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Novel framework towards integration of Environmental Carrying Capacity for Sustainable Spatial Planning: A Systematic Approach in Indian context

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Abstract: Environmental Carrying Capacity (ECC) refers to the anthropogenic influence which environment can sustain without irreversible damage to the system. Many metropolitan regions worldwide are experiencing the negative environmental consequences of exceeding the ECC due to unplanned expansion. In coastal and ecologically fragile areas, unregulated development further exacerbates these socio-ecological pressures, making ECC a crucial determinant for sustainable spatial planning. Despite these challenges, urban planning frameworks rarely operationalize ECC as a core principle in policy decisions and development plans, prioritizing instead short-term economic gains with weak sustainability.

This research makes an attempt to integrate ECC, as mechanism in spatial planning, employing multi-method approach through extensive and systematic review of literature, bibliometric analysis, and case study evaluations of real-world scenarios. In addition, a bibliometric analysis of 500+ ECC-related studies (1995–2025) from Scopus and Web of Science (WoS) databases has been conducted using Biblioshiny (R), and VOSviewer for visualization, exploring research trends, thematic areas, and methodological advancements. Moreover, an evaluation of 25+ Master Plans of Indian Cities under implementation have been assessed, to have clear understanding the extent of integration of ECC principles in urban development policies. This exploratory study highlights the inevitable requirement for a comprehensive framework to integrate ECC into urban planning. The study discusses challenges in current urban planning process and paves way to incorporate ECC principles in spatial planning. Based on the findings, the research conceptualizes an Integrated Spatial Planning Framework (ISP-F), which act as a blueprint, and catalyze in promoting sustainable spatial planning for transforming urban systems.

Keywords: Environmental Carrying Capacity, Evolutionary Study, Meta-Bibliometric Approach, Master Plans, Spatial Planning, Sustainable Urban Development

Introduction

Urbanization in India, post-Green Revolution and fueled by globalization in the 1990s, has led to a dramatic influx of population to urban centers, particularly in medium and large cities. By 2011, approximately 31% of India's population resided in urban areas, a figure expected to reach nearly 50% by 2039 (Census of India, 2019). The notion that cities can accommodate indefinitely, despite their carrying capacity and growing ecological footprint, is just an analogy. (Mahavir et al., 2014). Cities are growth engines, but growth and the rapid urban transition bereft of environmental concern is self-defeating, placing an immense strain on the natural environment (Mahavir et al., 2014, Seto et al., 2012). Increased population growth and urban expansion have an implication on the utilization of natural resources and environmental quality (George and Kini, 2016), viz. shrinking per capita land availability (Ahmed & Wang, 2019), deteriorating air and water quality, increased energy consumption, rising greenhouse gas emissions, and declining green spaces (McDonald et al., 2020); the after-effects which are still visible in the 21st century – indicating the consequences of an economic infinite growth paradigm on a finite space.

Figure 1: Growth of Urban Population

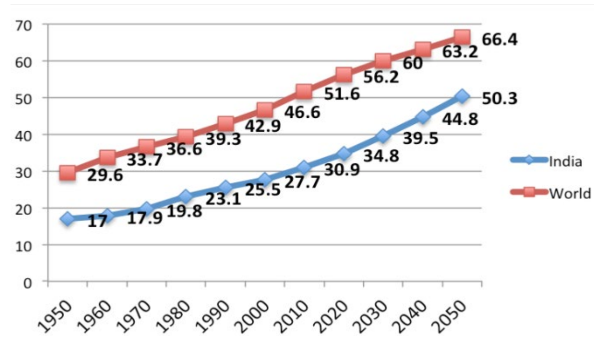


Figure 2: India's Growing ecological Debt (1961-2003)

Source: (Left) Data from Census of India Report 2019, (Right) Report on India's Ecological Footprint – A Business Perspective 2008

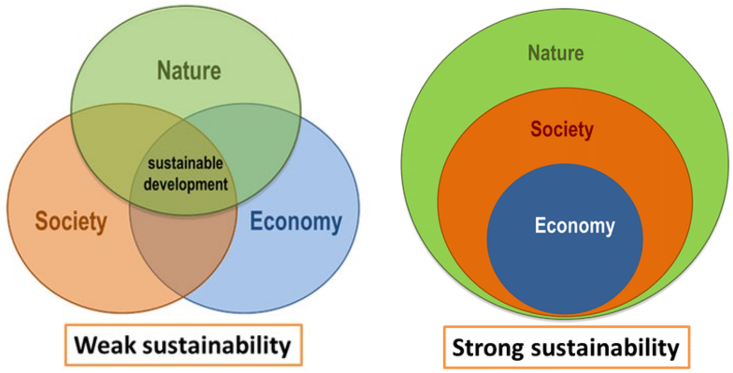
It is crucial for development activities to carefully account the environmental risks-benefits (Soemarwoto, 2004). India is growing at one of the fastest urbanization rates globally, with its urban population expected to reach 600 million by 2036 and nearly 50% of the total population by 2050 (United Nations, 2022; United Nations, 2024). The environmental footprint of urbanization has exceeded the biocapacity of many Indian cities, leading to irreversible damage to local ecosystems and increasing vulnerability to natural disasters (George & Kini, 2016). According to the Central Pollution Control Board (CPCB, 2023), over 80% of urban wastewater in India remains untreated, leading to extensive water pollution and degradation of aquatic ecosystems (Singh et al., 2022). Additionally, more than 40% of India's urban areas face critical groundwater depletion due to excessive extraction rates (NITI Aayog, 2019). Furthermore, uncontrolled urban sprawl has led to the destruction of forests and wetlands, reducing the ecological resilience of urban settlements (Sharma et al., 2024). Coastal cities such as Mumbai, Chennai, and Visakhapatnam are at high risk from sea-level rise, land subsidence, and extreme climate events, yet existing planning frameworks fail to incorporate environmental carrying capacity considerations (Mukherjee et al., 2022). Thus, to understand the effects of development activities on the bio-capacity or natural limits of the current environment, it is essential to manage this ecological imbalance and guide the planning process using this carrying capacity estimation (Yue et al., 2023). There are around 152 developing nations globally including India, each striving to meet their developmental aspirations. However, unchecked urban growth and overconsumption of resources pose a threat to future generations. The absence of ECC-based assessments in spatial planning has led to resource depletion and environmental degradation, emphasizing the need for a paradigm shift towards integrating carrying capacity evaluations into master planning processes. Addressing these issues requires redefining ECC parameters, assessment of the environmental carrying capacity for effective utilization of land and improving data-driven resource management (Abdelrahman et al., 2018). Embedding environmental sustainability as a core component of urban development strategies by considering environmental carrying capacity (Oh et al., 2005) and, integrating it with the spatial planning process for the urban regions at every stage of decision-making (Soemarwoto, 2004; Li et al., 2019) becomes essential. Translating into planning practice, the future spatial management of urbanized areas requires verification of available resources and the state of the environment as a base for allocating land for development to ensure sustainable development (Świąder et al., 2018, 2020).

Nexus between Urban Dynamics and Environment

The United Nations Brundtland Commission in 1987 defined sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their needs." Wackernagel and Rees (1996) argue, however, that the world's ecosystems are not capable of sustaining current levels of human consumption of resources and ecosystem services without irreversible damage. At its core, sustainability is about ensuring natural systems are capable of sustaining human settlements without depleting essential resources (Giddings et al., 2002).

The concept of sustainable development entails the understanding of spatial carrying capacity, which imposes limits on urban growth through consideration of land availability, resource limitations, and ecosystem vulnerability (Oh et al., 2005). The weak sustainability-strong sustainability debate illustrates this phenomenon as well. Weak sustainability argues that human-created capital can substitute for natural capital, meaning that technological progress and economic development can make up for loss of the environment. Strong sustainability argues, however, that natural capital is unique and requires tedious conservation and sustainable management of resources (MacDonald et al., 1999; Neumayer, 2002; Folke et al., 2016).

Figure 3: Representation of Weak Sustainability and Strong Sustainability



Source: Brundtland Commission Report, 1987; Giddings, 2002

Shift from weak sustainability to strong sustainability, urban planning must take on a multidimensional paradigm encompassing environmental, social, and economic indicators (Giddings et al., 2002). This shift requires a policy shift to a holistic and integrated assessment of the interrelation between the natural environment and human well-being, further developing a normative approach to measuring the sustainability of urban-environmental interrelation from the strong sustainability perspective. The implementation of environmental carrying capacity-based frameworks in spatial planning can provide an empirical basis for determining the limits of urban expansion, ensuring that development does not exceed the environment's capacity to regenerate (Huang et al., 2023; Nazer et al., 2023).

Environmental Carrying Capacity and its implication in Urban Planning.

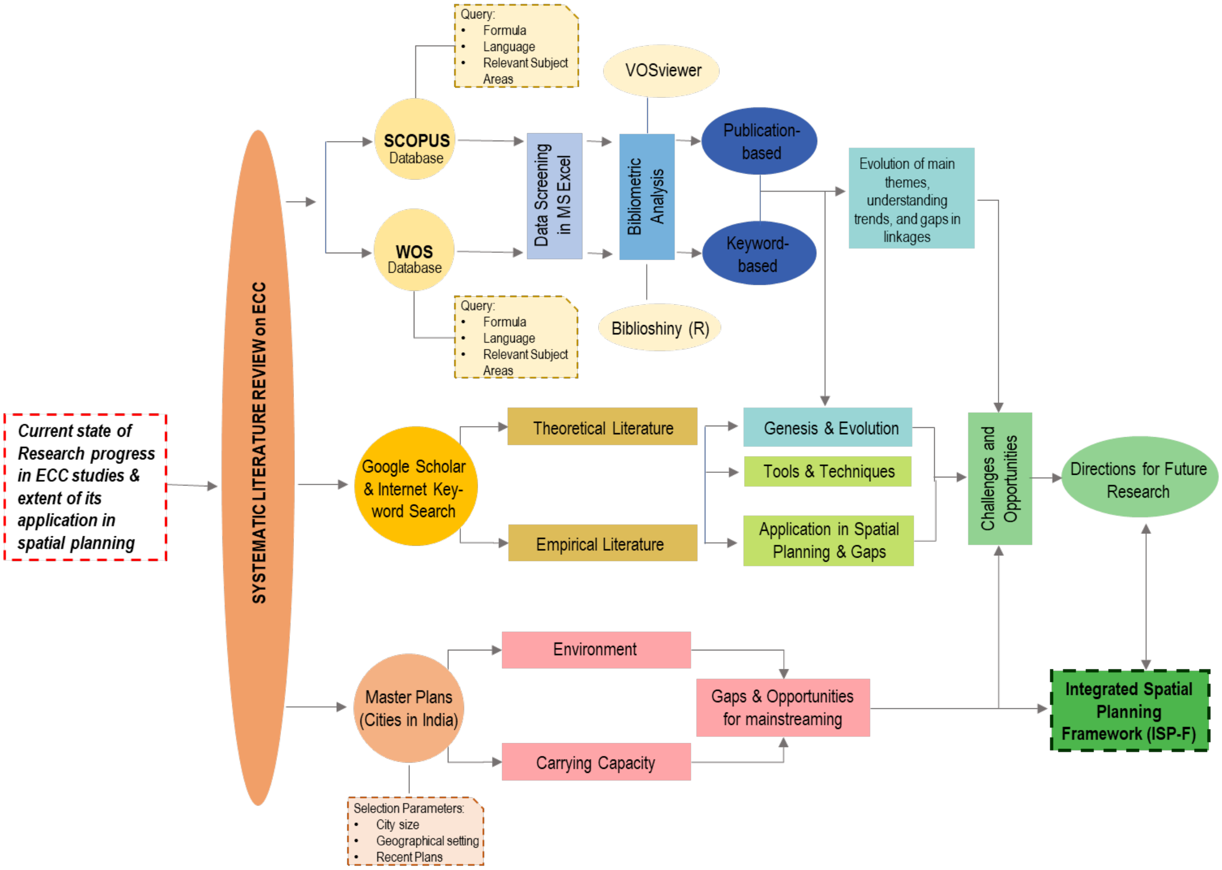
Environmental Carrying Capacity (ECC) plays a vital role in sustainable urban planning by establishing the maximum limits of human activity within ecological boundaries (Wackernagel & Rees, 1998; Rees & Wackernagel, 2008). Carrying capacity-based planning is aimed at the management of the supply-demand deficits or the "Carrying Capacity Differential". (Bishop et al, 1974). ECC supports resource optimization and ecological protection (Wu, 2014), while also ensuring a holistic approach to urban resilience by taking into account both the supportive capacity (resource availability) and assimilative capacity (waste absorption) of urban environments (Carey, 1993). Qian et al. (2017), Liu et al. (2018) and Walling & Vaneeckhaute (2020), all highlight the importance of regional assessments in ECC-based planning to facilitate sustainable transformations. In parallel, Spatial Planning seeks to balance economic, social, and environmental needs and addresses the challenges of urban expansion ((Pahuluan et al., 2017, Fuseini & Kemp, 2015). However, political and economic pressures often result in unsustainable land-use decisions (Wang et al., 2018), making it essential to consider spatial carrying capacity. Despite progress in urban areas, ECC remains underutilized in spatial planning. The disconnect between urban growth and ecological limits highlights the urgent need for a more integrated approach to ECC. This thereby underscores the need for effectively estimating carrying capacity and systematically integrating it into planning policies through regulatory frameworks, data-driven decision-making, and cross-sectoral coordination as a foundational strategy that informs sustainable spatial planning and ensuring long-term urban resilience.

Study Methodology

This research explores the development of Environmental Carrying Capacity (ECC) studies and its applications for sustainable spatial planning to develop a novel framework for guiding integration of ECC in spatial planning in India though systematic meta-bibliometric approach. For achieving this principal research goal, three research tasks are designed in this study, and the methodological multi-stage process is illustrated in Figure 4.

Figure 1: Methodology adopted for systematic literature review

First, the theoretical foundations and conceptual advancements in ECC is established, tracing its ecological origins



Source: Developed by authors, 2025

and expansion into spatial planning, before presenting the key findings of the bibliometric review. Second, Scopus & Web of Science (WoS) is chosen for covering high-impact journals and conference proceedings in environmental planning, sustainability, and urban studies. Using data extracted from Web of Science (WoS) and Scopus database, performance analysis and science mapping techniques are employed, that entails keyword mapping, concurrence analysis, and thematic clustering with Biblioshiny (R) and VOSviewer. The objective of these two stages of analysis is to systematically examine ECC research trends, knowledge gaps, and interdisciplinary linkages.

This study employs Scopus and Web of Science (WoS) because of their rigorous indexing standards, interdisciplinary coverage, and reliability in reducing selection bias in databases. To capture the contemporary evolution of Environmental Carrying Capacity (ECC) from an ecological concept to an applied planning tool, the study focuses on the period 1995–2025, during which ECC research expanded significantly in both scope and methodological sophistication. Using a carefully refined set of keywords, search filters and avoiding conceptual drift, the publications were retrieved for undertaking the bibliometric analysis. Thus, through harmonization of search strings across databases, systematic removal of duplicates, and metadata cleaning, the internal biases in the literature selection were mitigated to the extent possible. Further, for the conceptual review of the genesis and evolution of ECC, reliance on seminal, widely cited, and open-access basic literature ensured balanced representation across ecological, planning, and sustainability domains, thereby reducing interpretive bias in synthesizing theoretical advancements.

Additionally, this paper examines Master Plans in India to evaluate consideration of environmental factors and the idea of carrying capacity in urban planning strategies. To minimize selection bias here, the Master Plans were chosen using a stratified approach covering diverse city sizes, geographic regions, and ecological contexts - coastal, inland, and environmentally sensitive regions etc., ensuring that the sample reflects the heterogeneity of India's urban systems. Furthermore, the paper presents the gaps and scope for integration of carrying capacity limits as an essential component of plan making process. Finally, this paper suggests a comprehensive guiding framework by collating the assessment of ECC's academic trajectory, and learnings from study of spatio-development plan preparation process in India.

Genesis of notion for Environmental Carrying Capacity in Development Planning.

Rooted in ecological and planning disciplines, the idea of carrying capacity which emphasized the balance between population growth and resource availability (Hardin, 1968) - has evolved to address various aspects of sustainability in spatial development. The environment's carrying capacity is influenced by both its stocks (the available resources) and flows (the consumption and regeneration of those resources). Under the research domain of 'Ecology', Carrying Capacity is conceptualized as the environment's ability to sustain a population without degradation (Godschalk, 1975). This was later adapted to focus on the extent to which urban systems can support development without overburdening infrastructure, resources, and environmental functions (Schneider et al., 1978). Joardar (1998) refers 'carrying capacity' to the capacity of urban areas to sustain economic, social, and environmental functions without exceeding their ecological limits. Expanding this perspective, literature in early 2000s also emphasized the socio-economic aspect, highlighting the need to limit human activities within the regenerative capacity of the natural system to avoid long-term sustainability challenges.

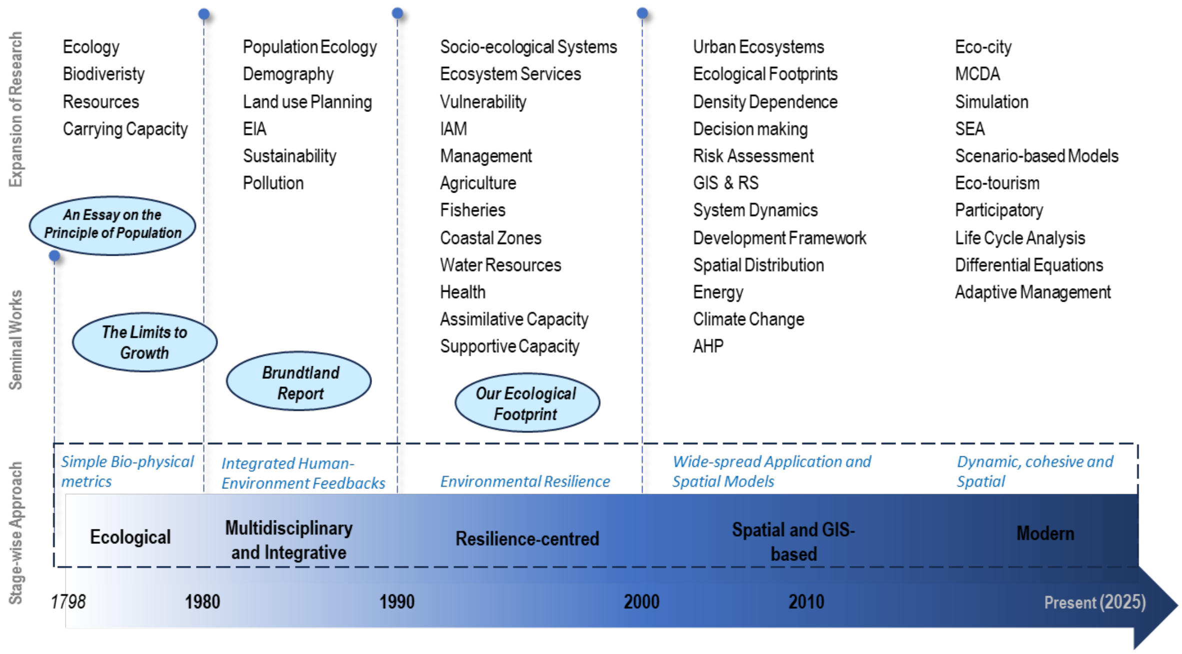
Environmental Carrying Capacity (ECC) builds upon this broader concept by focusing specifically on environmental limits. Rees and Wackernagel (1996) defined ECC as the capacity of the environment to absorb human-induced pressures like pollution, deforestation, and land-use change without irreversible ecological damage. Pahuluan et al. (2017) further emphasized that ECC balances human needs with ecosystem health, ensuring both biodiversity conservation and sustainable resource use. Liu and Borthwick (2011) extended this concept, comparing environmental stressors such as industrial emissions and waste production to ecosystem resilience and resource availability. The relationship between environmental pressure and ecological thresholds is central to Environmental Carrying Capacity. Liu (2012) argued that ECC assessments should guide development planning to prevent exceeding these thresholds. Studies have applied ECC in various planning contexts, such as land-use allocation (Huang et al., 2023) and regional economic development (Zhang & Xu, 2010). From a policy perspective, Bishop (1974) and Witten (2000) highlighted carrying capacity as a critical tool in urban sustainability, particularly for zoning regulations and maintaining ecological equilibrium. ECC is influenced by a multitude of factors, including ecological, social, and economic variables, requiring a comprehensive understanding for effective application. To further understand the concept and its applications, the authors have attempted an evolutionary study on Environmental Carrying Capacity concept in the light of spatial planning.

Evolutionary trends of Environmental Carrying Capacity (Pre-1980s to Present)

The concept of Environmental Carrying Capacity (ECC) has evolved significantly from its initial ecological roots in the mid-20th century, where researchers began to recognize the limits of natural systems in supporting human activity (Carson, 1962; Odum and Barrett, 1971; Odum, 1975), to its present-day application in sustainable spatial planning. The foundation for this discussion can be traced back to the Malthusian Theory (Malthus, 1798), which had argued that the growth in population would outstrip the availability of resources, the focus being on environmental constraints. This evolution, as presented in Figure 5, reflects an increasing recognition of the need to integrate multiple dimensions-biophysical, socio-economic, and spatial—into understanding the limits of sustainable development.

Next page

Figure 2: Evolutionary Trends in Environmental Carrying Capacity (ECC) Research: Key Concepts, Seminal Works, and Stage-Wise Development



Source: Developed by the authors based on literature review, 2025

Early Ecological Approaches (Pre-1980s) in Planning.

In the mid-20th century, the work of scholars such as Meadows et al. (1972) in “The Limits to Growth” highlighted the finite nature of resources and the necessity of integrating ecological considerations into planning processes. This seminal report underscored the importance of understanding ECC in the context of sustainable development, emphasizing that unchecked growth could lead to ecological collapse (Rockström et al., 2009). Early methodologies were biophysical and based on straightforward metrics such as resource availability (e.g., food, water, space) and population dynamics (Boserup, 1965). These approaches were simple, often linear, and did not account for complex interactions between human activities and the environment (Barbier, 1990). The concept gained traction in spatial planning as planners began to incorporate ecological principles into land-use decisions. The notion has evolved significantly, particularly as urbanization and industrialization have intensified pressures on the environment. While early models provided basic insights into the limits of ecosystem resilience, they were reductive and failed to incorporate human-environment feedbacks (Turner et al., 1990). Furthermore, these models were highly context-specific, limiting their general applicability in urban and coastal environments where ecosystems are subject to rapid change.

3.1.2. Multidisciplinary and Integrative Approaches (1980s-1990s) in Planning.

In the 1980s and 1990s, the discourse around ECC expanded with the introduction of the concept of sustainable development, notably articulated in the Brundtland Report (World Commission on Environment and Development, 1987). This report called for a balance between development and environmental preservation, further solidifying the role of ECC in spatial planning frameworks. ECC research began to incorporate socio-economic dimensions, particularly in urban and regional planning contexts. Integrated Assessment Models (IAMs) emerged as a key tool, combining ecological, economic, and social factors to model the sustainability of human-environment systems. These models expanded the concept of ECC beyond mere population limits to include factors like resource consumption, waste generation, and social well-being (Funtowicz & Ravetz, 1990). Planners began to adopt methodologies to assess ECC, integrating it into environmental impact assessments (EIAs) and land-use planning (Glasson and Therivel, 2013). While IAMs provided a more holistic understanding, they were often criticized for being too generalized and static, failing to account for regional and local variations in ecosystem dynamics and socio-economic conditions

(Selman and Parker, 1999). Furthermore, IAMs often lacked the spatial specificity necessary for urban and coastal planning (DeFries et al., 2004).

Rise of Resilience-centred Approach (1990s-2000s) for transforming urban systems

As climate change and environmental degradation became pressing global issues, ECC research began discussing the concepts of resilience and vulnerability (Walker et al., 2004). The 1990s saw a proliferation of studies focusing on the quantification of ECC. For instance, Costanza et al. (1997) introduced the concept of ecosystem services, which provided a framework for understanding the benefits that ecosystems provide to human societies. This work emphasized the need for spatial planners to consider not only the carrying capacity of physical resources but also the ecological services that underpin human well-being (TEEB, 2010). The idea of environmental resilience—the capacity of ecosystems to withstand or adapt to changes—became central to understanding ECC (Holling, 1973). Researchers began to develop dynamic models to assess the adaptive capacity of ecosystems and the impact of human activities (Folke et al., 2002). Wackernagel and Rees (1998) responded to the limitations of ECC analysis by developing the ecological footprint, a measurable indicator of human impact on ecosystems. While resilience frameworks offered a more adaptive approach to ECC, they were still often limited to ecological contexts and did not fully engage with spatial planning issues, particularly in urban settings. The emphasis on vulnerability also led to models that were overly focused on risks rather than the potential for sustainable growth (Adger, 2006). Moreover, most resilience models were site-specific and failed to offer generalized frameworks applicable to larger, urban regions (Cumming et al., 2005).

Confluence of Spatial Planning and GIS-based Approach (2000s-2010s)

In the 21st century, the integration of ECC into spatial planning has become increasingly sophisticated, with the advent of spatial models for assessing ECC. Geographic Information Systems (GIS) and Remote Sensing technologies have emerged as powerful tools for assessing, visualizing ECC, and model the spatial distribution of environmental resources, land use, human activities and environmental impacts (Bhatta, 2010; Lechner et al., 2013) These models allowed for the analysis of land use patterns, resource allocation, and ecological footprints at a regional scale (Foley et al., 2011). Agent-Based Models (ABMs) and System Dynamics Models (SDMs) were used to simulate complex interactions between human and environmental systems, offering a more dynamic and interactive view of carrying capacity. This technological advancement has facilitated more informed decision-making processes that align with sustainable development goals. Despite the promise of GIS and spatial models, most research in ECC has been overly technical and lacks a clear connection to policy implementation (Olsson et al., 2006). Spatial models often fail to incorporate the social dimensions of environmental management, such as community participation, governance, and the role of local knowledge (Wright et al., 2009).

Urban Dynamics and Participatory Approach in contemporary world (2010s-Present)

In recent years, ECC research has embraced dynamic systems models that incorporate feedback loops, non-linear interactions, and uncertainties. Models like Multi-Criteria Decision Analysis (MCDA) have been used to assess trade-offs between competing land use options, considering economic, social, and environmental criteria (Huang et al., 2011). Scenario-based modeling has gained traction, allowing researchers to explore how different policy interventions, climate change impacts, and technological advancements affect ECC over time (Guan & Rowe, 2016). In addition, the literature has also highlighted the importance of stakeholder engagement in the assessment of ECC, leading to more equitable and sustainable outcomes (Luyet et al., 2012). Despite these dynamic models offering a more flexible approach in an uncertain complex socio-environmental systems, these models still tend to oversimplify the role of governance structures and institutional frameworks in shaping carrying capacity (Nugroho & Uehara, 2023). The spatial dimension of carrying capacity has often been overlooked in favor of broader system dynamics, which diminishes the relevance of these models for practical spatial planning. As highlighted by Folke et al. (2016), adaptive management strategies are essential to navigate these uncertainties and ensure that spatial planning remains responsive to changing environmental conditions (Beechie et al., 2010; Garmendia et al., 2010). Recent literature underscores the necessity of integrating land-use planning with ECC assessments to promote sustainable socio-ecological development.

Key Learnings from Evolutionary study

The evolution of Environmental Carrying Capacity (ECC) thinking offers critical guidance for developing a novel, integrated ECC framework. First, it is essential to move beyond static thresholds such as population-resource ratios and incorporate ecosystem resilience, feedback loops, and ecological assessments into the analytical structure. Second, spatial specificity should be achieved through GIS-based assessments, while dynamic system modeling must be used to capture the non-linear linkages inherent in urban environments. Third, the integration of participatory processes—including stakeholder inputs and institutional considerations—will enhance contextual relevance and governance applicability. Finally, to ensure that ECC analysis informs real-world planning decisions, the framework should directly align with the structure and components of Master Plan or development plans, using parameters like land use, zoning regulations, infrastructure capacity, and risk exposure zones. The integration of ECC into planning processes has thus become a cornerstone for spatial planning strategies (Zhang et al., 2017), to foster resilience and sustainability in human-environment interactions. Further, to understand quantitatively the focus of research in the ECC domain, bibliometric analysis has been carried out.

Bibliometric Analysis of Environmental Carrying Capacity research

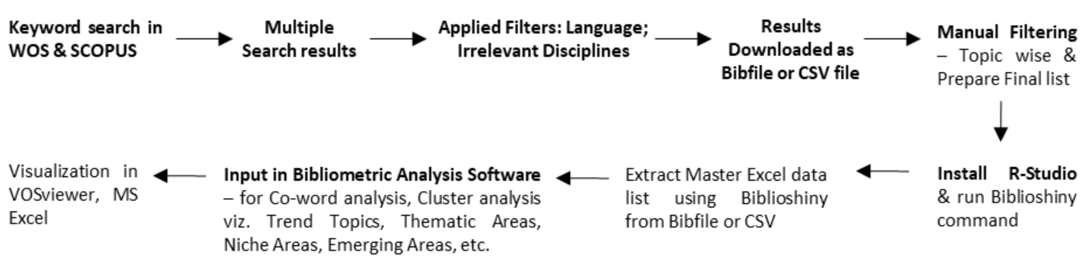
The bibliometric analysis of ECC research aims to present a methodical summary of the interdisciplinary linkages and publication patterns in ECC studies. By leveraging performance analysis and science mapping techniques using data from Scopus and Web of Science (WoS), this study identifies research progress globally, key thematic areas, emerging research fronts, and gaps in ECC application. For analysis, title, keyword, author, and publication year-specific information is retrieved from the databases. The insights gained from keyword mapping, concurrence analysis, and thematic clustering using Biblioshiny (R) and VOSviewer will help in strengthening the integration of ECC principles into spatial planning frameworks.

Materials and Methodology adopted for Bibliometric Analysis

For a thorough, multidisciplinary coverage of the research domain and for better variability of results, this study uses both the Web of Science (WoS) and Scopus databases – utilizing WoS for its curated, high-impact scholarly content and Scopus for its extensive subject indexing across disciplines including environmental and urban studies.

First, the bibliometric study was carried out using WoS database in the domain of 'Environmental Carrying Capacity' for the time-span 2009-2023 (~15 years). The basic search string used for this study was (TI=("Environmental Carrying Capacity" OR "Ecological Carrying Capacity" OR "Urban Carrying Capacity" OR "Carrying Capacity") OR AB=("Environmental Carrying Capacity" OR "Ecological Carrying Capacity" OR "Urban Carrying Capacity" OR "Carrying Capacity")). After manual filtering by the author 318 documents was selected. After this Bibliometric analysis have been carried out in online web-based data anaylsis framework Bibliometrix (R-Language based software package Biblioshiny). The steps adopted for Bibliometric analysis is presented in a flow diagram in Figure 6.

Figure 3: Flow diagram for Bibliometric analysis using Bibliometrix (R)



Source: Method diagram generated by authors, 2025

Further, the bibliometric study was carried out using Scopus database. The search string ("Environmental Carrying Capacity" OR "Ecological Carrying Capacity" OR "Urban Carrying Capacity" OR "Carrying Capacity") AND ("Spatial Planning" OR "Urban Planning" OR "Regional Planning") AND ("Sustainable Development" OR "Sustainability Indicators" OR "Sustainable Land Use") AND ("Master Plan" OR "Development Plan") and other modified search paths were utilized with publication period not set. This yielded 433 results with publication year ranging from 1995 to 2024. This was further screened to minimize irrelevant results, by limiting the relevant subject area, setting 'Exactkeywords', and setting the language filter to 'English' language, which retained 155 search results (papers from 1998 to 2024 found). The exact key words used were viz. Sustainable Development, Sustainability, Land Use Planning, Climate Change, Ecosystems, Ecosystem Services, Environmental Protection, Environmental Impact, Environmental Management, Environmental Policy, Spatiotemporal Analysis, Spatial Distribution, Urban Planning, Urbanization, Urban Development, GIS, Remote Sensing, Decision making, Governance Approach, Strategic

Approach, Integrated Approach, Regression Analysis, Spatial Analysis, Sensitivity Analysis, Vulnerability, Risk Assessment, etc. The downloaded '.csv' file included some papers from multi-disciplinary domains such as bio-sciences, earth sciences, energy, arts, humanities and management etc. which was again filtered manually. This file was screened manually further based on based on journal titles or source title or author key word or index key word mentioning "carrying capacity". The researchers also checked the instances of usage of "Environmental Carrying Capacity" or "Ecological Carrying Capacity" specifically in the abstract, key words and title resulting only in 13 papers. As the count was less, 155 papers selected have been considered for further analysis, without considering the 'title' filter. This data was then converted in different raw data forms to input in bibliometric analysis software. After this Bibliometric analysis have been carried out using Bibliometrix.

In addition, VOSviewer has been employed, to bring out select analytical visualizations to gain insights into emerging research in ECC. The results have been compared with the previous bibliometric study literature on carrying capacity related domains. The bibliometric study results have helped to structure the guiding framework for integrating environmental carrying capacity in spatial planning.

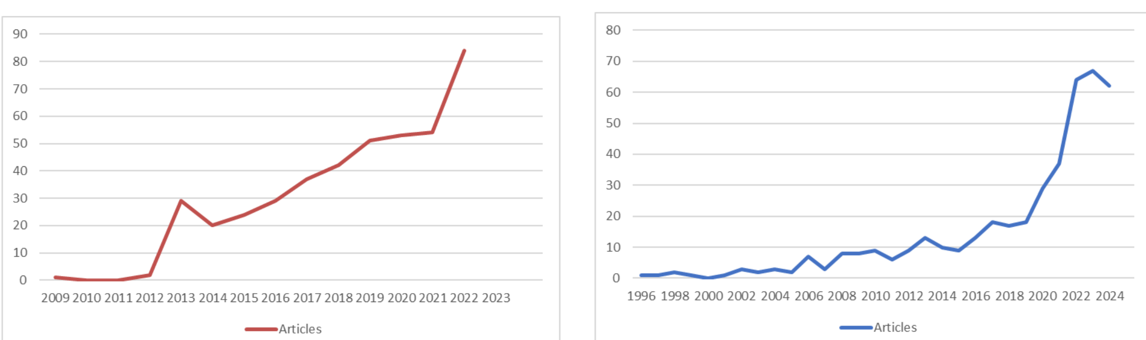
Results and Findings from Bibliometric Analysis

The analysis involved examining annual publication trends, country-wise production, co-authorship patterns, and the frequency and co-occurrence of keywords. Advanced techniques such as co-word analysis, cluster analysis, and thematic mapping were employed to identify core research domains. Visual tools like the three-field plot (linking Authors, Keywords Plus, and Author Keywords), keyword temporal evolution through Sankey diagrams, and trend topic analysis were used to explore the intellectual structure and emerging directions of ECC literature. The results and findings have been grouped under two broad heads – publication-based analysis and keyword-based analysis in the subsequent sections.

Results and Findings from Publication-based Analysis

The inferences drawn are from the bibliometric study on ECC using both WoS and Scopus database. Firstly, research on environmental, urban and resource carrying capacity has grown gradually since the early 20th century, with a significant increase in the late 1990s and a sudden spike post 2010 as per WoS database and post 2016 as per Scopus database (Figure 7). Notably, the rise in number of papers from 1990s originates from a single paper authored by William E. Rees, which has garnered global recognition as the most frequently cited document.

Figure7: Growth of Annual Publication based on WoS (Left) and Scopus (Right) database

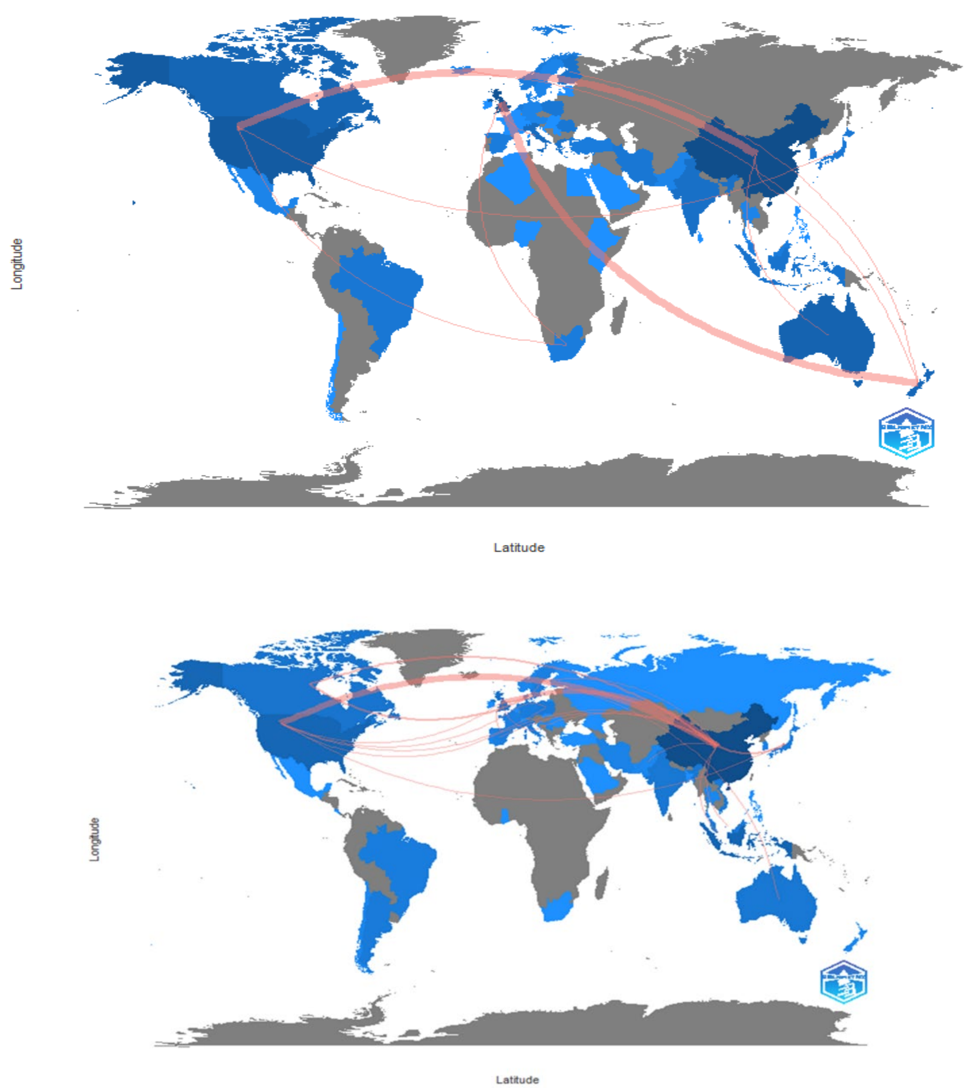


Source: Developed by authors in Biblometrix, 2025

Secondly, Scopus and WoS datasets reveal that ECC research began incorporating the concepts of resilience and vulnerability in early 1990s and slowly progressed into embracing dynamic system-based quantification and modelling. Thirdly, contemporary research focus on employing a range of models and techniques, including AHP, TOPSIS, GIS, Remote Sensing, system dynamics, MATLAB, Machine Learning, and others, for effective determination of carrying capacity using spatial models.

Furthermore, both Scopus and WoS database indicates that China is leading in paper production and research collaborations on "Environmental Carrying Capacity," "Carrying Capacity," and "Sustainable Development." The United States and UK follow suite, showing an inclination towards environmental planning and management of resources as well as increasing interests in academic arenas and policy with regard to sustainability issues. The Scopus database reveals that, according to the Country Collaboration networks generated using Bibliometrix, the levels of research collaboration between China and North America, and (USA), and Europe (UK) and New Zealand are high amongst 39 different countries. Similarly, the WoS database reveals that, according to the Country Collaboration networks generated using Bibliometrix, the levels of research collaboration between China, North America, and Europe are high amongst 22 different countries, with a presence of strong international partnerships through frequent co-authorships. However, there remains limited representation and significantly lower research output from countries in India and the broader Southeast Asian region, underscoring a critical gap and the need for more localized studies on environmental carrying capacity in these contexts. The Country Collaborations based on Scopus (Top) and WoS (Bottom) database is presented in Figure 8.

Figure 8: Country Collaborations based on Scopus (Top) and WoS (Bottom) database



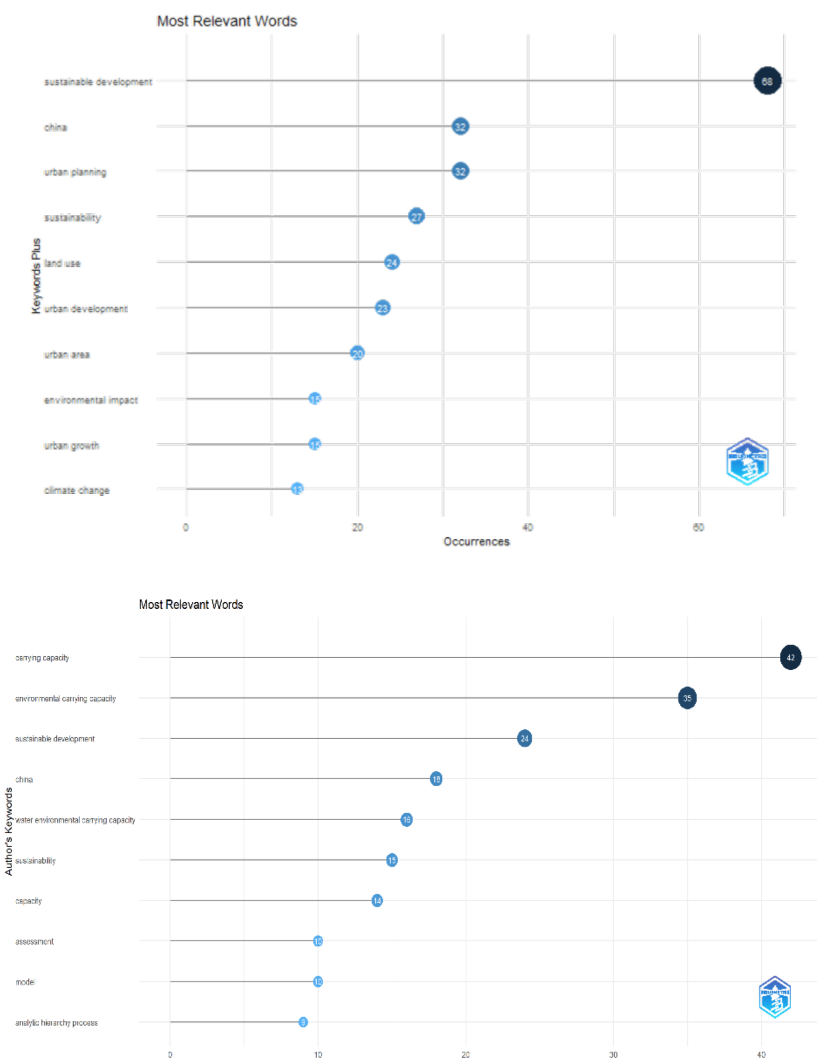
Source: Developed by authors in Biblometrix, 2025

Results and Findings from Keyword based Analysis

Firstly, to understand the thematic focus of research in the domain of carrying capacity, the keyword analysis – assessing the most frequently keywords, Three-field plot, co-occurrence analysis, keyword temporal evolution, thematic analysis – in Bibliometrix (R) using WoS and Scopus datasets separately was carried out.

The output of the most frequently used keywords is depicted in bar chart formats in Figure 9. The Authors' Keywords have been considered to generate this output to understand the research trend. In the Scopus dataset, keywords like sustainable development, carrying capacity, land use planning, climate change and urban resilience are most frequently repeated indicating the direction of research focusing on sustainable spatial planning and resilience models broadly. The top 5 terms that occur most frequently in the WoS dataset are carrying capacity, model, management, sustainable, and system indicating a clear interest in research direction focusing on systematic models for environmental assessment, integration of sustainability principles in planning and management frameworks. However, the most frequently used keywords from most papers rarely included direct references to master plans, zoning regulations, or urban planning instruments.

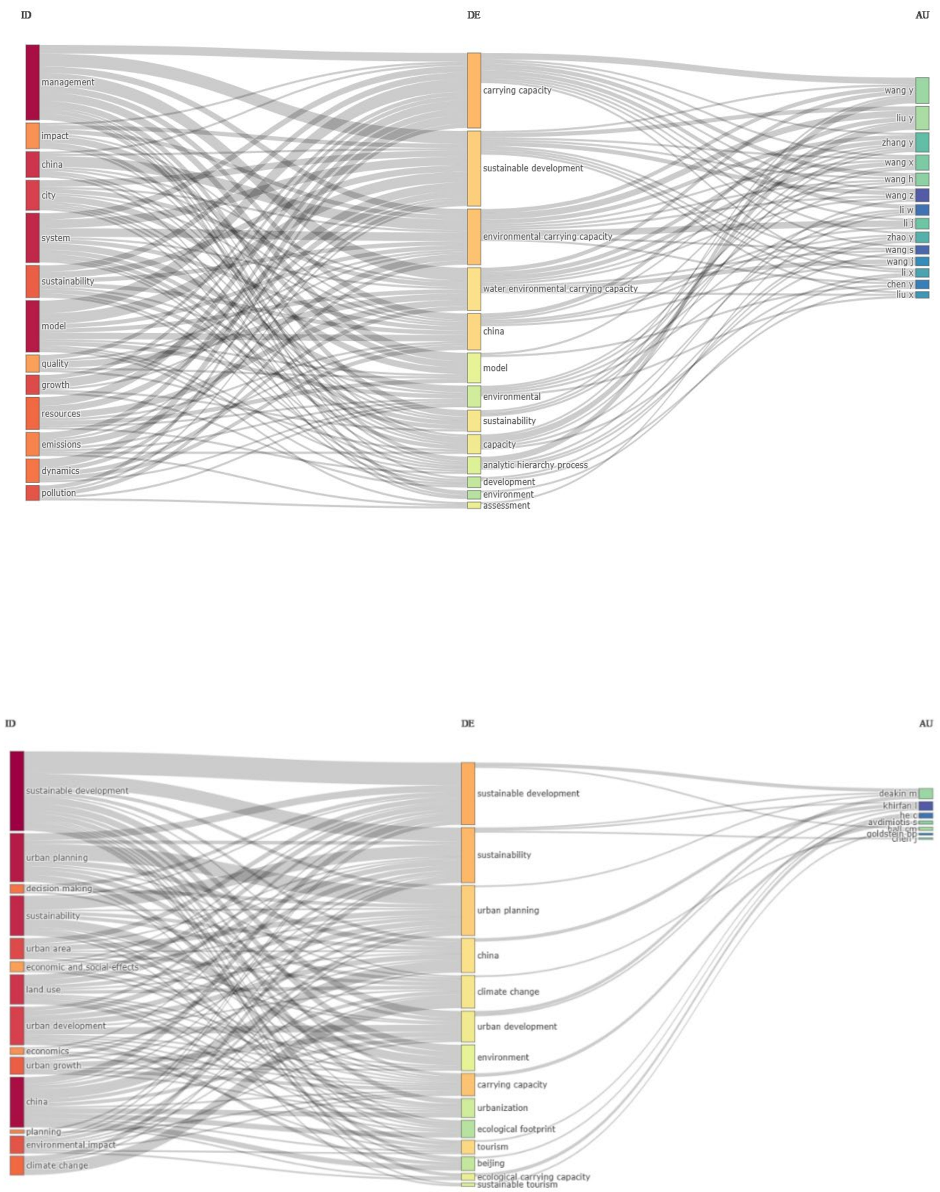
Figure 9: Most frequently occurring words based on Author Keywords in Scopus (Top) and WoS (Bottom) database



Source: Developed by authors in Biblometrix, 2025

Secondly, the three-field plot (or Sankey diagram, Figure 10) was generated linking Author Keywords (Left, ID), Keywords Plus (Middle, DE), and Authors (Right, AU), to get further insights into the structure and thematic focus of research in ECC. Analysis of WoS database reveal that 'Carrying capacity', 'Sustainable development', and 'Environmental carrying capacity' are central themes in the literature, tightly linked with author keywords like sustainability, management, and city, showing their strong relevance. The authors, Wang Y, Liu Y, Zhang Y, and Zhao Y ae the leading contributors in key ECC themes in WoS. Analysis of Scopus database reveal that 'Sustainable development', 'Urban Planning' and 'Carrying capacity' are the central themes, which are linked with author keywords like land use, decision making, environmental impact and climate change. The authors, Deakin M and Hall CM are the leading contributors in key ECC themes in Scopus.

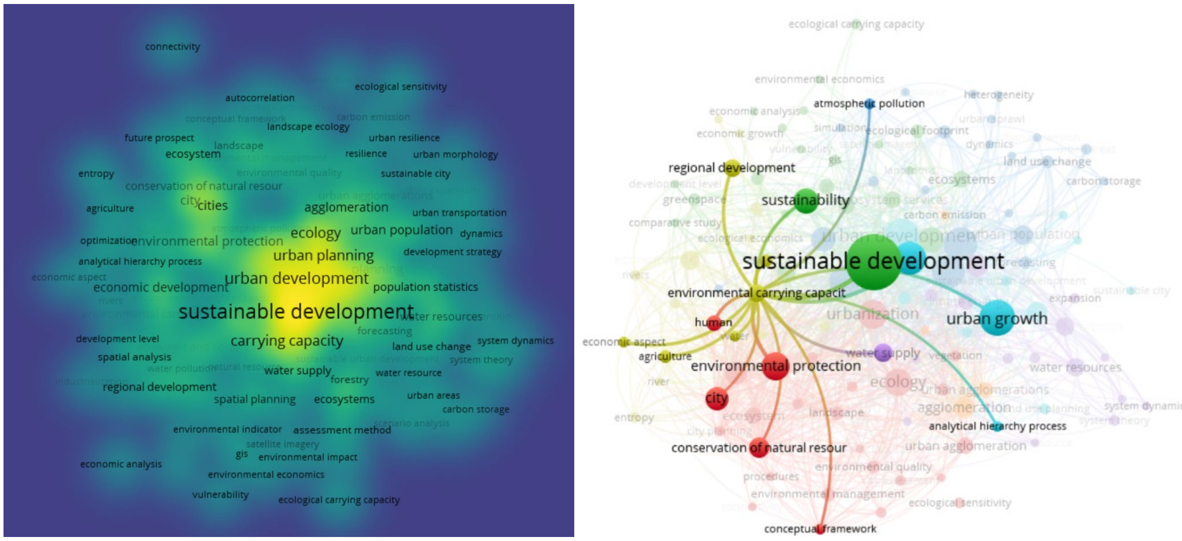
Figure 10: Three-field plot showing the relationship between Author Keywords (ID), Keywords Plus (DE), and Authors (AU) in ECC research in WoS (Top) and Scopus (Bottom)



Source: Developed by authors in Biblometrix, 2025

A significant body of ECC research is focused on China's urban planning context in both databases. The three-field plot analysis highlighted author keywords clustering around sustainability and environmental management, but only a few authors explicitly focused on urban-scale ECC application.

Figure 11: Keyword Co-occurrence Analysis outputs from VOSviewer



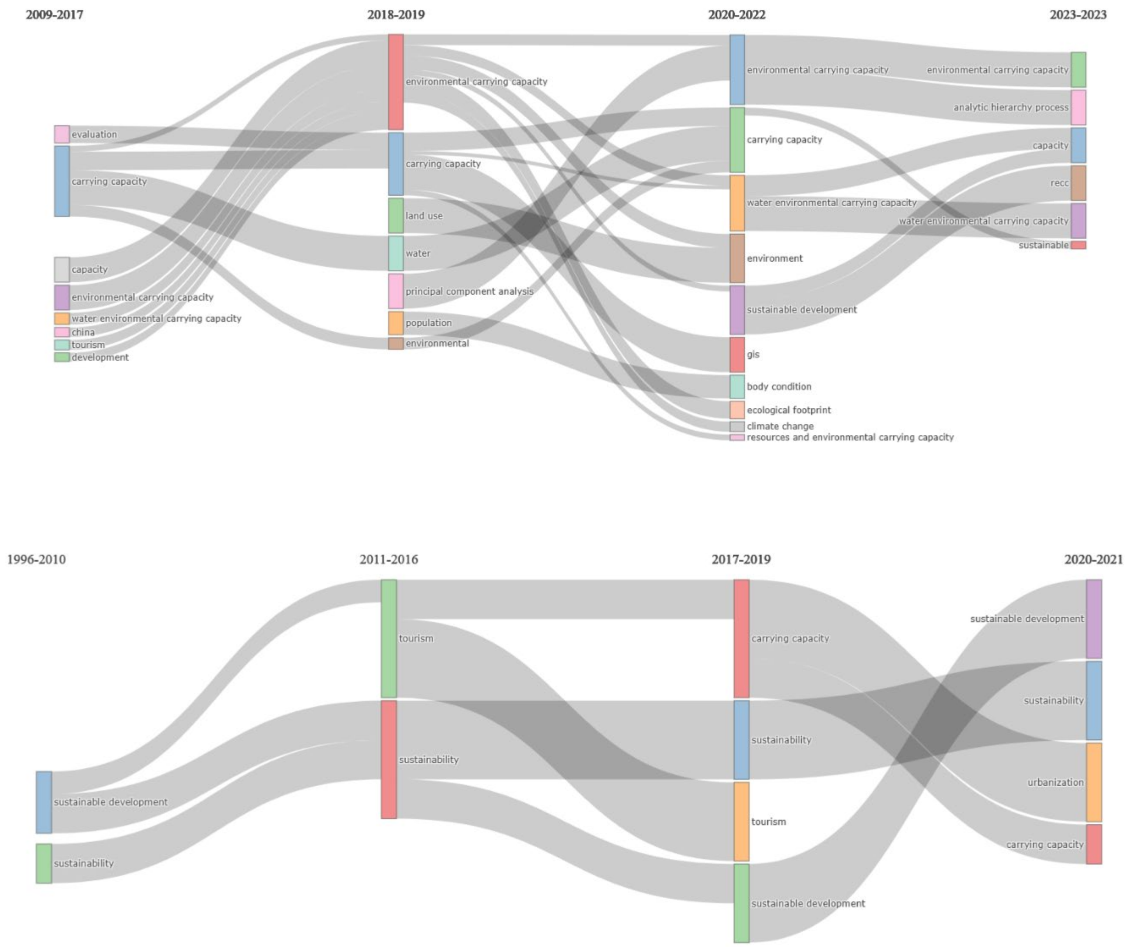
Source: Developed by authors, 2025

Thirdly, to understand the link between the keywords and the key thematic clusters, the co-occurrence analysis was carried in VOSviewer (Figure 11). The minimum co-occurrence of key words was set at 03, giving largest set of connected items as 122 items and 07 clusters. The results highlight strong associations between terms like "Sustainability," "Carrying Capacity," "Land Use Planning," and "Environmental Impact Assessment," indicating interdisciplinary linkages and emerging research trends in sustainable spatial planning.

Specifically, the key word ‘Environmental Carrying Capacity’ is linked with Sustainable Development, Urban Growth, Environmental Protection, Regional Development, and Conceptual Framework, in the order of importance revealing strong associations. Yet, spatial planning tools such as zoning, density planning, or infrastructure thresholds were underrepresented in the connected clusters.

Next Page

Figure 12: ECC Keyword Temporal Evolution Sankey diagram (Top) based on WoS and (Bottom) Scopus

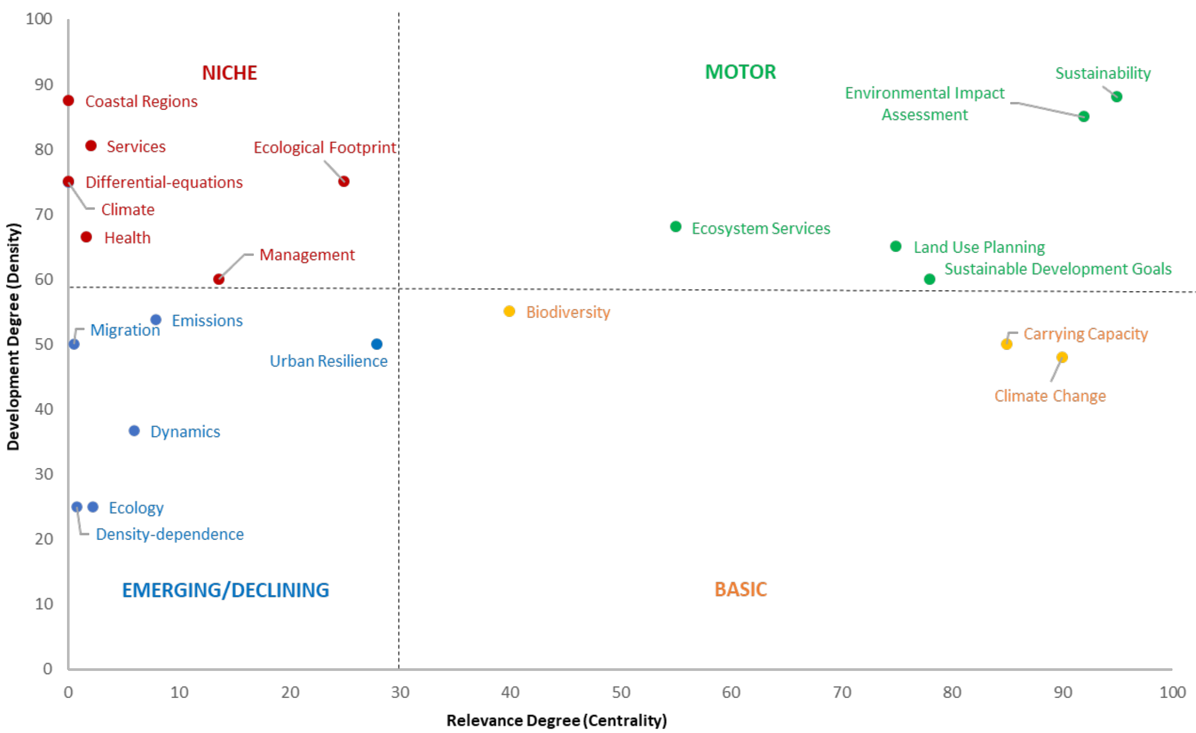


Source: Developed by authors in Biblometrix, 2025

Further, the keyword temporal path (Figure 12) based on WoS database was generated based on Author keywords to understand thematic development and methodological shift in ECC research. The development of the keywords suggests a clear shift from straightforward analysis of environmental limitations towards more complex, model-based, and spatial assessment of ECC. Keywords used in recent literature shows increased integration of ecological, climatic, and vulnerability considerations along with the increasing use of GIS tools and MCDM techniques, including AHP. New trends connect ECC with sustainability, climate resilience, and regional spatial planning paradigms implying a shift towards more dynamic and context-specific strategies.

The keyword temporal path based on Scopus database based on Author keywords reveal that a shift from theoretical debates on sustainable development and sustainability to operational concerns such as carrying capacity in the context of tourism, and then institutionalization of carrying capacity in wider sustainability research. Recent research interest shows widening scope of ECC into application of ECC ideas in urban and spatial planning contexts, and a shift from theoretical to model-based assessments of ECC, yet the evolution toward concrete application in statutory urban planning frameworks has been minimal.

Figure 13: Thematic analysis based on relevance and keywords development



Source: Developed by authors in MS Excel, 2025

Finally, Thematic analysis was carried out in MS Excel (Figure 13) based on relevance (Centrality) and development (Density) of the keywords for segregating the identified keywords into four quadrants: Motor Themes, Basic Themes, Niche Themes, and Emerging or Declining Themes. Motor themes such as Sustainability, Environmental Impact Assessment, and Land use Planning are well-established and deeply interconnected within the literature. Basic Themes such as Carrying Capacity, Climate Change and Biodiversity are elementary ideas but might need additional theoretical integration or domain-specific refinement. Niche Themes such as Coastal regions, Ecological Footprint and Management are specialized and developed but still in isolation from mainstream discourse. Emerging or Declining Themes such as Urban resilience and Dynamics are new research areas that are yet to attain prominence and less in applicability. Overall, sustainability-related themes dominate the discourse, with motor and basic themes forming the backbone of environmental carrying capacity research. While Environmental Carrying Capacity is a foundational concept (basic theme) in sustainability discourse, it is still a developing research field that requires additional empirical validation, interdisciplinary integration, and dynamic modelling approaches to improve its applicability in real-world spatial planning and environmental policy development.

Scientific Tools and Techniques for Modeling ECC

ECC assessment in urban development relies on various models, instruments, and approaches, such as the UDI-ECC Coupling Model (Hu et al., 2021), which integrates urban development and ECC indicators to analyze sustainability, the CRECC Evaluation Model (Liu et al., 2023), which considers environmental, economic, and social dimensions, and the RECC (Huang et al., 2023) and URECC-LC (Shen et al., 2020), focusing on urban durability and lifecycle analysis. Other approaches involve the use of ecological models that assess the limits of resource availability and ecological impacts, such as the PSR and DPSIR (Drivers, Pressures, State, Impact, Response) models that allow for the analysis of environmental changes driven by anthropogenic factors.

ECC estimation incorporates multiple methodologies emphasizing environmental pressures and sustainability. Techniques such as Ecological Footprint Assessment (Wackernagel & Rees, 1996), Ecosystem Services Valuation

(Costanza et al., 1997), the IPAT formula (Impact = Population × Affluence × Technology), Life Cycle Assessment (LCA), and Dynamic System Analysis highlight the importance of maintaining ecological constraints to prevent environmental degradation. Integrating these approaches provides a holistic perspective of urban impacts on the environment.

Statistical techniques such as the Analytic Hierarchy Process (AHP) and the Entropy Weight Method are commonly used to evaluate and prioritize indicators that affect ECC based on their contribution to sustainability. Moreover, Coupling Coordination Degree (CCD) and Geographically Weighted Regression (GWR) models are used to assess the spatial distribution and coordination between urban development and ecological limits, providing insights to identify unsustainable growth areas. Ordinary Least Squares (OLS) regression tests analyze interrelationships between indicators, helping predict urban planning impacts. Geospatial technologies like Remote Sensing and GIS-based Spatial Analysis are essential tools in ECC studies, offering insights into land use and environmental changes. System Dynamics Modeling is another key method, simulating complex urban-ecological interactions and forecasting long-term impacts. Stakeholder Engagement and Participatory Approaches play a crucial role in ECC assessments, incorporating local perspectives into planning and policy decisions.

Key Learning from Bibliometric Analysis

The Bibliometric analysis suggests a growing emphasis on data-driven decision making, inter-disciplinary approaches and policy formulation across thematic research area related to carrying capacity to address environmental challenges and enable practical application of sustainability-led spatial planning models. As per Tailor et al. (2023) in the domain of Urban Carrying capacity and bibliometric study of abstracts by the author reveals that most papers are single-factor focus based studies (land-based, water-based, air-based, infrastructure-based) and low numbers papers are on comprehensive resource analysis.

Overall, the bibliometric study reveals that sustainability, carrying capacity assessments, and spatial planning have become major fields of research, but much work still needs to be done to incorporate carrying capacity assessments into the actual practices of urban and regional planning. Overall, only 13 papers across both databases directly addressed ECC in the context of spatial or urban planning, and among those, very few translated the research into actionable strategies for decision-making or policy formulation, indicating a critical research and application gap in linking ECC with spatial planning practices. Trend indicates that future studies need to emphasize on developing data-driven methodologies for multi-factorial carrying capacity models that integrate land, water, and infrastructure with ecological considerations. Importantly, ECC is not static; it adapts to changing environmental conditions, making it essential for planners to incorporate dynamic tools and real-time data (Barrow, 1999).

Application of ECC in India*: Progress in Integration within Urban Policies and Planning Frameworks*

Environmental concerns in Indian spatial planning have undergone great change, especially due to global sustainability movements and increased awareness of environmental risks due to urbanization. As landmark agreements, including the 1972 Stockholm Conference, the Brundtland Commission Report (1987), and Agenda 21 (1992), influenced global sustainability policy, India's formal integration of ecological concerns into planning documents only started gaining momentum after 1972 (UNEP, 1972; Brundtland, 1987). While subsequent environmental policy development, including the Environmental Protection Act (1986) and the National Environmental Policy (2006), took place, the integration of Environmental Carrying Capacity (ECC) into spatial planning is still insufficient, with urban policies largely centering on infrastructure and socio-economic development at the cost of ecological sustainability (George & Kumar, 2016).

The Supreme Court of India in 2023 ordered a study on carrying capacity for the Himalayan region, with an emphasis on the necessity of scientific evaluation in sensitive areas (NDTV news report, 2023). This resulted in the recommendation of 13 Himalayan states to undertake carrying capacity evaluations, led by an expert committee (Business Standard, 2023). Although this is a considerable development for carrying capacity integration in planning, its general use remains limited. The URDPFI Guidelines (2014) brought carrying capacity-based planning but primarily concentrate on socio-economic information, remaining silent on ecological sustainability in urban development projections (Bedi & Mahavir, 2022, DuPuy et al., 2025).

Urban-level advancement has been made in carrying capacity evaluation of infrastructure but lags behind in environmental assessment. In Madhya Pradesh's Gwalior, a study used the IIT Guwahati SAFE model to calculate urban land needs, providing a quantitative solution to carrying capacity-based planning (Bhagwat & Devadas, 2021). Environmental Carrying Capacity is not implemented in Indian Master Plans, in many cases reduced to a mere standalone environmental chapter rather than integral to urban expansion plans (Munshi et al., 2015).

A systematic evaluation of recent Master Plans across various Indian cities was conducted as part of this study to assess the integration of notion of carrying capacity in urban planning in India. For selecting Master Plans in India, the criteria considered included – (a) City size (target to study Metropolitan, Large, Medium and Small towns); (b) Varied Geographical settings, such as coastal cities, inland cities, and fragile ecosystems, where environmental constraints are more pronounced; (c) Recent and relevant Plans (or Plan periods extending beyond 2025). Each Master Plan that was identified was analyzed based on three key dimensions: (1) Plan consideration of 'Environment'; (2) Sectoral Focus, evaluating the extent to which 'Environment' is analysed, and (3) Assessing whether carrying capacity of environmental component is explicitly quantified and incorporated as a planning consideration; If yes, determining whether quantifiable carrying capacity thresholds are defined. The review of 28 Master Plans reveals that while most cities include sections on environment, the focus remains largely descriptive, and limited to profiling, quality assessments, or vulnerability analyses; with no comprehensive attempt to quantify Environmental Carrying Capacity (ECC). The findings also reveal inconsistencies and gaps in the application of carrying capacity across spatial planning documents, with almost all plans lacking standardized methodologies for assessing environmental aspects and integrating carrying capacity considerations. Other than the recent Master Plan for Shimla where 'carrying capacity' has been considered in the planning strategies, in response to the NGT (National Green Tribunal) directives for hilly areas; and the Bangalore Revised Master Plan where, carrying capacity with respect to water availability has been quantified; no other Master Plan attempted to quantify or assess the carrying capacity of any environmental component. The Master Plan Study Summary Table presented in Table 1 provides an overview of the level of environmental considerations and ECC incorporation across different urban contexts.

Table 1: Review of Master Plans of Indian cities

S.No	City/ Region	Plan Horizon Period	Dedicated Section on environment	Sub topics of environment considerations	Type of Environmental Analysis	Carrying Capacity of Environmental components	Areal extent (sq.km.)	Population (2011 Census)
1	**Delhi**	2021	Yes	Bio-diversity, Ecology, Green belt	Quality analysis	Not Discussed	1484.00	1,10,00,000
2	**Goa**	2021	Yes	Eco-Tourism, Ecology	Impact assessment	Not Discussed	3702.00	14,58,000
3	**Jaipur**	2025	No	Discussed briefly under Quality of Life and other chapters	Profiling	Mentioned in text only wrt Industrial citing and Tourist destinations. No study carried out	541.00	36,02,000
4	**Guwahati**	2025	Yes	Geology, Limnology, Water Management	Quality analysis - Water, Air, Wetlands	Not Discussed	262.00	9,68,549
5	**Chennai**	2026	Yes	Pollution, Climate change, Disaster Management	Quality analysis - Air, Water	Not Discussed	426.00	46,46,732

6	**Amritsar**	2031	Yes	Environment	Profiling	Not Discussed	1394.19	20,14,626
7	**Jalandhar**	2031	No	Mentioned under Infrastructure	Profiling	Not Discussed	775.00	16,38,770
8	**Chandigarh**	2031	Yes	Ecology	Impact assessment	Carrying capacity mentioned about air-quality. (No further details)	114.00	10,54,686
9	**Noida**	2031	Yes	Green Belt Development, Protection and Conservation of Forest, Pollution	Quality analysis - Water, Air, Land, Noise	Not Discussed	203.00	6,41,381
10	**Puri**	2031	Yes	Environment, Disaster	Quality analysis, Disaster Vulnerability	Not Discussed	296.33	3,13,340
11	**Hyderabad**	2031	Yes	Environment	Profiling, Quality Analysis	Not Discussed	5965.00	96,00,000
12	**Bangalore**	2031	Yes	Environment and Ecology	Profiling	Carrying Capacity with respect to water availability	1219.00	90,40,000
13	**Jammu**	2032	Yes	Ecology, Disaster management, Groundwater management strategy	Quality analysis - Water	Not Discussed	240.00	5,02,197
14	**Nilambur**	2034	Yes	Bio-diversity, Ecology	Impact assessment	Not Discussed	29.69	46,366
15	**Surat**	2035	Yes	Physiology, Climate, Urban Heat, Flood, Pollution	Quality Analysis	Not Discussed	715.00	48,05,101
16	**Kakinada**	2035	Yes	Environment, Green Belt	Profiling	Not Discussed	161.80	5,74,463

17	**Kozhikode**	2035	Yes	Environment & Bio-Diversity Conservation, Wetlands Management	Quality analysis - Air, Water	Not Discussed	91.00	4,31,560
18	**Mumbai**	2036	Yes	Status of Environment	Issue Identification	Not Discussed	4254.00	2,28,04,355
19	**Coimbatore**	2038	Yes	Ecology	Impact assessment	Not Discussed	18235.00	89,24,235
20	**Kochi**	2040	Yes	Climate, Natural Resources, Disaster, Pollution, CRZ	Profiling, Vulnerability, Quality analysis – Air, Water, Noise, Risk Assessment	Not Discussed	94.88	6,02,046
21	**Trivandrum**	2040	Yes	Climate, Environment, Disaster Management	Profiling, Pollution and Hazards	Not Discussed	212.84	9,66,000
22	**Shimla**	2041	Yes	Environment and Disaster Management	Eco-sensitivity, Vulnerability & Risk, Conservation	Carrying Capacity assessed based on NGT directives for hilly areas, and considered in strategization	224.50	2,41,429
23	**Dehradun**	2041	Yes	Environment, Ecology and Disaster	Profiling, Vulnerability	Not Discussed	505.50	9,83,586
25	**Pune**	2041	Yes	Bio-diversity, Pollution	Quality analysis, Impact assessment	Not Discussed	729.00	94,29,408
26	**Visakhapatnam**	2041	Yes	Seismicity, Disasters, Coastal environment, Pollution	Quality analysis - Air quality and Water quality, Vulnerability	Not Discussed	6501.65	50,70,000
27	**Karaikal**	2041	Yes	Environment and Disaster Management	Profilng	Not Discussed	160.00	2,00,222

28	**Kollam**	2041	Yes	Environmen t, Disaster	Profilng, Eco-sensitivity	Discuss the possibility to plan infrastructur e, coastal area and tourism based on carrying capacity; but no quantifcatio n attempt	71.73	3,87,942

Source: Compiled by the Authors, 2025

The development plans for the Indian cities, here Master Plans, fail to focus on environmental considerations, which may lead to future planned development achieving only 'weak sustainability'. In this juncture, Indian cities are at the risk of exceeding ecological capacity and exacerbating sustainability issues. Reforms by NITI Aayog (2021) prioritize coordinated urban and regional planning efforts, but do not include carrying capacity-based decision-making procedures. To couple with these concerns, insufficient and weak enforcement of plans, and non-cooperation between the city development stakeholders further prevent full integration into spatial planning (Kumar & Raoof, 2019). These loopholes necessitate statutory carrying capacity evaluation requirements with focus on environment, scientific modeling towards sustainability, and more robust linkages established between environmental stewardship and spatial development in the planning process.

Decrypting ECC: Challenges and Opportunities in Planning Perspective

Carrying capacity, though defined in various ways, extends beyond a simple scientific concept or a formula to determine limits for development. It is a dynamic process that provides guidance, emphasizing the need to recognize ultimate limits as a source of direction in urban planning (George & Kumar, 2016). The concept of sustainability plays a crucial role in establishing conditions for urban expansion, helping set goals that align with the boundaries of spatial carrying capacity while considering resources and environmental factors to facilitate comprehensive benefits. Furthermore, for balanced regional development, it is essential to concentrate population and economic activities in regions with high carrying capacity, while reducing activities in ecologically fragile areas. In areas of ecological significance or constraints, the concept of carrying capacity is particularly vital, highlighting its importance in ensuring that development aligns with environmental sustainability. The systematic literature review points out that the implementation of Environmental Carrying Capacity (ECC) in spatial planning proves challenging but rewarding, requiring a systematic and coordinated approach based on resource availability, environmental constraints, and sustainability considerations. According to literature review and review of Master Plans, the primary concern is the lack of environmental considerations in spatial planning, particularly in India, where urbanization often disregards ecological limits, resulting in unsustainable development patterns (Kumar & Raoof, 2019). While ECC estimation has been developed globally, its application in spatial planning is lacking, especially in the Indian context.

One of the key research gaps is the historical development and conceptualization of ECC in spatial planning. The current literature is not suitably responsive to how ECC estimation has developed over time and how it may be further developed to tackle issues of urban planning in contemporary times (George & Kumar, 2016). Despite conceptual evolution and technological advances, no framework comprehensively combines ECC assessment, spatial planning tools, and planning practice —particularly in rapidly urbanizing and ecologically sensitive contexts like India - the integration of ECC into spatial planning thus remaining fragmented and inconsistently applied. Persistent gap exists with absence of single comprehensive framework that integrates ECC assessment with spatial planning tools and practice. Bridging this divide requires the development of context-sensitive, institutionally supported models that can operationalize ECC parameters into actionable instruments such as Master Plans, Environmental Impact Assessments (EIAs), and zoning regulations. Techniques like ecological footprint analysis, GIS and remote sensing, and resilience thresholds based on the vulnerability and sensitivity offer valuable tools to inform land-use zoning, density regulations, and infrastructure provisioning.

In addition, the majority of the literature is concerned with measuring demand and increasing production capacity without adequately considering the availability of resources and ecological limits (Liu et al., 2022). Such one-dimensional approach to resource-demand management ignores the levels of carrying capacity that determine sustainable use of resources. Inadequate quantification of the incorporation of ECC in planning studies is another major shortcoming. Current studies discuss select aspects like pollution load estimation and suitability analysis instead of resource use and limits of ecosystem capacity. Also, these studies often examine individual stressors or factors, such as pollution or habitat loss, in isolation, overlooking the cumulative and synergistic effects that multiple stressors can have when combined. This is especially concerning in ecologically sensitive areas such as wetlands and coastal zones, where there is little research on ECC integration into spatial planning. These ecosystems are extremely vulnerable to overuse, and context-specific ECC assessment is required to avoid irreversible environmental damage (Hoff et al., 2022). There exists the need for better integration of cumulative and synergistic functions in ECC assessments. Another critical gap lies in the understanding of thresholds and resilience. While ECC is often associated with a fixed threshold—beyond which ecosystems can no longer function effectively—this perspective fails to account for the resilience of ecosystems. The social-ecological systems dimension is another critical area that requires further research, incorporating which can help to investigate the interactions and feedback loops between human societies and ecosystems more comprehensively. While much of the existing ECC literature focuses primarily on the ecological aspects, the social dimensions are often neglected. Research should thus explore the concept of dynamic carrying capacity, where ecosystems can adapt and reorganize in response to stress before reaching irreversible thresholds. Furthermore, vulnerability and sensitivity factors are overwhelmingly underestimated in ECC estimation. Spatial planning approaches seldom address interactions among environmental hazards, climate variability, and anthropogenic stressors. Carrying capacity is not uniform across landscapes and spatial heterogeneity remains underexplored in ECC research. Future research could investigate how these spatial variations influence carrying capacity and guide more localized and context-specific planning strategies within the spatial development processes, particularly in ecologically stressed areas. This study intends to address the gaps determined by proposing a theoretical model to develop an Integrated Spatial Planning Framework (ISP-F), as a step-wise approach to incorporating ECC in planning practice. By ensuring integration of ECC analysis in spatial planning, the proposed ISP-F should be designed to align urban growth with ecological limits while optimizing resource use and land allocation as voiced through the literature review.

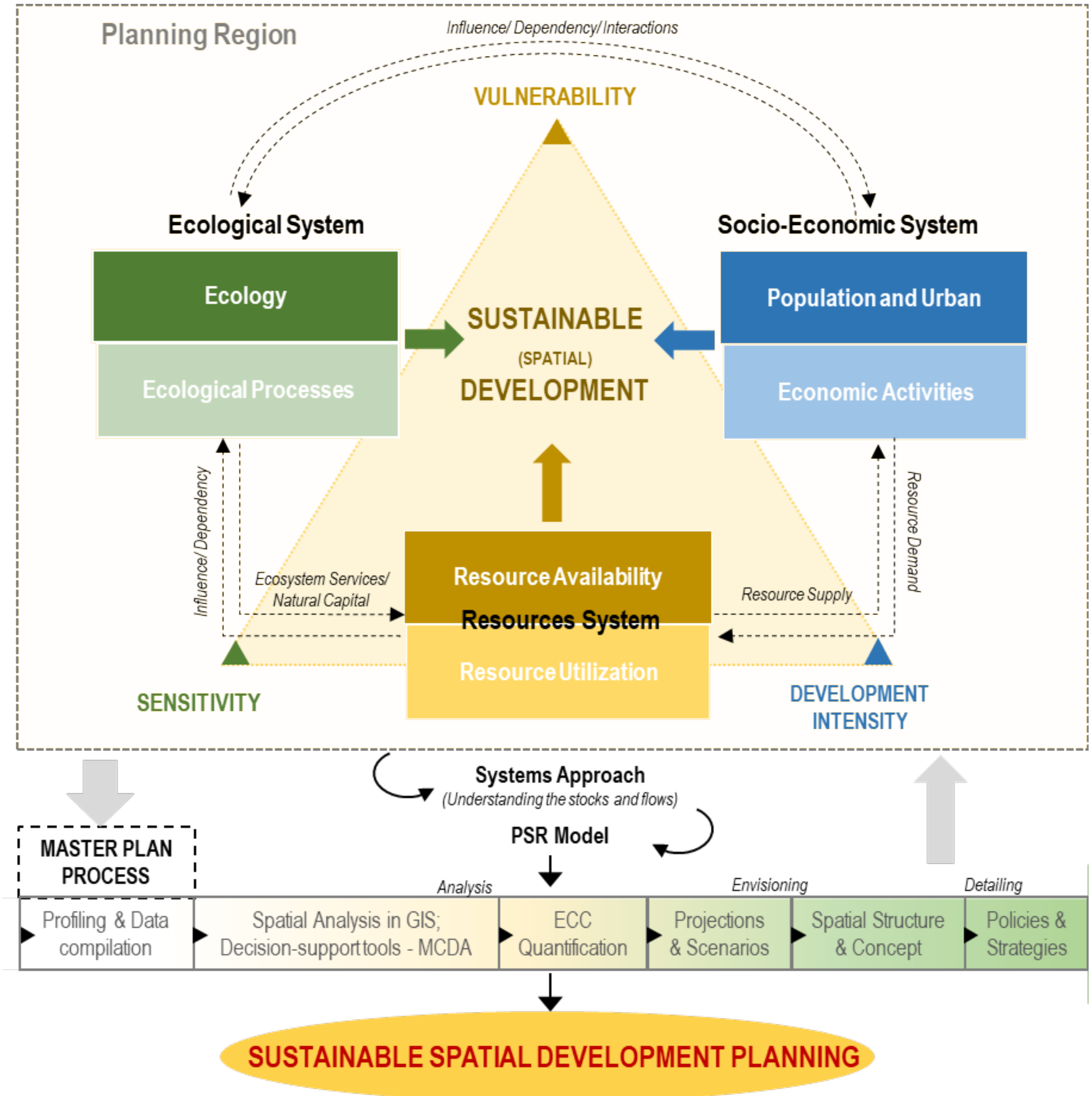
Conceptualized Integrated Spatial Planning Framework (ISP-F)

In this evolutionary research study on ECC, it can be inferred that Environmental Carrying Capacity has evolved from a static ecological concept to a dynamic, multi-dimensional planning tool that account for biophysical, socio-economic, and spatial dimensions. The systematic literature review carried out by the authors underscores the imperative for spatial planning to adopt an evolved ECC lens, beyond population and resource limits, to include ecosystem sensitivity, resilience, and adaptive capacity.

Building on this conceptual foundation and literature review, the theoretical construct for Carrying Capacity-based Sustainable Spatial Development Planning is designed based on three integral sub-systems: the Resource System, the Ecological System, and the Socio-Economic System, and interactions therein. Resource System is considered to provide essential resources—such as natural, human, infrastructure, and built resources—that sustain the functions of an urban region. The Ecological System offers a range of ecosystem services, including air and water purification, climate regulation, and biodiversity maintenance, which are vital to the well-being of the urban environment (Volk et al., 2022). The Socio-Economic System encompasses the societal interactions and economic activities that drive development and growth. These sub-systems interact in a dynamic and adaptable manner, with trade-offs and synergies that influence each other.

In the real-world, the interactions between the Resource and Ecological Systems may involve balancing resource extraction with ecosystem conservation, while the relationship between the Ecological and Socio-Economic Systems can reflect the fine balance between economic development and environmental preservation. The existing master plans analyze the population trends, socio-economic scenario, land use change, infrastructure gaps, development needs, and environment profile. ISP-F proposes to use this base to build this data and outputs further systematically to ascertain the urban development intensity, ecological sensitivity and hazard vulnerability and their correlation.

Figure 14: Integrated Spatial Planning (ISP-F) – Conceptual Framework



Source: Developed by authors, 2025

Based on the theoretical construct of relationships, the Integrated Spatial Planning Framework (ISP-F) have been uniquely designed (Figure 14) in this research as a mechanism to achieve sustainable development by championing the 'environment' – i.e. the Ecological System and the interaction between the Ecological and Resource systems. First, the ISP-F aims to comprehensively study the dynamic interactions between the city sub-systems, emphasizing the need to understand complex, non-linear systems, including their stock and flow challenges, and the feedback loops that arise from these interactions. Further, similar to selected literature on ECC measurement, the framework seeks to capture the cumulative and synergistic effects of multiple stressors and derives the pressure-state-response relationships. After this, the environmental carrying capacity is quantified in a novel manner spatially by considering the development intensity, environmental sensitivity, hazard vulnerability, supportive and assimilative capacities holistically. Further, the ISP-F proposes to integrate ECC into the urban development planning process – Master Plan preparation – by formulating future development strategies and interventions considering the spatial variation of carrying capacity limits of the local environments. ISP-F proposed aims to incorporate the concept of spatial heterogeneity incorporated to ensure that varying local conditions, such as differences in environmental components, are adequately addressed in the planning process (Xia et al., 2023). By incorporating these, the framework can promote a synergistic approach that supports sustainable spatial development, balancing urban growth with environmental conservation and societal well-being.

Conclusion

The integration of Environmental Carrying Capacity (ECC) into urban planning is essential for ensuring long-term sustainability, particularly as rapidly expanding cities continue to place pressure on natural systems. Despite this, the lack of comprehensive and dynamic frameworks for its application has hindered its full integration into planning practices. Based on systematic literature review, this study highlighted the persistent gap in mainstreaming ECC within spatial planning practices in India, where existing models often ignore cumulative impacts, spatial heterogeneity, and socio-ecological dynamics. Also, this research has highlighted the challenges and opportunities, particularly in the context of Indian cities.

Firstly, the bibliometric analysis undertaken revealed that although sustainability, carrying capacity, and spatial planning are expanding research domains, only 13 papers directly link ECC with urban or spatial planning across Scopus and Web of Science datasets. Most studies remain single-factor assessments, leaving a critical gap in multi-resource, integrated approaches. The proposed Integrated Spatial Planning Framework (ISP-F) responds to this gap by incorporating environmental thresholds, resource constraints, and socio-economic factors into a cohesive and holistic planning model supporting more resilient and ecologically balanced urban development. To strengthen the reliability of findings, this study also mitigated internal biases by using dual databases (Scopus and WoS), standardizing keywords, removing duplicates, and cross-validating thematic clusters.

Secondly, the review of 28 Master Plans across India demonstrated that, although most planning documents include environmental sections, the treatment remains largely descriptive, with minimal progression toward quantifying ECC. Only few plans mention carrying capacity, and even these references are fragmented, sector-specific, or introduced in response to external mandates rather than embedded as part of a systematic planning approach. This pattern reflects a significant national-level gap in operationalizing ECC within statutory planning processes, reinforcing the need for standardized methodologies and robust analytical frameworks to meaningfully integrate ECC into future urban and regional plans.

The proposed novel framework for Integrated Spatial Planning (ISP-F), attempts conceptualizing ECC as a tool for sustainable spatial development. This guiding framework aims to address the gaps in current planning practices by incorporating the concept of resource limits i.e. 'carrying capacity', promoting 'environmental considerations', mapping complex non-linear urban sub-systems, and considering the cumulative impacts of multiple stressors. By embracing a more holistic approach that integrates resource availability, environmental limits, and socio-economic factors, urban planning can move towards a more sustainable, resilient future.

Moving forward, it is crucial not only to develop the conceptual framework, but also suggest operational flows that can effectively integrate Environmental Carrying Capacity (ECC) into urban planning processes. The first step toward achieving this integration is improving data availability and modeling techniques to assess carrying capacity across spatial and administrative boundaries. The development of more robust quantitative tools for measuring carrying capacity, especially in terms of resource availability and ecological constraints, is essential for better decision-making in spatial planning. Furthermore, there is an urgent need to expand the scope of carrying capacity studies to include spatial heterogeneity and cumulative stressors such as climate change, pollution, urbanization etc. Research can also focus on the social-ecological systems perspective, integrating societal behaviors, ecological processes, governance mechanisms, and technological advancements into the planning process. This will ensure that both human and environmental dimensions are adequately accounted for in carrying capacity assessments. Future research should thus prioritize the development of dynamic, data-driven models that provide real-time assessments and predictive analytics. Advancements in machine learning, GIS-based spatial modeling, and AI-driven decision-support tools will enable planners to assess ECC thresholds more accurately and proactively.

In the context of Indian cities, where environmental considerations have often been sidelined in favor of economic and infrastructure development, it is crucial to mainstream ECC into policy frameworks and guidelines. Incorporating ECC into these frameworks will help local and regional authorities develop more sustainable planning policies and ensure that urban growth does not exceed the environmental limits of regions, particularly those of ecological significance like wetlands and coastal zones. Further, to facilitate the implementation of carrying capacity-based planning, greater collaboration is needed between government agencies, researchers, and local communities. Capacity-building initiatives for urban planners and policymakers should focus on training on scientific ECC methodologies, equipping them with technical expertise and decision-making tools for sustainability-driven urban development.

Ultimately, by making progress on the above stated points with regard to technological integration, capacity building and policy integration, the guiding framework of ISP-F developed can serve as a robust foundation for developing future-ready urban systems, ensuring that cities evolve into ecologically balanced and resilient spaces capable of sustaining future generations.

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Author Contributions

Conceptualization, R.R.; data curation, R.R.; analysis, R.R.; methodology, R.R., and A.R.; supervision, A.R. and A.T.; writing—original draft, R.R.; writing—review and editing, R.R., A.R. and A.T.

Conflicts of Interest

The authors declare no conflict of interest.

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