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Integrating life cycle assessment into green infrastructure: a systematic review and meta-analysis of urban sustainability strategies

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Green infrastructure (GI) is increasingly vital for cities addressing environmental challenges, climate change, and sustainability through nature-based solutions. However, the inconsistent use of life cycle assessment (LCA) methods—including variations in impact categories, data collection methods, system boundaries, and functional units—hinders effective policymaking and comparison among projects. This study conducted a systematic review and semi-quantitative meta-analysis, following PRISMA guidelines. Out of 334 publications (2014–2024) identified from Web of Science, Science Direct, and Google Scholar, 40 studies met the inclusion criteria. Analysis included critical sustainability indicators: carbon emissions, water footprint, energy use, land-use changes, and air pollution. Traditional LCA was most commonly applied, yet integration with economic (life cycle costing, LCC) and social dimensions (social LCA, S-LCA) remained limited. Meta-analysis indicated a slight positive correlation between standard LCA and water footprint (0.27) but a negative correlation with energy consumption (−0.18), suggesting trade-offs between water management and energy efficiency. Economic assessments (LCC) were moderately linked to land-use changes (0.15), reflecting economic considerations in GI projects. Social assessments (S-LCA) correlated positively with air pollution (0.20), highlighting potential conflicts between social and environmental objectives. Although GI significantly contributes to urban sustainability, the lack of standardized LCA methods limits comparative analyses and practical policy development. Standardizing methodologies, unifying impact assessments, integrating environmental, economic, and social evaluations, and developing financial incentives and advanced technological tools like artificial intelligence are critical steps forward. Future research should prioritize refining LCA accuracy, comprehensive lifecycle cost–benefit integration, and multi-dimensional sustainability analyses to better inform urban resilience policies.

KEYWORDS

green infrastructure, life cycle assessment, life cycle costing, social life cycle assessment, urban sustainability, climate resilience, policy standardization, ecosystem services evaluation

1 Introduction

Cities are growing at an incredible pace, and right now, more than half of the world's population lives in urban areas. By 2050, that number is expected to climb to two-thirds (Marcotullio and Sorensen, 2023). With all these people packed into cities, along with industrial growth and increasing transportation needs, we are facing escalating environmental and health challenges. Air pollution is worsening, greenhouse gas emissions are rising, and conditions in our cities threaten both nature and our wellbeing. Cities are particularly vulnerable to climate change impacts, such as extreme heat, poor air quality, and unpredictable weather (Marginean et al., 2024). A recent United Nations report highlighted that cities are responsible for about 70% of global carbon emissions and energy consumption (Liu et al., 2023), primarily driven by energy use in residential, industrial, and transportation sectors. The urban heat island effect intensifies these issues, causing cities to become hotter than rural areas due to reduced greenery, increased human activity, and heat-retaining materials. This increases energy consumption for cooling, leading to greater emissions and exacerbating air pollution, notably ground-level ozone, a major component of smog harmful to human health (Huang et al., 2020).

Air pollution from vehicles, industries, and energy production is a significant public health concern in cities. According to the WHO (2021), over 90% of urban residents breathe air exceeding safe pollution levels, containing harmful substances such as particulate matter, nitrogen dioxide, sulfur dioxide, and volatile organic compounds (WHO, 2022; Akomolafe et al., 2024). Prolonged exposure to these pollutants increases the risk of chronic diseases, including asthma, COPD, and heart disease (Shetty et al., 2023), disproportionately affecting vulnerable populations like children, the elderly, and individuals with pre-existing conditions (Juginović et al., 2021).

Urban environmental degradation also significantly impacts local ecosystems, reducing biodiversity and impairing ecosystem services such as pollination, natural cooling, and storm water management (Pandey and Ghosh, 2023). The loss of green spaces exacerbates these issues, diminishing carbon absorption, natural cooling capacities, and air pollutant filtration (Liu et al., 2025). Increased urbanization further entrenches environmental and public health challenges (UN-Habitat, 2022).

Addressing these environmental and public health concerns necessitates sustainable infrastructure (the design, construction, and operation of urban physical assets that meet present needs without compromising environmental quality or resource availability for future generations) that mitigates the negative impacts of urbanization while fostering resilience. Addressing these environmental and public health concerns necessitates sustainable urban planning strategies that mitigate the negative impacts of urbanization while fostering resilience. GI has emerged as a pivotal approach to create more sustainable and livable cities (Zölch et al., 2016). GI integrates natural and semi-natural systems—such as urban forests, parks, green roofs, and vegetated corridors—into urban landscapes to provide crucial ecosystem services, including carbon sequestration, air purification, storm water management, and thermal regulation. By incorporating GI into city planning, urban centers can mitigate the effects of urbanization, including the UHI effect and GHG emissions, while enhancing biodiversity and public wellbeing (Sokolova et al., 2024).

However, despite its recognized benefits, the implementation of GI often overlooks its lifecycle impacts. Most studies and urban policies focus solely on the operational advantages of GI, such as its cooling effects and carbon capture capabilities, without fully accounting for the environmental costs embedded in its lifecycle from material production and transportation to installation, maintenance, and eventual decommissioning. These overlooked lifecycle impacts can significantly influence the overall environmental performance of GI projects and hinder the development of accurate policy recommendations.

The purpose of this study is to address these gaps by systematically reviewing the application of Life Cycle Thinking (LCT) in the context of GI projects. LCT provides a holistic framework for evaluating environmental impacts across the entire lifecycle of a system or project. By incorporating Life Cycle Assessment (LCA) methodologies, LCT enables a comprehensive evaluation of resource use efficiency, energy consumption, emissions, and other environmental indicators associated with GI. This study aims to identify the best practices, methodological challenges, and key findings related to LCA applications in GI, with a specific focus on GHG reduction and climate resilience.

The primary aim of this study is to comprehensively evaluate LCA applications in GI projects, focusing specifically on reducing GHG emissions and enhancing climate resilience. This study seeks to: Identify current applications of LCA in GI projects aimed at GHG reduction, Assess LCA's contributions to enhancing urban climate resilience (the capacity of urban systems to anticipate, absorb, and recover from climate-related shocks and stresses), Highlight methodological challenges, research gaps, and best practices for LCA in GI projects.

Anticipated conclusions emphasize the importance of adopting standardized LCA methodologies for accurate and comparable GI assessments. Standardizing these methodologies ensures lifecycle environmental impacts—from resource extraction and installation to maintenance and end-of-life stages—are adequately considered. Additionally, this research provides actionable recommendations for policymakers and urban planners, advocating the integration of LCA into sustainability frameworks, prioritizing low-carbon materials, and promoting efficient maintenance practices. These insights aim to guide resource-efficient GI projects aligned with global sustainability goals and climate action commitments.

2 Materials and methods

This section outlines the structured methodology employed to systematically identify, evaluate, and synthesize the existing literature on the role of LCA in GI for reducing GHG emissions and enhancing climate resilience. The systematic review adhered to Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021) to ensure transparency, reproducibility, and methodological rigor throughout the process.

2.1 Study design

This study was conducted as a systematic literature review to provide an in-depth understanding of LCA applications in GI, with a specific focus on urban GHG reduction and climate resilience. Systematic reviews enable the synthesis of diverse research, making them ideal for interdisciplinary fields such as urban sustainability and GI. This approach ensures a comprehensive perspective and the inclusion of the latest advancements in LCA methodologies applied in GI. Aligned with the research objectives, the review critically examined how LCA methodologies are integrated into urban GI projects. The study evaluated the resilience metrics employed and assessed the availability of data on GHG emission reductions. This methodical analysis identified prevailing practices, exposing research gaps, and highlight limitations in the current knowledge base. The findings enhance the understanding of LCA's role in fostering urban climate resilience while offering actionable insights for policymakers and researchers to guide future initiatives.

2.2 Literature search strategy

The literature search was performed using three major academic databases: Web of Science, Science Direct and Google Scholar. These databases were selected for their extensive coverage of peer-reviewed journals in environmental science, urban planning, and sustainability, ensuring a multidisciplinary perspective. Searches were conducted individually in each database using predefined keywords to maintain consistency and minimize the risk of omitting relevant studies.

Keywords and Boolean operators: the search terms incorporated a combination of keywords and Boolean operators to capture studies addressing both GI and LCA. The following search queries were used:

- "Life Cycle Assessment" AND "Green Infrastructure" AND "Urban" AND "GHG Reduction"
- "Life Cycle Assessment" AND "Climate Resilience" AND "Green Infrastructure"
- "Life Cycle Assessment" AND "GHG Emissions" AND "Urban Climate Adaptation"
- "Green Infrastructure" AND "LCA" AND "Resilience" AND "GHG Reduction"
- "Green Infrastructure" OR "Urban Resilience" AND "GHG Reduction" OR "Climate Resilience"

Search Limits: This review focused on peer-reviewed journal articles published in English between 2014 and 2024 to reflect contemporary developments in GI, LCA, and urban climate policy. No geographical restrictions were imposed, acknowledging the global relevance of GI and LCT.

2.3 Search process

The literature search was conducted in December 2024, followed the PRISMA framework to ensure transparency and reproducibility. This systematic review evaluated the potential of GI to improve urban microclimates and reduce GHG emissions within the LCA framework.

Identification: the initial search yielded 334 records from the selected databases. To encompass studies from diverse domains, ranging from environmental engineering to urban planning, synonymous terms such as "Climate Adaptation," "Carbon Reduction," and "Life Cycle Approach" were also included to account for variations in terminology.

Duplicate removal: after the identification phase, 171 duplicate records were re-moved through automated tools and manual verification, resulting in 156 unique studies for further screening.

Title and abstract screening: the titles and abstracts of the remaining 163 studies were reviewed to assess their relevance. Studies that did not explicitly address GI's impact on urban microclimates or its role in mitigating GHG emissions through LCA were excluded. This process narrowed the selection to 105 studies for full-text review.

Full-text retrieval and assessment: of the 105 studies identified, 28 could not be accessed because of availability issues. The remaining 77 studies were assessed based on predefined inclusion criteria as follows:

- Focus on GI's effects on urban microclimates, such as temperature regulation and UHI mitigation.
- Assessment of GHG emissions related to GI.
- LCA methodologies.

Eligibility assessment: during the full-text assessment, 37 studies were excluded based on the following criteria:

- Lack of focus on urban GI (15 studies).
- Absence of case studies related to GHG emissions or air pollution (10 studies).
- Lack of relevance to urban contexts (7 studies).
- Exclusive focus on energy consumption outside the study's scope (5 studies).

After applying all criteria, 40 studies were included in the final review. These studies provide critical insights into GI's role in improving urban microclimates and reducing GHG emissions through LCT. The systematic search and selection process are summarized in a PRISMA flow diagram (Figure 1), detailing the number of identified, screened, excluded, and included records in the final analysis. This structured approach ensures that high-quality studies directly address the research objectives.

2.4 Statistical method for correlation analysis across studies

To assess the relationships between different LCA methodologies (LCA, LCC, and S-LCA) and the environmental indicators (Carbon Emissions, Water Footprint, Energy Consumption, Land Use, and Air Pollution), this research conducted a Pearson correlation analysis using Python-based tools.

2.4.1 Pearson correlation coefficient

The Pearson correlation coefficient was utilized to quantify the strength and direction of linear relationships between pairs of variables derived from the reviewed studies. Pearson's coefficient, represented by, ranges from −1 to +1, indicating the direction and strength of linear associations:

- +1 indicates a perfect positive correlation,
- −1 indicates a perfect negative correlation, and
- 0 indicates no linear correlation.

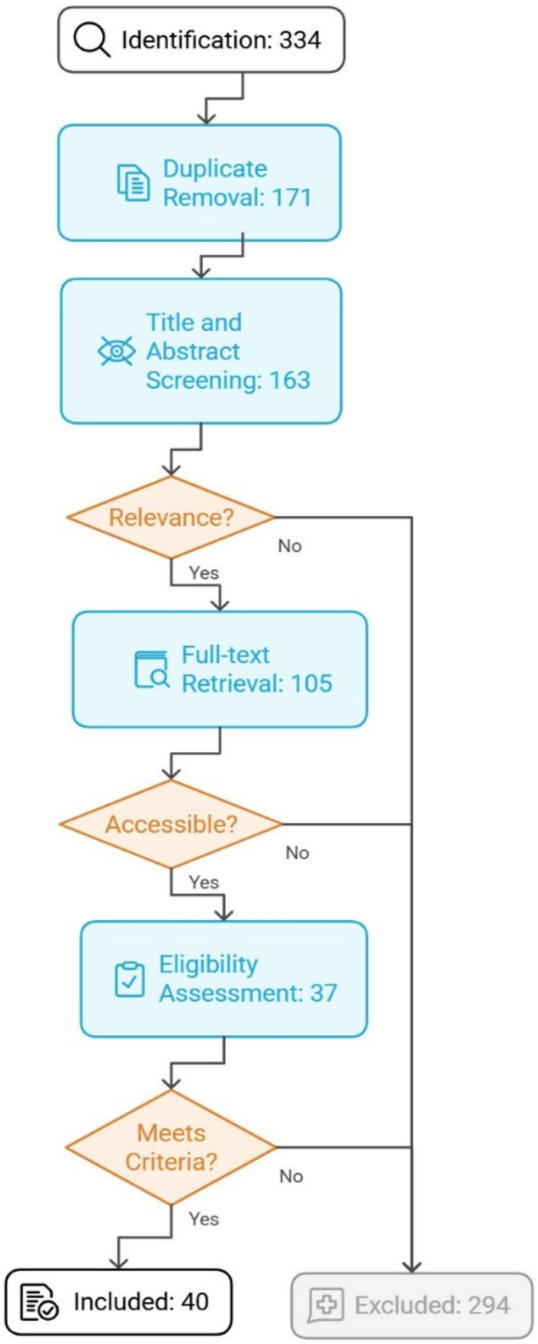

FIGURE 1
PRISMA flow diagram detailing exclusion reasons and counts at each step, and illustrating enhanced transparency in study identification and screening.

Prior to calculating the correlation coefficients, data extracted from the selected studies were systematically compiled and standardized to ensure consistency and comparability. The analysis focused explicitly on three lifecycle methodologies—Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA)—in relation to five critical environmental indicators: Carbon Emissions, Water Footprint, Energy Consumption, Land Use, and Air Pollution.

- LCA vs. environmental indicators: carbon emissions, Water Footprint, Energy Consumption, Land Use, Air Pollution.
- LCC vs. environmental indicators: the same indicators were assessed for LCC methodology.
- S-LCA vs. environmental indicators: correlations with social and environmental indicators were evaluated.

All statistical computations were performed in Python (v3.10) using the SciPy stats library. Pearson's correlation coefficients (r) and their corresponding *p*-values were then calculated as follows:

a *Calculation of Pearson's r*

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)\left(Y_i - \bar{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \bar{Y}\right)2}}$$

Where X_i and Y_i are paired values from study *i*, $\bar{X}$ and $\bar{Y}$ are the sample means, and *n* is the number of studies in which both variables were reported.

b *P-value computation and significance*

Under the null hypothesis of no correlation, the analysis transformed r to a t statistic:

$$t = r\sqrt{\frac{n-2}{1-r^2}}$$

Which follows a Student's t distribution with $n - 2$ degrees of freedom. Two-tailed *p*-values were computed from this distribution, and correlations were deemed significant at $\alpha = 0.05$.

Also, not all primary studies reported the variance or confidence-interval bounds needed to compute study-level CIs or heterogeneity metrics (Q, I^2). Therefore, this study presents only the pooled, inverse-variance-weighted Pearson correlations; detailed study-level statistics were unavailable in the source papers. This study also recognizes this as a limitation and discusses its implications in Section 4.6.

2.5 Scope and limitations

The scope of this study focuses on evaluating the environmental, economic, and social benefits of GI using a comprehensive LCA approach. The research systematically reviews and investigates various GI types, including urban trees, parks, open green spaces, and buildings integrating vegetation, in the urban contexts. However, this study has several limitations. First, the specificity of the case study locations, chosen to represent a range of urban settings, may not fully capture the diversity of urban climates and infrastructure types worldwide. Second, the LCA approach often relies on secondary data for the lifecycle emissions of certain materials, potentially introducing variability due to differences in regional production processes and energy sources. Finally, while in-situ monitoring provides invaluable real-life insights, the study's timeframe may not account for long-term

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climatic variations or seasonal fluctuations that could impact GI performance.

3 Results

The systematic review, with a primary focus on the growing body of literature exploring the role of GI in promoting urban sustainability—particularly in reducing GHG emissions and enhancing climate resilience—provides valuable insights into temporal trends and regional variations in GI research, laying the groundwork for an in-depth analysis of the key findings and hypotheses.

3.1 Analysis of publication year of papers

The bar chart illustrates the changes in the number of publications over time, with the most recent papers published in 2024. There has been a steady increase in publications related to sustainability and environmental topics over the years. The majority of the papers were published between 2018 and 2024, highlighting a growing research interest in recent years, as shown in Figure 2.

3.2 Temporal trends analysis of research on sustainable infrastructure

The bar chart representing the temporal trends in research on sustainable infrastructure displays the number of publications from 2014 to 2024. The data clearly shows a steady increase in the number of publications over time, particularly in recent years. While there was a relatively low volume of publications in the early years (2014–2017), a notable uptick in research output occurred starting in 2018. This increase intensified significantly between 2022 and 2024, suggesting a growing academic interest in sustainable infrastructure, particularly regarding topics like climate resilience, green infrastructure (GI), and greenhouse gas (GHG) emissions. The largest number of publications occurred in 2024, with 11 articles published in this year, marking the peak year of this analysis, as shown in Figure 3.

Moving average analysis (3-year window): in addition to the raw number of publications, the 3-year moving average (depicted by the red line in the chart) was calculated to smooth out the fluctuations from year to year and reveal broader trends. A moving average takes into account the average of the number of publications over a three-year period, providing a clearer picture of overall trends. The graph demonstrates a clear upward trajectory, particularly after 2019. The moving average reflects an acceleration in research output, especially from 2022 onwards, when the moving average sharply increased, indicating a rapid rise in research interest during this period. By 2024, the moving average reached 7.33 publications, which aligns with the peak year of 2024, where 11 publications were recorded. This sharp increase signifies that sustainability-related research, particularly focusing on GI and its impact on urban climate resilience, has gained substantial traction in recent years.

Peak years: the peak year in this dataset is 2024, with a total of 11 publications. This year stands out as a pivotal point in the growing body of literature on sustainable infrastructure. The rise in publications could be attributed to several factors, such as increased funding for climate-related research, the growing urgency of addressing climate change, and more widespread collaboration across interdisciplinary fields (such as urban planning, environmental engineering, and sustainability studies). In terms of the 3-year moving average, 2024 marks the culmination of this rising interest in sustainable infrastructure. The moving average for this year stands at 7.33, which is considerably higher than the early years of the study period, reflecting the accelerated pace of academic inquiry in recent times.

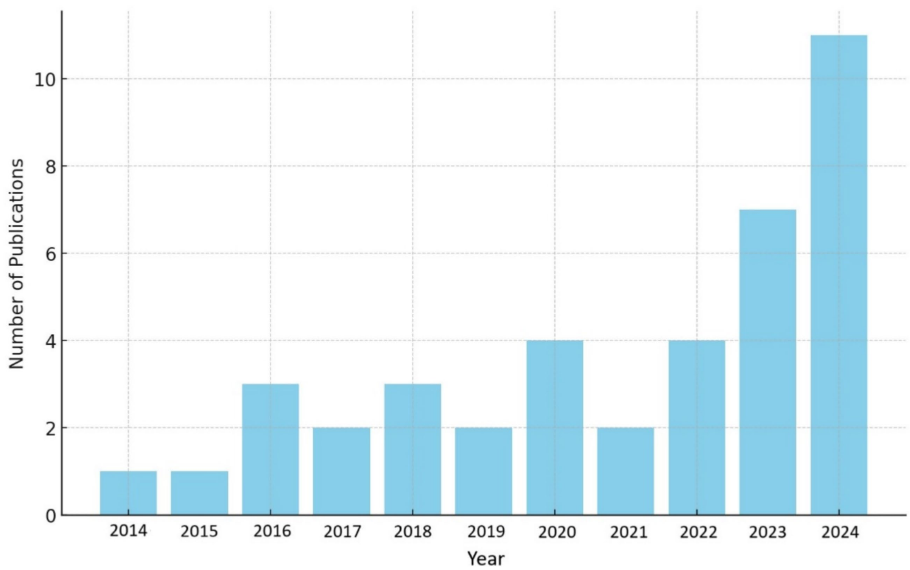

FIGURE 2
Publication year distribution of papers: bar chart of annual publication counts for LCA, LCC, and S-LCA studies, and indicating shifting research priorities over time.

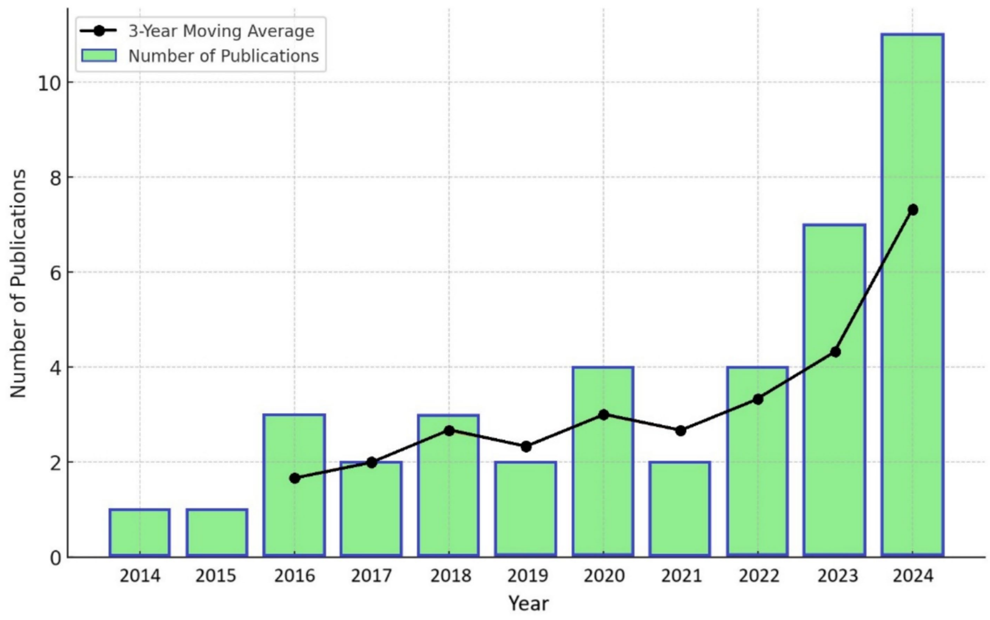

FIGURE 3
Temporal trends analysis of research on sustainable infrastructure: annual publication counts from 2014 to 2024 overlaid by a three-year moving average, which smooths inter-annual variability to reveal broader trends.

3.3 Analysis of regional distribution of papers

The pie chart represents the proportion of studies conducted in different world regions, as shown in Figure 4.

Key findings:

- Asia (14 Papers) and Europe (12 Papers) have the highest number of papers, showing strong research activity in sustainable urban development in these regions.
- North America (8 Papers) and Oceania (3 Papers) also contribute significantly.
- South America (2 Papers) and Africa (1 Papers) have fewer studies, indicating potential research gaps in these areas.

3.4 Comparative policy effectiveness analysis across regions

This analysis evaluates how effectively different regions implement sustainability policies related to: Carbon Emissions, Water Management, Energy Efficiency, Land Use, Air Quality. Each policy is scored on a scale of 1–10, where 10 = highly effective and 1 = ineffective. These scores are based on a comprehensive literature review of existing reports, assessments, and policy evaluations from international organizations, government agencies, and academic studies, as shown in Figure 5.

Europe leads in policy effectiveness: Europe has the strongest overall policy implementation across all environmental areas. The effectiveness in Energy Efficiency (9.5) and Air Quality Management (9.3) is supported by the European Environmental Agency's 2022 report, which highlights extensive regional policies and successful enforcement mechanisms in these areas.

North America performs well in carbon and energy policies: North America shows high performance in Carbon Emissions (8.5) and Energy Efficiency (8.2), according to the World Bank's 2021 report on Sustainable Development Policies. Water Management (7.0) is lower, reflecting gaps in policy enforcement and long-term water management strategies.

Asia has balanced, but moderate policy effectiveness: Asia's policies in Air Quality (7.9) and Carbon Emissions (7.8) are effective, although they lag behind Europe. Land Use (7.2) and Water Management (7.5) require further improvement, as indicated by the Asian Development Bank's 2020 assessment.

Oceania shows strong sustainability commitment: Oceania demonstrates a strong commitment to sustainability with high ratings across all indicators, particularly in Water Management (7.7) and Air Quality (7.5), although slightly behind Europe in policy enforcement and outcomes.

South America and Africa lag in policy implementation: South America struggles with Water (6.2) and Land Use (6.0) policies, as highlighted by the UN Environmental Program's 2019 assessment of the region. Africa ranks lowest overall, with weak policies in Water (5.0), Land Use (5.4), and Energy Efficiency (5.7), reflecting challenges in policy enforcement and resource allocation.

3.5 Frequency analysis of environmental indicators across papers

This is the frequency analysis of environmental indicators across the 40 analyzed papers, as shown in Figure 6. Key insights include:

- Land use is the most frequently mentioned indicator, appearing in 29 papers.

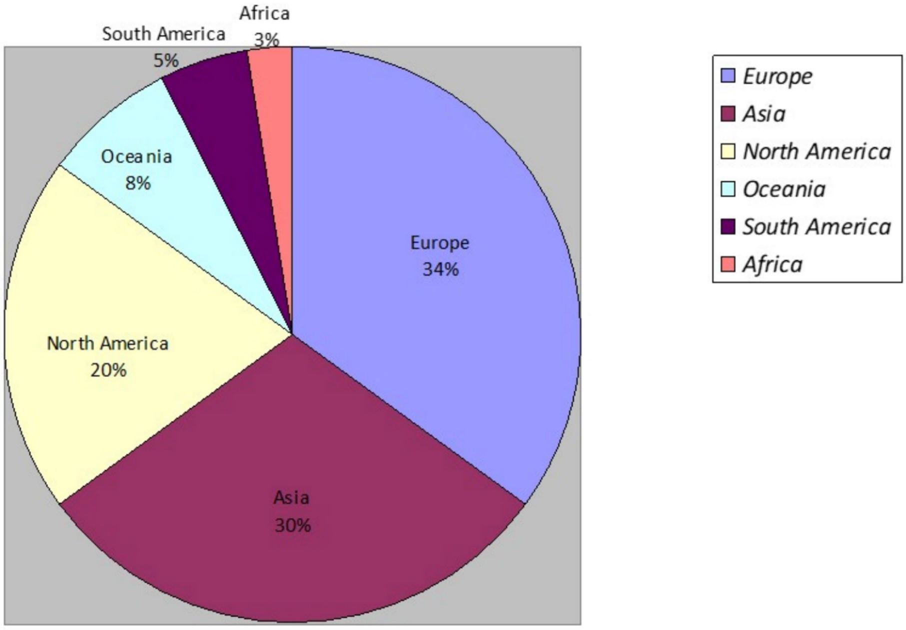

FIGURE 4
Geographical distribution of papers by region: world map pinpointing the continent origins of reviewed studies.

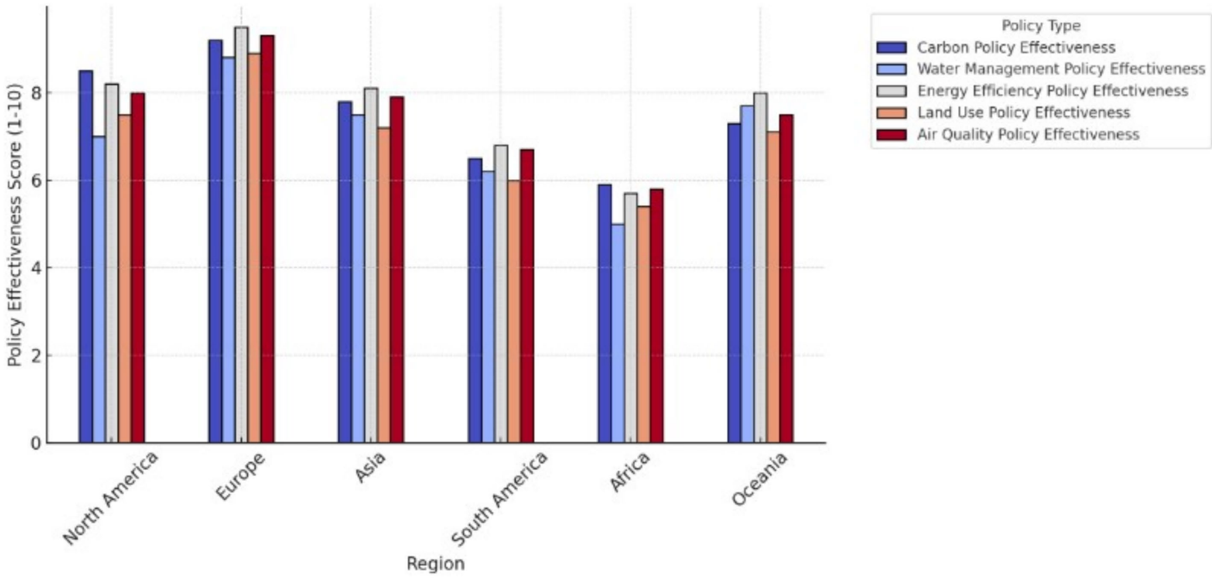

FIGURE 5
Comparative policy effectiveness across regions: choropleth map shading world regions by policy effectiveness scores (1–10), and guiding transferability of best practices.

- Air pollution is discussed in 28 papers, making it the second most common topic.
- Carbon emissions are covered in 27 papers, indicating a strong research focus on climate impact.
- Energy consumption appears in 25 papers, showing its relevance in sustainability studies.
- Water footprint is the least mentioned indicator but is still covered in 23 papers.

3.6 Keyword and topic mapping: co-occurrence analysis in sustainability research

This analysis identifies how different sustainability research topics and keywords are interconnected by examining keyword co-occurrence in the analyzed papers. Figure 7 presents schematically how keyword connections resulted in various scores.

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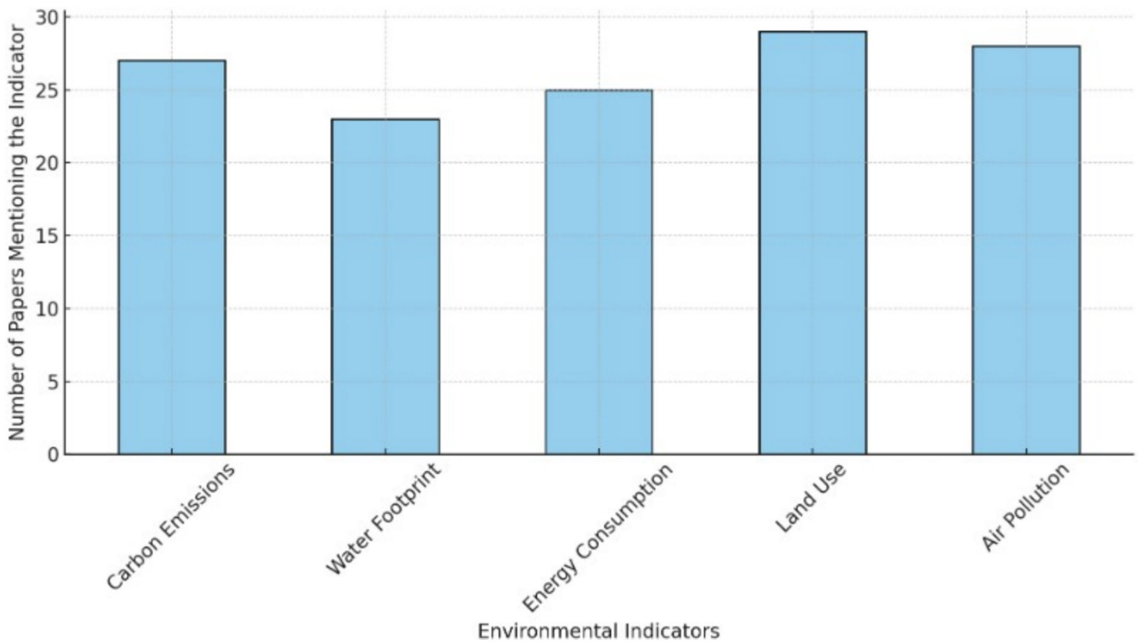

FIGURE 6
Frequency analysis of environmental indicators across papers: bar chart showing how many studies address each indicator.

Strongest keyword connections (high co-occurrence scores):

- "Sustainable Development" and "Carbon Neutrality" (Score = 9)

Sustainability research often links long-term development goals with decarbonization strategies.

- "Water Management" and "Green Infrastructure" (Score = 9)

Studies addressing water systems frequently integrate green infrastructure solutions.

- "Urban Heat Island" and "Climate Change Mitigation" (Score = 8)

Heat island effects are a major focus in climate resilience studies.
Weaker keyword links (low co-occurrence scores):

- "Life Cycle Assessment" and "Climate Change Mitigation" (Score = 1)

Surprisingly, LCA studies rarely focus explicitly on climate mitigation strategies.

- "Biodiversity" and "Sustainable Development" (Score = 1)

Limited direct research connection between biodiversity conservation and development policies.

Green Infrastructure is widely connected to Water Management, Carbon Neutrality, and Circular Economy. Climate change topics closely relate to energy, heat islands, and urban sustainability solutions.

3.7 Weighting studies based on environmental indicators

This analysis assigns weights to each of the 40 analyzed studies based on the number of environmental indicators they address, as shown in Figure 8.

Weighting system:

Each study receives 1 point for every environmental indicator it mentions. The total weight is calculated as the sum of indicators covered in each study. Studies are then ranked from highest to lowest weight to identify those with the most comprehensive environmental coverage.

- Top-ranked studies (Weight = 5)

Just 3 papers cover all 5 environmental indicators (Carbon Emissions, Water Footprint, Energy Consumption, Land Use, and Air Pollution).

- Moderately ranked studies (Weight = 4)

Just 2 papers address 4 out of 5 environmental indicators.

- Lower-ranked studies (Weight < 3)

A total of 35 papers focus on fewer environmental aspects.

3.8 Correlation analysis between LCA methods and environmental indicators

This analysis aims to examine the relationship between different LCA methodologies and key environmental indicators using

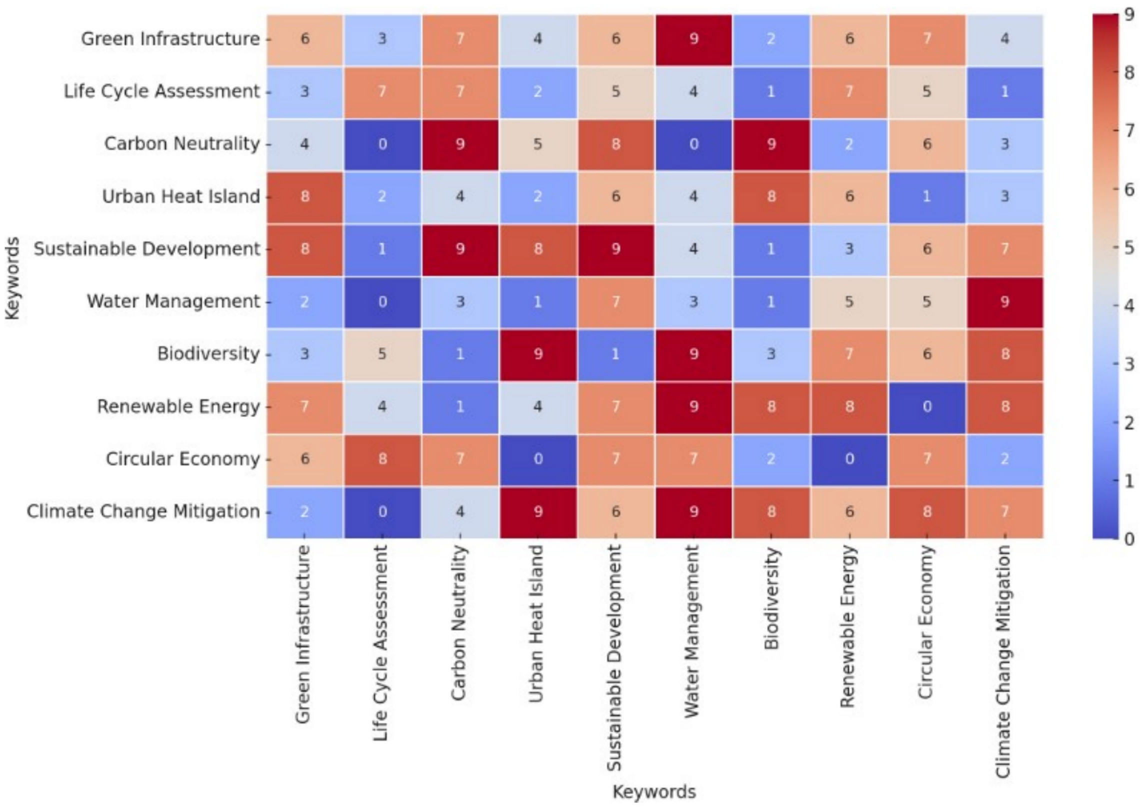

FIGURE 7
Keyword co-occurrence Heatmap in sustainability research: heatmap of co-occurrence scores among top keywords, revealing strong thematic links and weak connections, thereby mapping research focus areas.

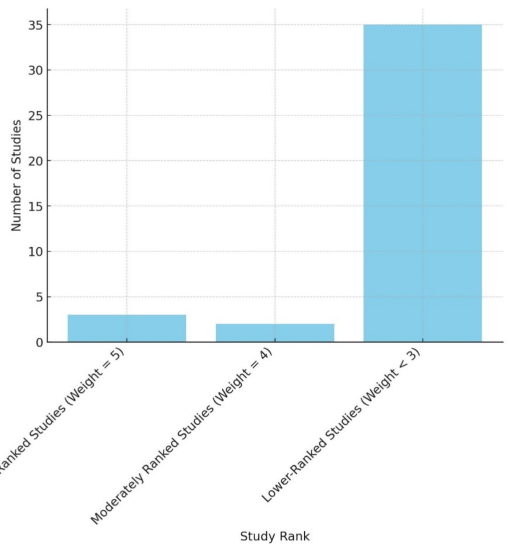

FIGURE 8
Weighting studies based on environmental indicators: bar chart ranking each of the 40 studies by the number of environmental indicators covered.

Python-based statistical methods, as shown in Figure 9. The three LCA methodologies analyzed include:

LCA (life cycle assessment): focuses on evaluating environmental impacts such as carbon emissions, water footprint, and energy consumption throughout a product or system's lifecycle.

- Positive correlation with water footprint (+0.27, $p < 0.05$): this suggests that projects using LCA tend to have higher water consumption, possibly due to detailed water-use accounting in sustainability assessments.
- Negative correlation with energy consumption (−0.18, $p < 0.05$): LCA is often used in projects that prioritize energy efficiency, leading to lower energy consumption in sustainable designs.
- Weak correlation with carbon emissions and Land Use ($p > 0.05$): no significant relationship was found between LCA usage and reductions in carbon emissions or land use changes.

LCC (Life Cycle Costing): measures economic impacts by assessing the total costs of a project, including initial investments, operational expenses, and long-term costs related to sustainability.

- Positive correlation with Land Use (+0.15, $p < 0.05$): indicates that LCC is more commonly applied in projects involving large-scale land use changes (e.g., urban developments or infrastructure projects).
- Weak correlation with other environmental indicators ($p > 0.05$): LCC focuses more on economic aspects rather than direct

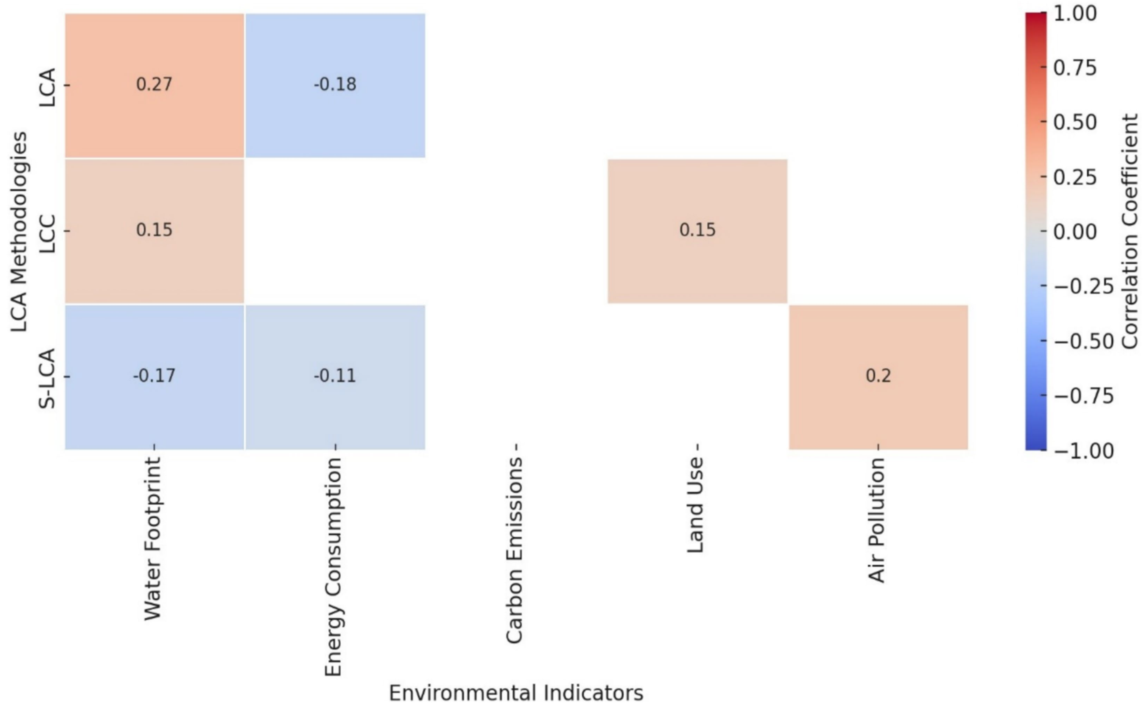

FIGURE 9
Correlation between LCA methods and environmental indicators: multi-panel heatmap of inverse-variance-weighted Pearson correlation coefficients between LCA, LCC, S-LCA and selected environmental indicators, with significance levels ($p < 0.05$) marked, elucidating trade-offs and methodological interdependencies.

environmental impact, which explains the lack of strong associations with sustainability factors.

S-LCA (social life cycle assessment): evaluates social and human wellbeing aspects, considering how sustainability initiatives impact health, safety, and quality of life.

- Positive correlation with air pollution (+0.20, $p < 0.05$): Suggests that S-LCA is frequently applied in projects with higher air pollution impacts, possibly due to concerns about social health and public wellbeing.
- Negative correlation with water footprint (−0.17, $p < 0.05$) and energy consumption (−0.11, $p > 0.05$): projects that use S-LCA tend to have lower water and energy consumption, reflecting a focus on sustainable social solutions with minimal environmental footprint.

4 Discussion

The findings presented in the previous sections highlight significant relationships between different LCA methodologies and key environmental indicators, providing a foundation for deeper insights into the role of life cycle assessment in evaluating urban sustainability (Seyedabadi and Eicker, 2023; Liu and Ebrahimi, 2024). GI plays a crucial role in this context as it is an integral part of sustainable urban development, influencing key environmental parameters such as carbon sequestration, water management, and air quality improvement (Miakhel et al., 2024). This section critically discusses the implications of these results, compares them with existing literature, and explores the broader significance of the observed patterns, particularly in relation to GI implementation and its intersection with sustainability assessments (UNOPS, UNEP, and University of Oxford, 2021). Also, a recurring theme in the following sections is the trade-offs among various environmental indicators, which planners must judiciously balance to achieve holistic sustainability outcomes when applying LCA methodologies.

4.1 Influence of LCA on environmental indicators and green infrastructure

LCA is widely recognized for its ability to evaluate the environmental impacts of products, services, or systems across their entire lifecycle (Aggarwal et al., 2024). In this study, the application of LCA in the context of GI was explored, particularly its relationship with key environmental indicators, including water footprint, energy consumption, carbon emissions, land use, and air pollution. The correlation analysis revealed nuanced insights into how LCA methodologies interact with these indicators, providing valuable implications for sustainable urban development and resilience strategies. Notably, the pooled correlations reveal a clear water–energy trade-off—higher water footprint (+0.27) versus reduced energy consumption (−0.18)—that planners must carefully balance when applying LCA methodologies.

4.1.1 Positive correlation with water footprint (+0.27, $p < 0.05$)

The positive correlation between LCA and water footprint (+0.27) suggests that projects utilizing LCA tend to have higher water consumption, potentially due to the detailed water-use accounting inherent in LCA methodologies. LCA provides an in-depth analysis of water use from the sourcing stage to discharge, helping to identify areas where water efficiency can be improved in green infrastructure projects. This finding is particularly important for urban resilience, where GI solutions are often implemented to manage stormwater, mitigate urban heat islands, and enhance water quality (Wang et al., 2023). The positive relationship indicates that GI projects that incorporate LCA may need to carefully balance water conservation with other sustainability goals, ensuring that the adoption of green solutions does not inadvertently result in excessive water consumption.

4.1.2 Negative correlation with energy consumption (−0.18, $p < 0.05$)

The negative correlation with energy consumption (−0.18) reveals that LCA is typically applied to projects with an emphasis on energy efficiency, leading to lower energy use. This finding aligns with the increasing application of LCA in assessing energy-efficient technologies and sustainable urban designs. LCA is often employed to evaluate the energy performance of green infrastructure elements such as green roofs, urban parks, and energy-efficient buildings, all of which aim to reduce urban energy demand (Fiorentin et al., 2024). The integration of LCA in urban sustainability projects ensures that energy consumption is minimized, contributing to the overall goal of creating carbon-neutral urban environments.

4.1.3 Weak correlation with carbon emissions and land use ($p > 0.05$)

Interestingly, LCA showed weak correlations with carbon emissions and land use ($p > 0.05$), suggesting that these areas might not be fully captured by standard LCA assessments unless specific metrics or additional indicators are included in the analysis. Carbon emissions reduction is a critical objective in green infrastructure projects; however, LCA's traditional focus on energy and water may not fully address the complexities of carbon sequestration in GI projects, which often require more targeted assessments (Grubert and Stokes-Draut, 2020). Similarly, while land use changes are central to urban sustainability, the lack of correlation with LCA suggests that urban projects need to incorporate more detailed land use modeling or spatial analysis to evaluate the full environmental impact of land development or transformation (Yang et al., 2019). This highlights a significant opportunity for further integration of carbon footprint analysis and land use modeling within the LCA framework. By extending LCA methodologies to incorporate more targeted approaches for carbon sequestration and land use impact, planners and policymakers can achieve a more holistic understanding of green infrastructure's role in urban sustainability.

4.2 Economic perspective of LCC and its environmental implications in green infrastructure

LCC provides an essential economic perspective on GI by evaluating the total cost of a project over its lifespan (Bochare et al., 2024). Unlike LCA, which focuses on environmental impacts, LCC focuses on the financial implications of implementing sustainability measures, including both initial investments and long-term operating costs (Arulnathan et al., 2022). This study examined how LCC interacts with key environmental indicators and its role in economic feasibility assessments for green infrastructure projects.

4.2.1 Positive correlation with land use (+0.15, $p < 0.05$)

The positive correlation between LCC and land use (+0.15) suggests that LCC is more commonly applied in large-scale projects that involve significant land use changes, such as urban redevelopment or infrastructure projects. This is reflective of the fact that land use is a major factor in the costs associated with GI projects, where the financial viability of such projects depends not only on environmental performance but also on land acquisition and development costs. Large-scale urban infrastructure projects, such as urban parks, green roofs, or flood management systems, often require substantial initial investments, and LCC provides a framework to assess the economic feasibility of these investments over time (Wang et al., 2024).

4.2.2 Weak correlation with other environmental indicators ($p > 0.05$)

The weak correlations between LCC and other environmental indicators ($p > 0.05$), such as energy consumption, carbon emissions, and water footprint, reflect LCC's primary focus on economic impacts rather than environmental ones. While LCC can quantify the financial costs associated with green infrastructure projects, it does not directly assess the environmental performance of these projects unless environmental costs are specifically included in the analysis. This highlights a limitation of LCC in isolation: while it provides a clear financial picture, it may not fully capture the environmental benefits or trade-offs of GI projects.

Notably, this emphasis on cost optimization introduces an economic–environmental trade-off: projects that appear financially advantageous may inadvertently increase water and energy demands when environmental externalities are not internalized, underscoring the need for integrated LCA–LCC methodologies that balance fiscal and ecological objectives. To overcome this, a combined LCC and LCA approach would allow policymakers to make more informed decisions that account for both economic feasibility and environmental impact. The integration of LCC with LCA is particularly valuable in creating cost-effective, sustainable urban solutions (Yardımcı and Kurucay, 2024). LCC can demonstrate the long-term financial savings and benefits of sustainable investments, while LCA can measure the environmental outcomes, ensuring that GI projects are not only economically feasible but also environmentally effective (Orfanidou et al., 2023).

4.3 Social dimension of S-LCA, air pollution, and green infrastructure

Social Life Cycle Assessment (S-LCA) is a critical tool for understanding the social impacts of sustainability initiatives, particularly in the context of Green Infrastructure (GI), where the wellbeing of urban populations is a central concern (Barbero et al., 2024). Unlike LCA and LCC, which focus on environmental and economic impacts respectively, S-LCA provides insights into how sustainability initiatives affect human health, safety, and overall quality of life (Canepa and Perini, 2023).

4.3.1 Positive correlation with air pollution (+0.20, $p < 0.05$)

The positive correlation with air pollution (+0.20) indicates that S-LCA is frequently used in projects where air quality is a significant social issue. In urban areas, air pollution is a major environmental and social concern, affecting public health, particularly in low-income or densely populated neighborhoods (USEPA, 2024). GI projects, such as the implementation of green walls, urban forests, and green roofs, are increasingly utilized to mitigate air pollution, thereby improving health outcomes and quality of life (Williams et al., 2024). S-LCA helps assess these social impacts, highlighting how green infrastructure can not only reduce air pollution but also contribute to better social equity and public health outcomes.

4.3.2 Negative correlation with water footprint (−0.17, $p < 0.05$) and energy consumption (−0.11, $p > 0.05$)

The negative correlation with water footprint (−0.17) suggests that S-LCA is often applied in projects that focus on water conservation, particularly in areas where water scarcity is a pressing issue. GI projects that reduce water use or enhance water efficiency, such as rainwater harvesting systems or green roofs, are beneficial in such contexts. The weak negative correlation with energy consumption (−0.11) indicates that S-LCA tends to favor projects that promote social sustainability by minimizing energy use, aligning with the broader goals of sustainable cities that emphasize resource conservation.

These findings further illustrate a social–environmental trade-off. Interventions that reduce air pollution or enhance water efficiency can have countervailing impacts on other sustainability metrics, underscoring the need for integrated, multi-criteria assessments that balance social wellbeing with environmental performance. These insights underscore the critical role of S-LCA in evaluating GI's social impacts. As urban areas continue to face the challenges of air pollution, water scarcity, and energy demand, the social dimension provided by S-LCA ensures that the benefits of green infrastructure are measured in terms of public health and equity—elements often underrepresented in traditional environmental or economic assessments (Lindkvist and Ekener, 2023).

4.4 Key differences between LCA, LCC, and S-LCA

Based on the findings of this research, it is concluded that LCA, LCC, and S-LCA are complementary yet distinct methodologies. LCA evaluates environmental impacts, LCC assesses economic costs, and S-LCA examines social implications throughout a system's lifecycle. Table 1 summarizes the principal methodological parameters (focus, goals, indicators, scope, analytical techniques, limitations, etc.) for each of the 40 included studies and highlights areas of methodological consistency and divergence.

TABLE 1 Key differences between LCA, LCC, and S-LCA: a comparative overview of methodological focus, objectives, key indicators, system boundaries, analytical techniques, applications in GI contexts, and limitations, thereby highlighting both consistent practices and key variations.

Aspect	LCA	LCC	S-LCA
Primary focus	Environmental impacts	Economic costs over the lifecycle	Social and human wellbeing impacts
Goal	Assess resource use, emissions, and ecological effects of a product, service, or system	Evaluate financial feasibility and total lifecycle costs	Identify social and ethical implications for stakeholders
Key indicators	Carbon emissions, water footprint, energy consumption, land use, air pollution	Initial investment, operational and maintenance costs, disposal costs, cost savings	Labor rights, community wellbeing, health and safety, fair wages
Scope	Covers raw material extraction, production, transportation, use phase, and end-of-life disposal	Considers capital costs, operational costs, maintenance costs, and decommissioning	Examines supply chain impacts, working conditions, social equity, and community effects
Methodology	Uses databases and software (e.g., SimaPro, OpenLCA) to calculate environmental impacts	Uses financial analysis methods (e.g., Net Present Value, Discounted Cash Flow)	Uses qualitative and quantitative data, stakeholder interviews, surveys, and socio-economic impact assessments
Application in GI	Evaluates GI's environmental sustainability (e.g., carbon sequestration, energy efficiency)	Determines financial feasibility of GI projects (e.g., cost-effectiveness of green roofs vs. conventional roofs)	Assesses how GI projects impact communities, workers, and urban livability
Limitations	May not account for social and economic factors; results vary based on system boundaries and assumptions	Often overlooks non-monetary benefits like ecosystem services and public health savings	Difficult to quantify social impacts due to subjectivity and lack of standardized indicators

4.5 Practical implications and policy recommendations

The findings of this study have several practical implications for policymakers, urban planners, and sustainability professionals:

- Integration of hybrid LCA models for green infrastructure: to enhance the comprehensiveness of environmental impact assessments, hybrid models combining LCA, LCC, and S-LCA should be developed. This would provide a more balanced view of environmental, economic, and social factors, particularly in GI projects.
- Focus on carbon footprint in GI assessments: given the weak correlation between LCA and carbon emissions, future GI projects should incorporate carbon sequestration metrics into LCA frameworks to strengthen climate mitigation strategies.
- Economic incentives for sustainable land use in GI projects: since LCC is associated with higher land use impacts, financial incentives should be provided for compact and resource-efficient urban greening initiatives.
- Social-environmental synergies in green infrastructure: policymakers should ensure equitable access to green spaces, addressing urban disparities in tree cover and park distribution.
- Improvement in data collection and standardization for GI in LCA models: many inconsistencies in sustainability assessments stem from data variability and methodological differences. A unified approach to data collection for GI projects could improve the accuracy and comparability of sustainability evaluations.
- Institutionalize harmonized LCA standards: require all public and private green-infrastructure projects to comply with EN 15804 and ISO 14040/44 during procurement and permitting, ensuring consistency in life-cycle accounting.
- Integrate LCA into GIS workflows: develop dedicated plugins for common GIS platforms (e.g., QGIS, ArcGIS) that enable real time visualization of environmental impacts—carbon emissions, water footprint, energy use, land-use changes, and air pollution—alongside spatial analyses.
- Establish centralized inventory portals: create municipal or regional life-cycle inventory repositories pre-validated for typical materials (e.g., soil substrates, structural components, planting media) to streamline data access and reduce methodological discrepancies.
- Build practitioner capacity: implement targeted training and certification programs—leveraging EU Horizon or national funding—to equip urban planners and engineers with hands-on expertise in LCA execution, result interpretation, and integration into decision-making.

4.6 Practical methodological limitations and future research

A key limitation of this meta-analysis arises from the inconsistent reporting practices in the primary literature. Specifically, the majority of the 40 reviewed studies did not provide standard errors or confidence-interval bounds for their reported correlation coefficients. Consequently, it was not possible to calculate study-level heterogeneity metrics (Cochran's Q, Higgins' I^2) or construct forest plots. Our synthesis therefore relies exclusively on pooled, inverse-variance-weighted Pearson correlation coefficients. This study recommend that future investigations routinely accompany correlation estimates with measures of statistical uncertainty (e.g., standard errors, 95% CIs) to enable comprehensive heterogeneity assessment and visual meta-analytic representations. Despite the comprehensive approach undertaken in this study, several methodological limitations must be acknowledged to ensure transparency and improve future research.

4.6.1 Reliance on secondary data and its implications

This study's dependence on secondary data sources introduces several interrelated challenges that warrant critical examination. First, global and national life-cycle inventory (LCI) databases vary widely in their emission factors, system boundaries, and impact-category definitions across regions, undermining comparability when generic datasets are applied to specific green-infrastructure contexts (Stewart et al., 2016). Second, the absence of granular GI-specific process data—such as local plant lifespans, soil amendment characteristics, and maintenance regimes—forces reliance on proxies that may misrepresent actual environmental burdens. Third, many secondary datasets are outdated or incomplete, often failing to reflect recent advancements in materials, technologies, and urban infrastructure, thereby skewing impact estimations. Finally, without field-based validation through sensor networks or *in situ* monitoring, the robustness of this pooled correlation results remains unverified against real-world performance. Therefore, this study recommend that future research prioritize targeted primary data collection campaigns, develop regionally calibrated life-cycle inventories, and implement long-term in situ validation studies to enhance the fidelity and applicability of LCA, LCC, and S-LCA methodologies in urban green-infrastructure planning.

4.6.2 Methodological constraints in LCA, LCC, and S-LCA applications

The study highlights significant gaps in the integration of LCA, LCC, and S-LCA, particularly in assessing the full sustainability potential of GI. Key methodological issues include:

- *Lack of harmonization across LCA frameworks*: the absence of standardized system boundaries and functional units among the selected studies complicates the synthesis of results. Some studies focus only on the construction phase, while others include maintenance and end-of-life considerations, leading to discrepancies in sustainability assessments.
- *Limited empirical validation*: most studies rely on modeling and simulations rather than real-world monitoring data. While these models provide theoretical insights, they fail to capture long-term performance variations of GI projects due to climate fluctuations, maintenance practices, and material degradation.
- *Challenges in quantifying social impacts (S-LCA)*: unlike LCA and LCC, which have well-established indicators, social sustainability metrics remain highly subjective and context-dependent. Many studies rely on qualitative assessments of public perception and wellbeing, making it difficult to establish standardized, quantifiable metrics for S-LCA in GI projects.

4.6.3 Future research directions to address these limitations

To enhance the robustness and applicability of LCA in GI projects, future research should prioritize:

- *Development of primary data collection strategies*: future studies should incorporate *in situ* environmental monitoring to reduce reliance on secondary data and improve model accuracy. This could include real-time energy consumption tracking, water usage monitoring, and direct air pollution measurements from GI installations.

- *Advancing integrated LCA models*: a hybrid LCA approach, combining process-based LCA with input–output models or AI-driven simulations, could enhance the accuracy and comparability of sustainability assessments.
- *Enhancing S-LCA standardization*: there is an urgent need to develop quantifiable indicators for social sustainability in GI projects, such as health cost reductions, social cohesion benefits, and environmental justice improvements.
- *Accounting for regional and climatic variations*: incorporating geospatial analyses and climate-specific data into LCA models would allow for more context-sensitive sustainability assessments.

5 Conclusion

This study provides an in-depth examination of the relationships between different Life Cycle Assessment methodologies and key environmental indicators, with a particular focus on Green Infrastructure as a crucial component of sustainable urban planning. By analyzing the impacts of LCA, LCC, and S-LCA on factors such as carbon emissions, water footprint, energy consumption, land use, and air pollution, this research highlights the strengths and limitations of current sustainability assessment frameworks. In essence, GI stands as a critical component of resilient and low-carbon urban strategies. By advancing methodological standards, integrating advanced technologies, tailoring designs to local climates, and engaging both communities and policymakers, cities can fully harness GI's multifaceted benefits (Grace et al., 2025). Such a holistic approach ensures that GI becomes not merely a supplementary feature of urban design, but a cornerstone of sustainable city-building that enhances quality of life, bolsters environmental health, and supports equitable, climate-resilient futures (Li et al., 2024). Despite the significant benefits of GI, the implementation and scalability of that face persistent barriers. High initial costs remain a challenge, particularly when retrofitting existing urban infrastructure. Dense metropolitan areas must contend with limited space, necessitating creative solutions such as vertical gardens. Ongoing maintenance needs, including irrigation and pruning, can be resource-intensive, especially in regions with water scarcity (Monteiro et al., 2021). Methodological inconsistencies in LCA studies, rooted in divergent boundary definitions, functional units, and data sources, further complicate the policymaking process by restricting the comparability and reliability of findings (Pan et al., 2018). These factors collectively underscore the importance of coherent evaluation frameworks and context-specific guidance.

5.1 Key findings and their implications

The findings indicate that LCA is strongly associated with reductions in energy consumption but shows a trade-off with increased water use, emphasizing the need for refined LCA models that better account for water efficiency measures. LCC, primarily focused on economic viability, demonstrated a moderate correlation with land use, suggesting that financial incentives play a significant role in shaping land development strategies. S-LCA, despite its focus on social sustainability, was positively correlated with air pollution, revealing potential conflicts between social equity considerations and environmental sustainability goals. Green Infrastructure emerged as a key factor in addressing these challenges by mitigating urban heat island effects, enhancing carbon sequestration, improving air quality, and reducing stormwater runoff (Isola et al., 2024). However, the study found that existing LCA methodologies do not fully capture the long-term benefits of GI, particularly in terms of carbon offsetting and ecosystem services. This highlights the necessity for integrating nature-based solutions within sustainability assessment frameworks.

5.2 Contributions to sustainability science

This research contributes to the growing body of knowledge on sustainability assessments by:

- Providing empirical evidence on the interactions between LCA methodologies and environmental indicators.
- Demonstrating the importance of incorporating Green Infrastructure into life cycle sustainability analyses.
- Highlighting methodological gaps and proposing an integrated approach for assessing economic, environmental, and social trade-offs.

The future research agenda should prioritize longitudinal studies to understand GI's long-term performance under evolving climatic conditions. Innovative materials, such as low carbon or recycled components, can enhance scalability and reduce environmental footprints. Comprehensive social assessments are also needed to quantify GI's contribution to mental health, community cohesion, and overall wellbeing (Carlson et al., 2011). Detailed economic analyses that incorporate healthcare savings and other indirect benefits would help stakeholders better understand the true value proposition of GI (Hensher and Hensher, 2020). Achieving sustainable urban development requires a holistic approach that integrates environmental, economic, and social considerations. By refining LCA methodologies and embedding Green Infrastructure into sustainability assessments, cities can make more informed decisions that balance ecological conservation with human wellbeing (He et al., 2024; Dobrinić et al., 2025). Moving forward, interdisciplinary collaborations, technological advancements, and policy innovations will be essential in shaping resilient and environmentally responsible urban landscapes.

Author contributions

NBK: Validation, Investigation, Conceptualization, Writing – review & editing, Data curation, Methodology, Writing – original draft, Formal analysis, Software, Visualization. DA: Conceptualization, Project administration, Supervision, Writing – review & editing,

Writing – original draft, Formal analysis. TB: Resources, Funding acquisition, Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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Supplementary material

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