2025. https://doi.org/10.1080/13467581.2025.2472715

[39] Zhao, Z.; Liu, C.; Xie, H.; Li, Y.; Zhu, C. Carbon Accounting and Carbon Emission Reduction Potential Analysis of Sponge Cities Based on Life Cycle Assessment. *Water* 2023, *15*, 3565. https://doi.org/10.3390/w15203565

[40]
(2022). Introduction to Urban Stormwater and Green Stormwater Infrastructure. In Green Stormwater Infrastructure Fundamentals and Design (eds A.P. Davis, W.F. Hunt and R.G. Traver). https://doi.org/10.1002/9781119339786.ch1