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Review Paper

Mapping the Evolution of Urban Sprawl Research: A PRISMA-Based Systematic and Bibliometric Synthesis

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ABSTRACT

Urban sprawl represents a major spatial manifestation of contemporary urbanization, reshaping land systems, ecological stability, and sustainability trajectories. This study presents a PRISMA-based systematic review combined with bibliometric and thematic synthesis to examine global urban sprawl research. Following structured screening of 183 records, 54 peer-reviewed journal articles were retained for detailed analysis. Bibliometric mapping using VOSviewer, quantitative comparison, and thematic synthesis were integrated to assess methodological evolution, geographic concentration, and sustainability integration. The findings reveal three developmental phases: an early exploratory stage, a consolidation phase dominated by spatial modeling, and a recent shift toward environmental and climate-related assessment. Methodologically, Cellular Automata and CA–Markov models account for 40.74% of studies, followed by remote sensing change detection (25.93%), while spatial regression approaches remain limited (3.70%). Urban expansion magnitudes show substantial heterogeneity, with a mean built-up growth of 119.7% and a strongly right-skewed distribution (Sk = 1.97; K = 2.38). Reported growth ranges from below 20% to over 500%, frequently associated with agricultural land conversion and land surface temperature intensification. Classification accuracies typically range from 83% to 91%, indicating high technical reliability. Research output is geographically concentrated in Asia (61.11%), particularly in China and India, while governance-oriented scholarship remains comparatively underrepresented. Overlay analysis indicates an emerging focus on climate change and ecosystem impacts, yet institutional evaluation remains peripheral. Overall, the field demonstrates strong technical maturity but limited integration of policy assessment, underscoring the need for cross-scale causal modeling and standardized sustainability metrics.

INTRODUCTION AND BACKGROUND

1.1. Urban Sprawl as a Global Challenge

Urbanization represents one of the most transformative processes shaping the twenty-first century, fundamentally restructuring land systems, socio-economic dynamics, and ecological stability across the globe (Halefom et al., 2024; Oleson et al., 2015). The rate of spatial urban expansion has significantly exceeded population growth in many regions, leading to the rapid outward spread of low-density, automobile-dependent development commonly referred to as urban sprawl (Artmann et al., 2019; Seto et al., 2012). While urban growth has historically been associated with economic productivity and innovation, its contemporary spatial manifestation increasingly raises environmental and sustainability concerns, particularly in rapidly developing regions of Asia, Africa, and Latin America (Güneralp et al., 2020; X. Liu et al., 2020).

Urban sprawl is typically characterized by dispersed built-up patterns, leapfrog development, segregated land uses, and inefficient land consumption. However, over the last decade, the concept has evolved beyond purely morphological interpretations toward a multidimensional understanding that incorporates governance, infrastructure systems, ecological fragmentation, and socio-spatial inequality (Bhatta, 2019; Ewing & Hamidi, 2015; Huang et al., 2023). Rather than being viewed solely as uncontrolled expansion, urban sprawl is increasingly conceptualized as a systemic outcome of complex interactions between demographic pressures, real estate markets, transport infrastructure investments, planning institutions, and policy failures (Z. Liu et al., 2021; H. Luo & Wu, 2021; Taubenböck et al., 2018).

The drivers of urban sprawl vary across geopolitical contexts but demonstrate notable structural similarities. Population growth and rural–urban migration remains primary demographic forces in the Global South, whereas suburbanization, housing affordability dynamics, and transportation infrastructure expansion play dominant roles in high-income economies (Halder, Kumar, Deepak, Kumar, et al., 2025; Salvati et al., 2020). Weak land-use regulation and fragmented metropolitan governance structures further accelerate peripheral expansion, particularly in rapidly urbanizing regions lacking coordinated spatial planning frameworks (Lehmann, 2019; Sweta Rupapara et al., 2025). Moreover, speculative land markets and infrastructure-led development corridors often stimulate dispersed settlement patterns that outpace environmental planning capacity.

The environmental consequences of such expansion are substantial and multidimensional. Urban sprawl contributes to accelerated land consumption, loss of agricultural land, ecosystem fragmentation, biodiversity decline, and increased carbon emissions through transport dependency (Angel et al., 2016; X. Li et al., 2022; Zhu et al., 2022). Remote sensing–based studies consistently demonstrate that urban land expansion has encroached disproportionately upon fertile agricultural zones and ecologically sensitive peri-urban landscapes (Halder, Kumar, Deepak, Mandal, et al., 2025; X. Liu et al., 2020). In addition, dispersed urban form intensifies energy demand for transportation and infrastructure provision, thereby increasing greenhouse gas emissions and undermining climate mitigation efforts (Ewing & Hamidi, 2015; R. Wang et al., 2021).

Beyond ecological degradation, urban sprawl has profound social implications. Low-density expansion frequently produces socio-spatial segregation, inequitable access to services, and infrastructure deficits in peripheral settlements (Tian et al., 2017; Xu et al., 2019). Informal and peri-urban communities often lack adequate transportation connectivity, water supply, sanitation, and green space provision, exacerbating vulnerability to environmental risks (Halder et al., 2026). These patterns underscore that urban sprawl is not merely a spatial configuration issue but a broader governance and equity challenge embedded within urbanization trajectories.

Over the past fifteen years, scholarly attention toward urban sprawl has intensified, reflecting growing recognition of its implications for sustainability transitions and climate resilience (Sathe & Rahman, 2024; S. Wang et al., 2021). However, despite abundant empirical case studies, the global research landscape remains fragmented across disciplines, scales, and methodological approaches.

1.2. Methods for Measuring Urban Sprawl

The quantification of urban sprawl has undergone substantial methodological evolution, largely driven by advancements in geospatial technologies and computational modeling. Early assessments relied heavily on census-based density indicators and land-use statistics; however, contemporary studies increasingly employ multi-temporal satellite imagery, GIS-based spatial modeling, and landscape metrics to capture the complexity of expansion dynamics (Bosch et al., 2021; Mokarram et al., 2024).

Remote sensing has emerged as the dominant tool for monitoring urban expansion at multiple scales. Landsat time-series datasets, Sentinel imagery, and MODIS-derived products enable consistent long-term observation of built-up growth patterns, urban footprints, and peri-urban transformation (Wan, 2014; J. W. Wang et al., 2020). The integration of machine learning classifiers, cloud-based platforms such as Google Earth Engine, and high-resolution imagery has significantly enhanced classification accuracy and temporal resolution (Rahaman et al., 2019). These advancements have allowed researchers to quantify sprawl intensity, detect fragmentation patterns, and assess spatial diffusion processes with unprecedented precision.

GIS-based modeling further complements remote sensing by enabling spatial overlay analysis, proximity assessment, and urban growth simulation. Cellular automata (CA), CA-Markov models, and geographically weighted regression (GWR) approaches are increasingly applied to examine drivers and forecast expansion scenarios (Jia & Wang, 2021; C. Wang et al., 2021). Such models provide insight into how infrastructure corridors, economic hubs, and topographical constraints shape expansion trajectories.

Landscape metrics have also become central to sprawl assessment. Indicators such as patch density, edge density, Shannon's diversity index, and fractal dimension are widely employed to quantify morphological dispersion and fragmentation (Sarkar & Chakraborty, 2025). These metrics move beyond simple density measures, offering a more nuanced understanding of spatial configuration and ecological connectivity. Similarly, entropy-based measures remain popular for evaluating spatial dispersion patterns, particularly in rapidly urbanizing regions (Bhatta, 2009). However, recent literature highlights scale sensitivity and methodological inconsistencies in entropy applications, emphasizing the need for integrated multi-indicator frameworks. Together, these methodological developments demonstrate that urban sprawl research has transitioned from descriptive mapping toward analytically sophisticated, multi-scalar modeling.

1.3. Sustainability and Environmental Implications

Urban sprawl is intrinsically linked to sustainability challenges, particularly in the context of climate change, ecosystem degradation, and resource efficiency. One of the most pressing concerns is accelerated land consumption. Empirical studies indicate that urban land expansion frequently outpaces population growth, leading to declining density and inefficient land use (Merlín-Uribe et al., 2013). Such patterns undermine compact city strategies and increase infrastructure provision costs.

Carbon emissions represent another critical dimension. Low-density urban form increases reliance on private vehicles and lengthens commuting distances, thereby elevating per capita transport emissions (Kumar, Maurya, Mandal, Halder, et al., 2025; Kumar, Maurya, Mandal, Mir, et al., 2025). Additionally, dispersed development patterns require extensive road networks and utility systems, contributing to embodied energy consumption.

Urban sprawl also intensifies urban heat island (UHI) effects through vegetation loss and increased impervious surfaces. Remote sensing studies reveal strong correlations between built-up expansion and elevated land surface temperatures (Miss, 2020). Furthermore, hydrological systems are disrupted as natural infiltration zones are replaced by impermeable materials, increasing flood risk and groundwater stress (Rai, 2019).

From an ecological perspective, fragmentation of habitats and peri-urban ecosystems reduces biodiversity and weakens ecosystem service provision (Y. Li et al., 2023). The cumulative impact of these processes underscores the urgency of aligning urban growth management with sustainability objectives, particularly under global climate commitments.

1.4. Planning and Policy Perspectives

In response to the negative externalities of urban sprawl, planning theory and practice have increasingly promoted compact city development, smart growth principles, transit-oriented development (TOD), and polycentric urban models (Artmann et al., 2019; Lehmann, 2019). These frameworks aim to enhance density, mixed land use, and sustainable mobility while preserving ecological assets.

However, implementation remains uneven. Institutional fragmentation, political economy constraints, and socio-cultural preferences for low-density housing frequently undermine compact development strategies (Salvati et al., 2020). Moreover, rapidly urbanizing regions often lack regulatory enforcement capacity to prevent informal or speculative peri-urban expansion.

Recent scholarship emphasizes the importance of governance integration, participatory planning, and cross-sectoral coordination to manage urban expansion effectively (Biswas & Kidokoro, 2011; Ghosh et al., 2022). Nevertheless, empirical evidence on the effectiveness of such policy instruments remains scattered across regional case studies.

1.5. Problem Statement and Knowledge Gaps

Despite substantial growth in urban sprawl research over the past two decades, several critical limitations persist. First, existing literature remains fragmented between spatial measurement studies, sustainability impact assessments, and policy-oriented analyses. Second, methodological heterogeneity limits comparability across regions and scales. Third, bibliometric assessments of the field remain limited, and few studies integrate systematic review frameworks with quantitative network mapping.

Furthermore, global comparative synthesis is insufficient. Much of the literature is concentrated in specific regions, particularly China, the United States, and parts of Europe, leaving underrepresentation in rapidly urbanizing African and South American contexts (Güneralp et al., 2020; Jimenez & de Adana, 2024; S et al., 2024; Seto et al., 2012). These gaps hinder comprehensive understanding of global sprawl dynamics and constrain evidence-based policy formulation.

In response to these limitations, this study undertakes a PRISMA-driven systematic review combined with bibliometric synthesis to analyze global urban sprawl research from last two decades. By integrating transparent literature screening with network-based mapping and thematic synthesis, this study provides a comprehensive, methodologically rigorous, and globally comparative assessment of urban sprawl scholarship.

Unlike previous reviews that focus either on environmental impacts or spatial metrics alone, this study integrates publication trend analysis, keyword co-occurrence mapping, country distribution assessment, and thematic content synthesis within a unified analytical framework. This mixed-method approach enhances transparency, reproducibility, and interpretative depth.

The objectives of this study are to:

- Quantify global publication trends on urban sprawl.
- Identify dominant research clusters through keyword co-occurrence analysis.
- Synthesize thematic developments in measurement methods, environmental impacts, and planning responses.
- Identify research gaps and propose future research directions.

Through this comprehensive approach, the study aims to advance understanding of urban sprawl as a complex, multidimensional sustainability challenge and provide a structured knowledge base to inform spatial planning and policy interventions worldwide. Urban sprawl is increasingly recognized not only as a morphological phenomenon but as a systemic transformation of land–infrastructure–ecology interactions. This pattern suggests a potential imbalance in thematic emphasis within the field, particularly when considered alongside the relatively limited representation of governance-related studies identified in the thematic analysis.

2. MATERIALS AND METHODS

This study adopts a mixed-method research design integrating a PRISMA-guided systematic review with bibliometric network analysis to provide a transparent, reproducible, and quantitatively grounded synthesis of global urban sprawl research. The methodological framework was structured to ensure rigor in literature identification and screening while enabling quantitative mapping of research evolution, thematic clusters, and geographic distribution. By combining systematic review protocols with bibliometric visualization tools, the study bridges qualitative depth and quantitative structure, thereby addressing fragmentation in existing urban sprawl scholarship.

The overall methodological workflow comprised four sequential stages: (1) database search and record identification, (2) PRISMA-based screening and eligibility assessment, (3) bibliometric mapping and statistical trend analysis, and (4) thematic content synthesis. Figure 1 illustrates the PRISMA framework. (Page et al., 2021a).

2.1. The PRISMA Framework

The PRISMA framework was employed to systematically collect, screen, and analyse articles from the Web of Science (WOS) database. This method ensures transparency and reproducibility, which are vital for academic rigor (Chaudhuri & Kumar, 2022; Fu et al., 2022). The WOS Core Collection was selected as the sole database for this study due to its high-quality indexing standards, rigorous journal selection process, and structured citation metadata, which are essential for reliable bibliometric network construction. WOS is widely adopted in systematic reviews and bibliometric analyses because it ensures consistency in bibliographic records and minimizes duplication across indexed sources. However, it is acknowledged that reliance on a single database may limit coverage compared to multi-database approaches incorporating Scopus or Dimensions. A web search was done on January 14, 2026, as the initial step. Boolean operators (AND, OR) were applied to refine the results and ensure the selection of pertinent studies. "Urban sprawl" is first introduced in this paper and use of a title-based search strategy was intentionally adopted to prioritize precision over recall. This approach ensures that selected studies explicitly focus on urban sprawl or closely related concepts, thereby improving thematic relevance and reducing inclusion of peripheral studies where urban expansion is not the primary research objective. However, this strategy may exclude relevant studies that discuss urban sprawl within abstracts or keywords but do not explicitly mention it in the title. Furthermore, comprehensive relevant literature retrieval is built on urban sprawl in sustainability perspective. Criteria for eligible literature through WOS are further classified in Table 1. The search was performed using the Title field to enhance specificity and reduce irrelevant retrieval. Boolean operators were applied to refine results. The exact search query used was: Title = ("urban sprawl" OR "urban expansion" OR "urban growth" OR "urban footprint") AND (("land use" OR "land cover" OR "remote sensing" OR "GIS" OR "sustainability" OR "landscape metrics" OR "urban planning" OR "urban form")) AND ("remote sensing" OR "GIS" OR "geospatial" OR "satellite" OR "Landsat" OR "Sentinel") and then search method topic was selected.

This structured query ensured that retrieved records explicitly addressed urban expansion processes in connection with geospatial measurement techniques, land-use dynamics, or sustainability-related frameworks. The inclusion of geospatial terms (e.g., Landsat, Sentinel, satellite, GIS) ensured methodological relevance, particularly given the study's focus on measurement approaches and bibliometric mapping.

Table 1. Criteria for eligible literature through WOS (excluded if not meeting these criteria).

Category	Inclusion Criteria	Exclusion Criteria
Database	Web of Science Core Collection	Other databases
Document Type	Peer-reviewed journal articles	Review articles, conference papers, editorials, and book chapters (excluded to ensure inclusion of primary empirical studies only)
Language	English	Non-English publications
Topical Scope	Explicit focus on urban sprawl/expansion/growth measured using geospatial or land-use techniques	Studies unrelated to spatial expansion or lacking geospatial dimension
Methodological Relevance	Use of remote sensing, GIS, satellite data, landscape metrics, or geospatial modeling	Purely theoretical discussions without empirical measurement

Criteria used to ensure methodological consistency and topical relevance in the PRISMA screening process. As shown in Table 1, the inclusion criteria prioritize empirical rigor and geospatial relevance, ensuring alignment with the study's objective of synthesizing measurement-based urban sprawl research. It is important to distinguish between the present study as a systematic review and the exclusion of review articles from the analyzed dataset. The objective of this study is to synthesize primary empirical research rather than secondary syntheses. Including review papers could lead to duplication of findings and overrepresentation of certain studies already summarized in prior reviews. Therefore, only original research articles with extractable methodological and quantitative information were retained for analysis.

Conference papers were excluded despite their relevance in geospatial and remote sensing research because they often provide limited methodological detail, preliminary results, and less standardized reporting compared to peer-reviewed journal articles. Given the study's emphasis on quantitative comparison, reproducibility, and bibliometric network construction, the inclusion of only full-length journal articles ensures greater consistency, reliability, and comparability across the analyzed corpus.

The PRISMA framework provides a structured four-stage approach that Identification, Screening, Eligibility, and Inclusion—allowing systematic filtering of literature while minimizing selection bias. The detailed flow of records through each stage is illustrated in Figure 1.

The literature search was conducted in the WOS Core Collection database using the predefined search query described in Section 2. The search yielded 183 journal articles, representing the initial dataset for review. This broad retrieval strategy was designed to capture a comprehensive body of scholarship addressing urban sprawl in relation to sustainability and geospatial methodologies.

During the identification phase, preliminary filtering was applied to remove records that did not meet basic inclusion requirements. Specifically, 7 articles were excluded because they were not written in English, were classified as review papers, or were categorized as early access publications. After this initial refinement, 176 records progressed to the screening stage.

The screening phase involved a systematic examination of titles, abstracts, and subject categories to assess disciplinary relevance and thematic alignment. First, 40 studies were excluded because they belonged to irrelevant disciplines that did not align with the spatial, environmental, or sustainability focus of the study.

The remaining 136 articles underwent detailed title and abstract screening to evaluate their conceptual and methodological relevance. During this step, 82 records were excluded due to insufficient alignment with the core research objectives—particularly the absence of a clear connection between urban sprawl and sustainability dimensions, or lack of empirical geospatial analysis. Additionally, studies that were not fully accessible were removed to ensure consistency in full-text evaluation. Following this stage, 54 articles remained eligible for full-text assessment.

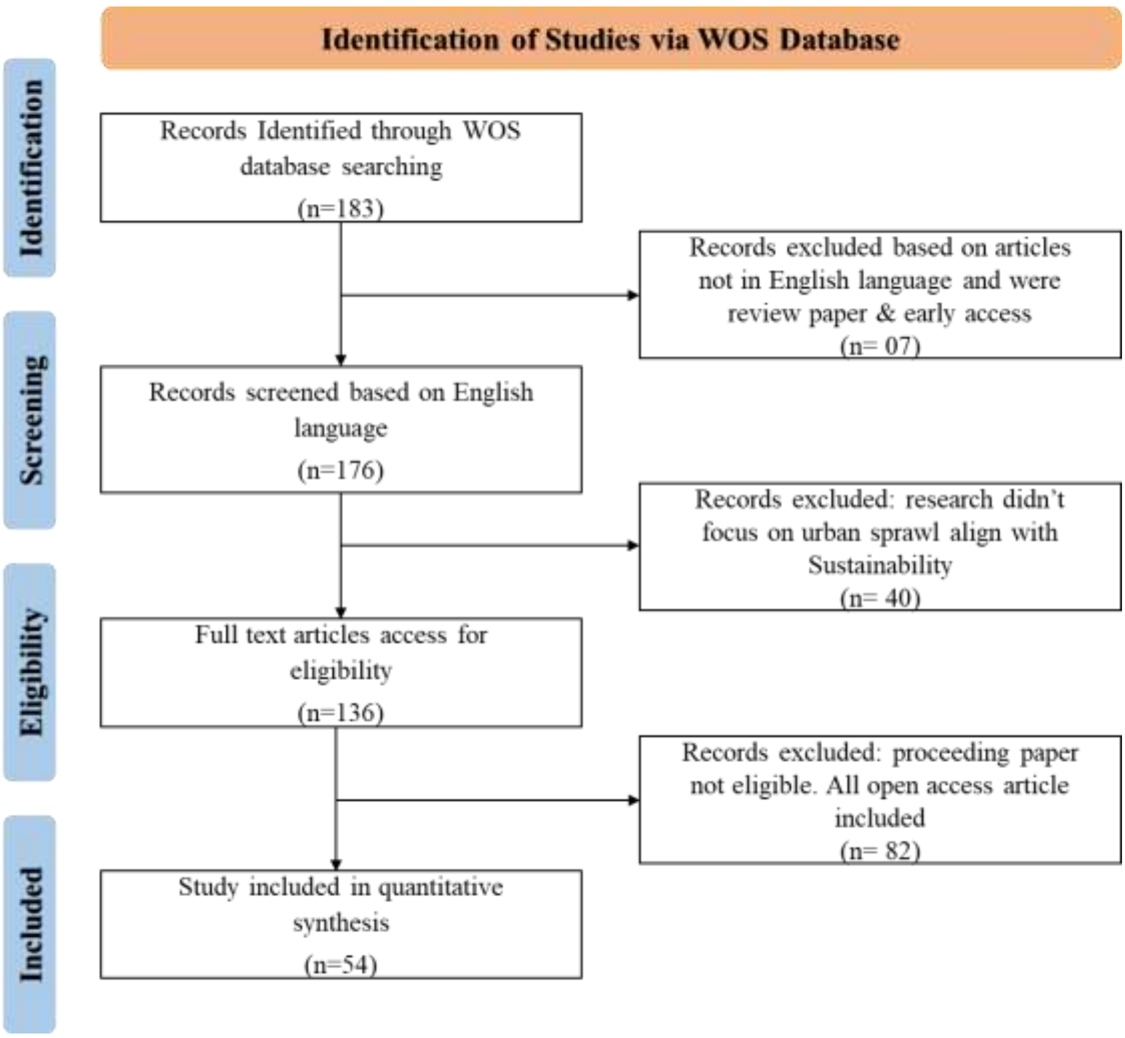

Figure 1. PRISMA framework of the study, Source: PRISMA 2020 (Page et al., 2021b)

In the eligibility phase, full texts of the 54 remaining studies were carefully reviewed against predefined inclusion criteria. This evaluation emphasized:

- Explicit focus on urban sprawl, expansion, or growth,
- Integration of sustainability-related analysis,

- Application of geospatial, remote sensing, GIS, or land-use methodologies,
- Empirical assessment within built or urban environments.

Each article was assessed for methodological robustness and thematic consistency. Only studies demonstrating clear analytical linkage between spatial expansion processes and sustainability implications were retained.

After full-text assessment, 54 studies were ultimately selected for detailed analysis and synthesis. These studies formed the final corpus for both bibliometric mapping and thematic content analysis. The included articles collectively represent the most relevant and methodologically rigorous scholarship addressing urban sprawl through geospatial and sustainability lenses within the defined time frame.

The structured progression from 183 initially identified records to 54 included studies, as illustrated in Figure 1, demonstrates the methodological transparency and systematic rigor of the review process. By applying clearly defined criteria at each stage, the study ensures that the final dataset reflects high-quality, thematically consistent research capable of supporting robust bibliometric and thematic synthesis.

In the supplementary material, a comprehensive list of all 54 studies included in the systematic review is presented, along with citation details. Each study is systematically documented with information such as authors, year of publication, title, and number of citations, providing a transparent overview of the research corpus. The meticulous application of the PRISMA framework ensures that all selected studies are highly relevant to the study's themes and research objectives.

2.2. Bibliometric Analysis

Bibliometric analysis was conducted to examine the structural characteristics and thematic organization of the selected literature. The analysis was performed using VOSviewer (version 1.6.19), a software tool designed for constructing and visualizing bibliometric networks (van Eck, 2010). The objective of this stage was to identify patterns of keyword co-occurrence, temporal distribution of research topics, and geographic publication distribution within the final dataset of 54 articles.

Following PRISMA screening, the complete bibliographic records of the included articles were exported from the Web of Science Core Collection in plain text format, including full metadata and cited references. Author-provided keywords were extracted as the primary analytical unit, as they most directly reflect the conceptual focus defined by researchers. Prior to network construction, the dataset underwent a cleaning and standardization process to ensure semantic consistency. Variations in spelling and terminology were harmonized, synonymous expressions were unified where conceptually appropriate, and compound keywords were standardized to avoid artificial fragmentation of the network. Only author keywords were retained in order to minimize indexing noise associated with automatically generated database terms.

It is important to note that bibliometric network analysis provides a descriptive representation of relationships among research themes based on co-occurrence patterns. Such analysis does not establish causal relationships but rather identifies structural tendencies and thematic proximities within the literature. Therefore, interpretations derived from bibliometric outputs should be understood as indicative and are complemented in this study by thematic content analysis and quantitative comparison.

The bibliometric procedures described above were designed to provide a reproducible and quantitative foundation for subsequent thematic interpretation. While this section details the analytical workflow, interpretation of network structures, cluster composition, temporal progression, and geographic patterns is presented in the Results section.

2.2.1 Publication Trend Analysis

To examine overall research growth, annual publication counts for the period 2008–2025 were extracted from the dataset. An exponential regression model was fitted to the time-series data in order to assess whether publication output followed an accelerating trajectory. The model was expressed in the form:

$$y = ae^{bx}$$

Where:

- y represents number of publications
- x represents year
- a and b are fitted coefficients

2.2.2 Keyword Co-occurrence Analysis

Keyword co-occurrence analysis was performed to identify conceptual linkages within the research field. A minimum occurrence threshold of three appearances per keyword was applied to ensure that only recurrent and analytically meaningful terms were included in the visualization. This threshold was selected to balance inclusivity with interpretability, preventing excessive network sparsity while retaining significant thematic signals. Link strength between keywords was calculated using the association strength normalization method, which adjusts for differences in overall frequency and provides a proportional measure of relatedness. Network visualization was generated using the VOSviewer layout algorithm, in which node size corresponds to keyword frequency, link thickness represents co-occurrence strength, and spatial proximity indicates conceptual similarity. Clusters were automatically identified using VOSviewer's modularity-based clustering technique, grouping keywords that exhibit stronger internal connectivity relative to the rest of the network.

In addition to standard cluster visualization, an overlay visualization was generated to incorporate a temporal dimension into the network structure. Overlay mapping assigns a color value to each keyword based on the average publication year of the articles in which the keyword appears. The average publication year is calculated by averaging the publication dates of all documents associated with a given term, thereby enabling examination of chronological shifts in thematic emphasis. This approach allows simultaneous observation of structural prominence and temporal positioning within the same network configuration. The overlay visualization does not alter cluster formation but supplements the structural map with temporal information, facilitating analysis of how research topics have evolved over time.

2.2.3 Country Distribution Analysis

Geographic distribution of research production was assessed using corresponding author affiliation data available in the WoS records. Each article was assigned to a country based on the institutional affiliation of the corresponding author, and publications were aggregated to identify national contributions within the dataset. This analysis was intended to reveal spatial patterns in knowledge production and high-light geographic concentrations of empirical research activity.

2.3 Thematic Content Analysis

In addition to bibliometric network mapping, a qualitative thematic content analysis was conducted to provide in-depth interpretation of the conceptual domains identified through keyword co-occurrence analysis. While bibliometric techniques reveal structural relationships and temporal dynamics among research terms, they do not capture the substantive analytical focus, methodological nuance, or interpretative depth of individual studies. Therefore, a systematic thematic synthesis was undertaken to complement quantitative mapping and ensure comprehensive understanding of the research landscape.

Thematic content analysis was applied to the full texts of the 54 articles included after PRISMA screening. The process followed an inductive–deductive hybrid approach. Initially, a deductive framework was informed by the major keyword clusters identified through VOSviewer. These clusters served as preliminary thematic anchors. Subsequently, an inductive reading of each article was performed to identify recurring analytical patterns, methodological approaches, research objectives, and policy implications that may not have been fully captured through keyword analysis alone.

During the first stage of coding, each article was examined to extract information related to research objectives, spatial scale, methodological techniques, environmental indicators, modeling approaches, and policy dimensions. Open coding was applied to identify recurrent conceptual elements across studies. In the second stage, codes were grouped into higher-order thematic categories based on conceptual similarity and frequency of occurrence. This iterative comparison process enabled refinement of thematic boundaries and ensured internal coherence within each category.

The final thematic structure was organized into four overarching domains: (1) geospatial modeling and urban expansion simulation, (2) spatial form and landscape metrics, (3) environmental and climate-related impacts, and (4) planning and governance dimensions. These domains emerged from convergence between bibliometric clusters and qualitative synthesis of article content. Each included study was assigned to one or more thematic domains depending on its primary analytical focus. Where studies spanned multiple dimensions, cross-classification was permitted to reflect interdisciplinary integration.

To enhance methodological rigor, thematic classification was conducted systematically across all studies using a standardized data extraction matrix. The matrix recorded key attributes including geographic context, temporal coverage, remote sensing datasets used, modeling techniques applied, environmental indicators assessed, and policy relevance discussed. This structured extraction procedure minimized subjective bias and ensured consistency across the review corpus.

The thematic analysis did not aim to quantify effect sizes or perform meta-analysis, as the methodological heterogeneity of included studies—ranging from satellite-based change detection to regression modeling and landscape ecology assessments—rendered statistical aggregation inappropriate. Instead, the objective was to synthesize patterns of conceptual emphasis, methodological evolution, and research direction within the field of urban sprawl studies.

Integration of bibliometric mapping with thematic content analysis strengthened interpretative robustness. The co-occurrence network provided macro-level structural insight, while full-text thematic synthesis allowed micro-level contextual interpretation. This combined approach ensured that thematic conclusions presented in the Results section are grounded both in quantitative network evidence and qualitative examination of study content.

Through this multi-layered analytical framework, the study moves beyond descriptive bibliometric reporting and enables a deeper understanding of how urban sprawl research has evolved conceptually, methodologically, and geographically over the selected study.

2.4 Methodological Rigor and Limitations

To ensure methodological robustness:

- Search query design was pilot-tested for sensitivity and specificity.
- Screening criteria were applied consistently across stages.
- Bibliometric thresholds were standardized.
- Keyword normalization procedures minimized semantic duplication.

Despite efforts to ensure methodological rigor, several limitations should be acknowledged. First, the exclusive use of the WOS database may introduce selection bias, as relevant studies indexed in Scopus, Dimensions, or other databases were not included. Second, the adoption of a title-based search strategy, while improving specificity, may have reduced the total number of retrieved records by excluding studies where urban sprawl is not explicitly stated in the title. Third, the final dataset of 54 studies reflects the application of strict inclusion criteria emphasizing geospatial methodologies and sustainability integration, which may limit the breadth of global representation. Future studies could adopt multi-database search strategies and broader query fields (e.g., abstract and keywords) to assess the sensitivity of results and enhance coverage.

Additionally, the exclusion of review articles and conference proceedings may limit the breadth of conceptual and emerging research captured, particularly in fast-developing domains such as geospatial modeling. However, this decision was necessary to maintain analytical consistency and ensure that all included studies provide comparable empirical evidence.

3. RESULTS

3.1. Publication trends

The annual publication distribution reveals three distinct developmental phases in the evolution of the research domain (Figure 2). The initial phase (2008–2014) is characterized by sporadic and low publication output, with only two contributions recorded across seven years, indicating a nascent and exploratory research stage. The emergence phase (2015–2018) shows a gradual increase in scholarly activity, rising from 2 publications in 2015 to 5 publications in 2016, reflecting early consolidation and growing academic recognition.

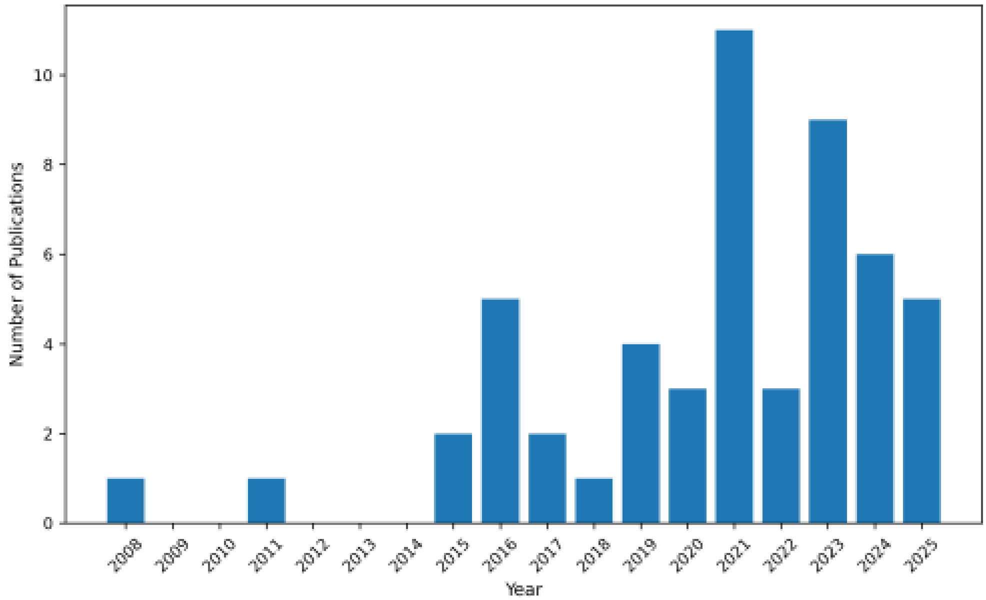

Figure 2. Annual Publication Trend on Urban Sprawl and Sustainability.

A pronounced expansion phase (2019–2025) is observed thereafter, marked by sustained productivity and higher annual outputs. The most significant surge occurred in 2021 (n = 11; 20.37% of total publications), representing the peak research intensity within the study period. Although minor fluctuations are visible in 2022 and 2024, the overall trend remains upward, with consistently high publication counts above pre-2018 levels. Notably, approximately 68% of total publications were produced during 2021–2025, underscoring a strong recent acceleration of research interest.

The distribution pattern suggests a transition from conceptual exploration to methodological refinement and large-scale application in recent years. The post-2020 surge may be associated with increased global emphasis, interdisciplinary integration, and policy-driven research expansion within the field.

3.2. Keyword Co-Occurrence and Temporal Evolution (Overlay Visualization)

To explore the intellectual structure and temporal evolution of urban sprawl research, a keyword co-occurrence overlay visualization was generated using VOSviewer (version 1.6.19). The map, presented in Figure 3, illustrates network connectivity among author keywords and highlights their average publication year using a color gradient.

Before discussing thematic clusters, it is important to note that overlay visualization provides both structural and temporal insights simultaneously. Larger nodes indicate frequently occurring keywords, while color intensity reflects research recency.

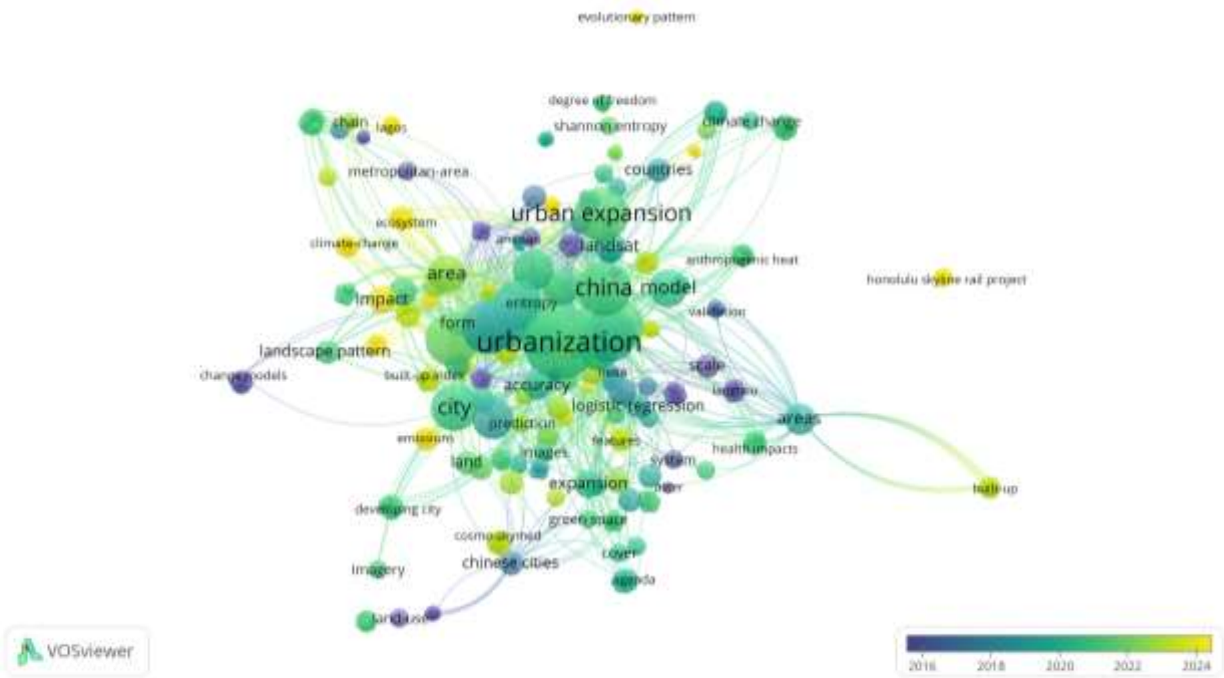

Figure 3. Overlay Visualization of Keyword Co-Occurrence Network.

In overlay visualization, node size represents keyword frequency, link thickness indicates co-occurrence strength, and node color represents average publication year (blue = earlier studies; yellow = recent studies)

As shown in Figure 3, the keyword co-occurrence network is highly centralized around the terms “urbanization,” “urban expansion,” “China,” “model,” “city,” and “Landsat,” forming a dense and strongly interconnected research core. The size and position of these nodes indicate their dominant frequency and structural importance within the field. The tight interlinkages among methodological terms such as “model,” “logistic regression,” “scale,” and “prediction” suggest that urban sprawl research has been heavily grounded in quantitative spatial modeling frameworks. In particular, the prominence of “China” reflects the geographical concentration of empirical investigations in rapidly urbanizing Chinese metropolitan regions, where large-scale remote sensing datasets and dynamic land transformation processes provide fertile ground for spatial analysis. The overlay color gradient further reveals a clear temporal transition in the intellectual trajectory of the field. Earlier studies, represented in blue to green tones (approximately 2016–2018), primarily emphasized methodological consolidation, focusing on urban growth modeling, logistic regression techniques, scale sensitivity analysis, and accuracy validation using Landsat-based mapping. During the mid-phase (2019–2021), research attention shifted toward morphological and landscape quantification, as evidenced by the clustering of terms such as “entropy,” “Shannon entropy,” “landscape pattern,” “form,” “area,” and “built-up index.” The strong interconnections between “entropy” and “form” indicate sustained reliance on entropy-based indicators for measuring spatial dispersion and fragmentation, while the inclusion of “ecosystem” and related terms reflects increasing integration between landscape ecology and urban morphology.

More recently, the overlay visualization highlights the emergence of sustainability-driven themes, marked by yellow hues corresponding to the 2022–2024 period. Keywords such as “climate change,” “anthropogenic heat,” “emissions,” “health impacts,” and “green space” signal a substantive shift from purely morphological assessment toward evaluating the environmental and socio-ecological consequences of urban expansion. The strengthening links between “urban expansion” and climate-related terms demonstrate growing recognition of the sprawl–carbon nexus and its implications for climate mitigation and urban resilience. This thematic evolution indicates that the field is transitioning from examining how cities expand to critically assessing what expansion causes in terms of environmental degradation and human well-being. In addition, peripheral nodes such as “Lagos,” “Amman,” “Lanzhou,” “Honolulu skyline rail project,” and “Chinese cities” reflect case-study-driven research across diverse geographic contexts. Although these nodes are less densely connected than the central modeling cluster, they illustrate the application of established methodological frameworks to specific regional and infrastructural settings.

Overall, the overlay visualization reveals three defining structural characteristics: strong centralization around the concept of urbanization, a pronounced China-centric empirical core, and an emerging sustainability orientation. The network density suggests a high degree of methodological cohesion, which may reflect a level of technical consolidation within the field. This interpretation is further supported by the dominance of established modeling approaches identified in the thematic analysis. However, the relative absence of policy-oriented terms such as “smart growth” or “governance” suggests that translation of empirical findings into planning frameworks remains underdeveloped. Taken together, the bibliometric evidence indicates that urban sprawl research has progressed through successive phases of methodological development, spatial-form quantification, and sustainability integration, with future advancement likely to depend on stronger incorporation of governance and policy dimensions.

The interpretations derived from the bibliometric network are further corroborated through qualitative thematic synthesis (Section 3.4) and quantitative comparison (Section 3.5), ensuring that conclusions are not based solely on co-occurrence patterns but supported by multiple lines of evidence.

3.3. Analysis of country distribution

The geographical distribution of publications provides insight into regional research leadership, emerging contributors, and global participation patterns within the selected domain. Based on the analysis of 54 publications, research output is concentrated in a limited number of countries, with a clear dominance by Asian nations. As shown in Table 2, research productivity is highly uneven across countries. People’s Republic of China leads significantly with 21 publications (38.89%), followed by India with 7 publications (12.96%). In contrast, most other contributing nations exhibit limited publication frequency, indicating that the research field remains regionally concentrated rather than globally distributed.

Table 2. Global distribution of publications across contributing countries.

Country	Number of Publications	Percentage (%)
People's Republic of China	21	38.89
India	7	12.96
Japan	3	5.56
USA	3	5.56
Australia	2	3.70
Jordan	2	3.70
Italy	2	3.70
Saudi Arabia	2	3.70
Belgium	1	1.85
England	1	1.85
Ethiopia	1	1.85
Germany	1	1.85
Malaysia	1	1.85
Oman	1	1.85
Poland	1	1.85
Portugal	1	1.85
South Africa	1	1.85
Spain	1	1.85
Sri Lanka	1	1.85
Turkey	1	1.85

Together, China and India contribute more than 50% of the total publications, highlighting Asia as the primary research hub in this domain.

Japan and the USA each contributed 3 publications (5.56%), demonstrating moderate but consistent research activity. Several countries—including Australia, Jordan, Italy, and Saudi Arabia, show intermediate engagement (3.70% each), suggesting expanding but not yet dominant research presence. The remaining countries contributed single publications (1.85% each), indicating emerging participation. While European representation is geographically diverse, publication volume remains comparatively low. African representation is limited to South Africa and Ethiopia, underscoring a potential geographic research gap.

Overall, the findings suggest a strong regional concentration of research in rapidly urbanizing Asian countries, with limited but geographically dispersed global participation.

3.4. Thematic Content Analysis

The thematic content analysis was conducted based on the 54 studies retained after PRISMA screening. The comprehensive characteristics of these studies are presented in Supplementary Material S1, which includes standardized information on geographic location, primary methodological approach, quantified outcomes, key inferences, and thematic domain classification. The coding procedure integrated methodological descriptions, empirical findings, and analytical objectives to derive four overarching domains: (1) geospatial modeling and urban expansion simulation, (2) spatial form and landscape metrics, (3) environmental and climate-related impacts, and (4) planning and governance dimensions.

The thematic classification reflects both structural patterns observed in the bibliometric network (Figure 3) and empirical evidence extracted from Supplementary Material S1. Together, these domains illustrate the multidimensional architecture of contemporary urban sprawl research.

3.4.1. Geospatial Modeling and Urban Expansion Simulation

Geospatial modeling constitutes the dominant analytical orientation within the reviewed corpus. Most studies employ satellite-based land use/land cover (LULC) classification combined with spatial simulation frameworks to quantify urban expansion dynamics. Multi-temporal Landsat imagery forms the empirical backbone of numerous investigations, enabling consistent long-term monitoring of built-up growth (Mashagbah, 2022; Molla, 2024; Pan, 2024).

CA–Markov and Cellular Automata modeling approaches are widely applied to simulate future urban expansion scenarios and evaluate spatial suitability patterns. As summarized in Table 3, CA–Markov / Cellular Automata modeling accounts for 40.74% of the reviewed studies, representing the most frequently applied methodological framework. These models integrate transition probability matrices and neighborhood rules to simulate edge expansion and infill processes (Mashagbah, 2022; Molla, 2024).

Remote sensing change detection approaches (25.93%) further reinforce the modeling core by quantifying historical land conversion trajectories prior to simulation (Gupta, 2023; Roy, 2021). In several cases, multi-temporal classification demonstrates substantial growth magnitudes. For example, built-up land in Hawassa increased by 573.65% over the study period, accompanied by a 56.81% decline in agricultural land (Molla, 2024). Similarly, Himalayan cities such as Dehradun and Shimla experienced expansion exceeding 110% and 138%, respectively (Gupta, 2023).

The statistical distribution of extracted expansion magnitudes further reinforces heterogeneity within this domain. The computed skewness ($Sk = 1.97$) and kurtosis ($K = 2.38$) indicate a strongly right-skewed and leptokurtic distribution, suggesting that extreme-growth contexts disproportionately influence aggregate expansion statistics.

Model performance metrics also demonstrate high technical reliability. Object-oriented random forest classification achieved 91% overall accuracy with a Kappa coefficient of 0.86 in long-term urban extraction (Pan, 2024). Such performance levels confirm methodological maturity and support the central positioning of "model," "urban expansion," and "Landsat" in Figure 3.

Thus, both thematic coding and bibliometric structure confirm that urban sprawl research remains strongly anchored in predictive and simulation-based geospatial analysis.

3.4.2. Spatial Form and Landscape Metrics

The second thematic domain focuses on morphological quantification of urban form using entropy indices and landscape metrics. These approaches assess spatial dispersion, fragmentation, and structural heterogeneity rather than solely measuring areal expansion.

Shannon entropy is frequently applied to quantify sprawl intensity and settlement dispersion (Gachowski, 2025; Mashagbah, 2022; Roy, 2021). Longitudinal analyses consistently report increasing entropy values associated with outward diffusion and peri-urban growth phases. Landscape metrics that including patch density, edge density, and connectivity indices—provide additional insight into fragmentation dynamics and transitions between diffusion and coalescence phases (Asempah, 2021; Y. Li, 2024). While modeling studies emphasize expansion magnitude, spatial-form investigations prioritize configuration and structural organization.

3.4.3 Environmental and Climate-Related Impacts

An expanding subset of studies links urban expansion with environmental and climatic consequences. These investigations integrate remote sensing–derived biophysical indicators such as NDVI, NDBI, NDWI, and LST with growth mapping to assess ecological degradation and thermal intensification (Alqurashi, 2016; Dinda, 2021).

Significant correlations between land surface temperature and built-up density have been documented (Gupta, 2023), confirming the sprawl–heat nexus. In certain high-altitude contexts, accelerated urban expansion has increased ecological instability and landslide risk (Pan, 2024). Rapid land conversion has also resulted in substantial agricultural loss, as observed in Ethiopian and Middle Eastern contexts (Mashagbah, 2022; Molla, 2024).

3.4.4 Planning and Governance Dimensions

The planning and governance domain remains comparatively underrepresented yet conceptually important. Several studies integrate spatial simulation outputs with scenario-based planning frameworks and sustainability recommendations (Criado, 2020; Waleed, 2023). However, empirical assessment of policy implementation effectiveness remains limited.

Governance-related terms appear less central within the bibliometric network (Figure 3), and their temporal growth remains modest relative to environmental themes (Figure 5). This structural asymmetry suggests that urban sprawl research remains predominantly diagnostic rather than prescriptive.

Bridging the gap between technical modeling outputs and institutional reform mechanisms represents a critical direction for future research. While thematic synthesis reveals conceptual structure, quantitative comparison provides empirical magnitude differentiation across contexts.

The planning and governance domain, although comparatively underrepresented, reveals several recurring policy frameworks across the reviewed studies. These include compact city strategies, transit-oriented development (TOD), urban growth boundaries, and landscape-based planning approaches aimed at controlling spatial expansion and improving land-use efficiency. In rapidly urbanizing regions, particularly in Asia, policy recommendations frequently emphasize densification, mixed land use, and infrastructure-led development control. In contrast, studies from Europe and North America more often reference regulatory instruments such as zoning controls, green belts, and growth management policies.

Despite the presence of these frameworks, empirical evaluation of policy effectiveness remains limited. Most studies incorporate governance elements in a prescriptive or scenario-based manner rather than through measurable outcome assessment. This suggests a disconnect between technical modeling capabilities and institutional implementation. Furthermore, governance responses appear highly context-dependent, reflecting differences in regulatory capacity, planning traditions, and socio-economic conditions.

Overall, the reviewed literature indicates that while a range of planning strategies has been proposed to manage urban sprawl, systematic comparative evaluation of their effectiveness remains scarce. Strengthening the integration between geospatial modeling outputs and policy assessment represents a critical direction for future research. Notably, governance approaches differ significantly between regions, with rapidly urbanizing countries emphasizing growth management and infrastructure coordination, while developed regions focus more on containment policies and sustainability-oriented land-use regulation.

3.5 Quantitative Comparative Analysis and Regional Patterns

To complement the thematic synthesis presented in Section 3.4, a statistically grounded quantitative comparative analysis was undertaken using all extractable numerical indicators from the 54 studies retained following PRISMA screening. Although the reviewed literature exhibits substantial methodological heterogeneity in terms of spatial scale, temporal coverage, and analytical techniques, a sufficient volume of empirical data was available to construct a standardized comparative database. The compiled dataset includes percentage urban expansion, absolute built-up area transitions (reported in km^2 or hectares), annual urban growth rates, magnitudes of land-use conversion, entropy-based dispersion indices, composite urban growth intensity measures derived from multi-indicator frameworks, and modeling performance statistics such as classification or prediction accuracy. These variables were harmonized to enable cross-study comparability and aggregated analysis. The present section applies statistical distribution assessment, regional differentiation, methodological performance evaluation, and temporal trend analysis to synthesize structural patterns within the global urban sprawl literature. By integrating empirical variability across geographic contexts and analytical approaches, this quantitative framework provides a robust, evidence-based interpretation of the magnitude, dynamics, and methodological evolution characterizing contemporary urban expansion research. Out of the 54 studies retained following PRISMA screening, 8 provided fully extractable quantitative indicators, such as percentage built-up growth, annual expansion rates, entropy sequences, or standardized intensity indices—reported with sufficient numerical detail to allow harmonization, statistical aggregation, and calculation of summary distribution metrics (mean, standard deviation, skewness, and kurtosis).

3.5.1 Regional Distribution of Selected Studies

The geographic distribution of the 54 selected studies is illustrated in Figure 4. Asia accounts for 33 studies (61.11%), representing the dominant geographic focus of empirical urban sprawl research. Europe contributes 9 studies (16.67%), followed by smaller proportions from the Middle East, North America, Africa, and Oceania.

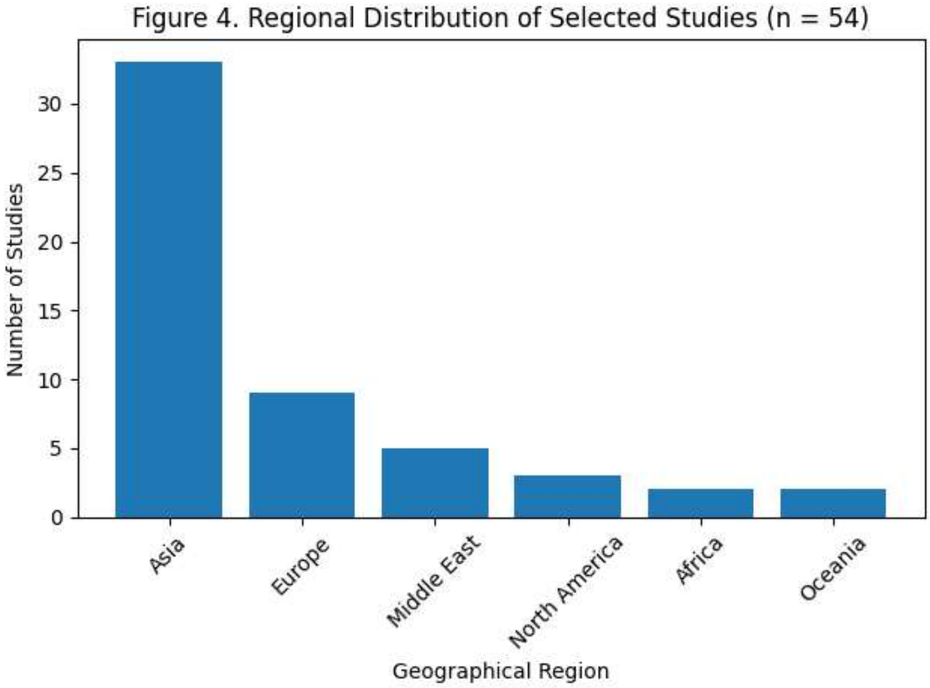

Figure 4. Regional Distribution of Selected Studies (n = 54)

This regional concentration directly corresponds with the bibliometric centrality observed in Figure 3, where "China" and associated regional keywords occupy a dense and structurally central cluster. Rapid urban transformation across Asian metropolitan systems has generated extensive satellite-based monitoring and modeling initiatives (Du et al., 2021).

However, this geographic imbalance has methodological implications. Because a majority of quantitative datasets originate from Asian contexts, global interpretations of sprawl magnitude and dynamics may be disproportionately influenced by high-growth emerging economies rather than mature urban systems in Europe or North America.

The methodological composition of the reviewed corpus is summarized in Table 3.

Table 3. Distribution of Primary Methodological Approaches (n = 54)

Primary Methodological Approach	Frequency	Percentage (%)
CA–Markov / Cellular Automata Modeling	22	40.74
Remote Sensing Change Detection	14	25.93
Entropy / Landscape Metrics	7	12.96
Geospatial Analysis	5	9.26
Supervised LULC Classification	4	7.41

Spatial Regression / GWR	2	3.70

As indicated in Table 3, modeling-oriented frameworks dominate the field. CA–Markov and Cellular Automata approach account for nearly 41% of all studies, confirming that predictive simulation and spatial suitability modeling represent the primary analytical paradigm. Remote sensing change detection constitutes the second-largest group, reinforcing the centrality of Landsat-based monitoring observed in Figure 3.

The comparatively limited representation of spatial regression techniques (3.70%) suggests underutilization of advanced econometric modeling approaches capable of isolating socioeconomic drivers of sprawl. While geographically weighted regression (GWR) offers localized explanatory capacity, it remains marginal relative to simulation-based modeling.

This methodological imbalance reveals a structural asymmetry: the field demonstrates strong capacity for spatial prediction and classification but comparatively weaker emphasis on causal inference and governance-driven evaluation.

3.5.2 Urban Expansion Magnitudes: Absolute and Relative Growth

Several studies report precise built-up area transitions, enabling absolute magnitude comparison.

In Hawassa, Ethiopia, built-up land expanded from 584.73 ha to 3,939.03 ha, representing a total increase of 573.65%, with an annual growth rate of 15.50% (Molla, 2024). During this period, 3,148.74 ha of agricultural land were converted to built-up areas, corresponding to a 56.81% agricultural loss rate. Future projections estimate expansion to 5,009.85 ha by 2030 and 6,794.73 ha by 2050, indicating sustained growth momentum.

In Dehradun, India, built-up area increased from 32.19 km^2 to 68.37 km^2, a 112.4% increase, while Shimla expanded from 12.38 km^2 to 29.47 km^2, representing a 138.0% increase (Gupta et al., 2023). These transitions illustrate rapid urbanization in ecologically sensitive mountainous regions.

In Irbid, Jordan, expansion rates demonstrate deceleration: 19.22% (2000–2010) followed by 8.04% (2010–2020) (Al-Bilbisi, 2019), suggesting emerging spatial saturation dynamics.

In Raiganj, India, built-up share increased from 4.30% to 20.25%, a rise of 15.95 percentage points, indicating significant structural transformation of urban morphology (Roy, 2021).

Due to substantial heterogeneity in reporting formats across the reviewed literature, only a subset of studies provided directly comparable percentage-based urban expansion data suitable for statistical aggregation. Therefore, the quantitative synthesis presented in this section is based on a limited sample ($n = 8$) and should be interpreted as a descriptive and exploratory analysis of comparable cases, rather than a statistically representative meta-analysis of the entire dataset.

Within the subset of studies reporting comparable percentage-based expansion values ($n = 8$), the calculated mean expansion is 119.70%, with high variability (standard deviation = 190.07). The distribution exhibits positive skewness ($Sk = 1.97$) and leptokurtic characteristics ($K = 2.38$), indicating the presence of extreme values within the sample.

The observed positive skewness suggests that extreme-growth contexts may disproportionately influence the calculated average within this limited sample. The leptokurtic distribution ($K > 0$) indicates heavy tails and frequent outliers.

The 573.65% increase in Hawassa (Molla, 2024) functions as a statistical extreme, while moderate-growth cases such as Irbid (8–19%) illustrate slower expansion trajectories. This heterogeneity reinforces the conclusion that urban sprawl intensity is structurally uneven and regionally contingent.

Such distributional properties justify the use of boxplot visualization and robust statistics rather than relying solely on arithmetic means. However, these statistical measures are derived from a small subset of studies and are sensitive to outliers, particularly cases with exceptionally high expansion rates (e.g., >500%). Therefore, these values should not be interpreted as global benchmarks but rather as indicative of the variability and asymmetry present in reported urban expansion patterns.

3.5.3 Land Conversion Intensity and Agricultural Loss

The Hawassa case provides one of the most comprehensive land conversion datasets. The conversion of 3,148.74 ha of agricultural land into built-up area represents both spatial expansion and functional transformation of land systems (Molla, 2024).

In Dehradun and Shimla, urban expansion coincided with measurable increases in land surface temperature (LST), with statistically significant correlations between LST and built-up indices ($p < 0.05$) (Jaswal & Thakur, 2023; Olokeogun, 2020). These findings illustrate the linkage between land conversion and environmental intensification.

Thus, expansion magnitude cannot be interpreted independently from functional land-use change. High expansion percentages frequently correspond with agricultural displacement and ecological fragmentation.

3.5.4 Intensity Index Standardization: UHE and UVE

Beyond area-based metrics, multi-index growth intensity indicators provide standardized comparative measures.

In the Beijing–Tianjin–Hebei region, the Urban Horizontal Expansion index (UHE) increased from 0.44 to 0.50, while the Urban Vertical Expansion index (UVE) increased from 0.30 to 0.53, with suburban UVE rising from 0.35 to 0.60 (G. Q. Li, 2025; X. Y. Li, 2011).

These values indicate a transition from predominantly horizontal sprawl toward increased vertical densification in suburban areas. Unlike absolute area growth, index-based measures enable cross-city normalization and structural comparison.

The inclusion of such standardized intensity metrics strengthens quantitative synthesis by moving beyond raw percentage growth toward structural differentiation of growth typologies.

3.5.5 Entropy and Spatial Dispersion Metrics

Entropy values provide insight into spatial configuration rather than magnitude.

In Saudi Arabia, Shannon entropy increased sequentially from 0.700 to 0.779 to 0.840, indicating progressive spatial dispersion and increasing sprawl intensity (Alqurashi, 2016). This numeric series represents the only fully extractable entropy progression from abstract-level data.

Other studies (Feng, 2016; Hanoon, 2023; Kara, 2021) report high entropy levels qualitatively but do not provide explicit numeric sequences in abstracts. This highlights a limitation of abstract-based quantitative synthesis.

The entropy trajectory from 0.700 to 0.840 suggests substantial movement toward spatial disorder, approaching upper dispersion thresholds in sprawl measurement literature.

3.5.6 Modeling Accuracy and Technical Reliability

Model performance metrics provide an important dimension of quantitative synthesis. (Pan, 2024) report 91% overall classification accuracy with a Kappa coefficient of 0.86, indicating strong agreement beyond chance.

A PLS-CA model achieved 85.8% accuracy, compared to 83.5% for a logistic-regression-based CA model (Feng, 2016). These values demonstrate consistent performance across simulation-based frameworks.

The relatively narrow accuracy range (83–91%) suggests methodological stability and technical maturity within geospatial modeling approaches.

3.5.7 Temporal Shift in Research Emphasis

Figure 5 illustrates the longitudinal evolution of thematic priorities within the 54 selected studies, organized into three sequential research phases. The figure reveals a clear structural transformation in the intellectual orientation of urban sprawl scholarship, reflecting both methodological consolidation and thematic diversification.

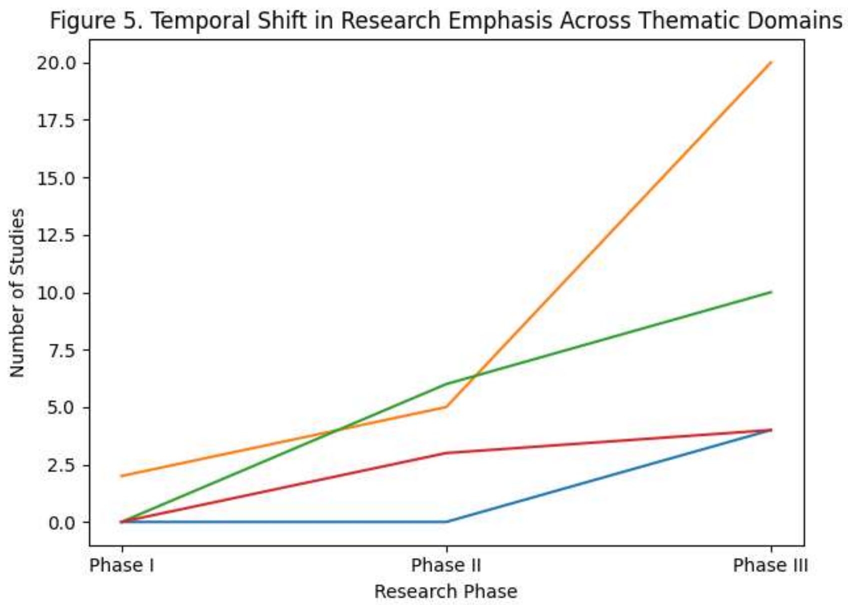

Figure 5. Temporal Shift in Research Emphasis Across Thematic Domains.

In Phase I, research activity is overwhelmingly concentrated in geospatial modeling and urban expansion simulation. Studies during this period primarily focused on multi-temporal Landsat classification, supervised LULC mapping, and the development of Cellular Automata–based predictive frameworks (Alqurashi, 2016; Feng, 2016; X. Y. Li, 2011). Emphasis was placed on classification accuracy, spatial validation, and methodological robustness (L. Ding, 2022; Shao, 2021), indicating that the central objective was reliable detection and quantification of built-up growth. Environmental and governance-oriented studies were comparatively limited, suggesting that early scholarship prioritized spatial measurement over socio-ecological interpretation.

In Phase II, the thematic landscape becomes more diversified. There is a noticeable rise in studies applying entropy indices and landscape metrics to examine fragmentation, dispersion, and morphological transformation (Magidi, 2019; Manesha, 2021; Rahman, 2016). This shift signals growing integration of landscape ecology principles into urban growth analysis. Concurrently, environmental impact studies gain visibility, linking expansion dynamics with land surface temperature variability, agricultural land conversion, and ecosystem change (Criado, 2020; Gupta, 2023; Yan, 2021). Although modeling remains dominant, research increasingly moves beyond "how much cities expand" toward "how expansion alters ecological systems."

In Phase III, Figure 5 shows sharp acceleration in modeling studies alongside sustained growth in environmental research. Advanced hybrid modeling approaches and multi-decadal simulations become more prevalent (Asempah, 2021; Kara, 2021), while climate-oriented analyses—such as carbon emissions, anthropogenic heat flux, and vertical–horizontal expansion indices—gain prominence (Deng et al., 2024; L. Zhang, 2023). This phase reflects a paradigmatic shift toward consequence-oriented inquiry, framing urban sprawl as a socio-ecological transformation rather than solely a spatial phenomenon.

Despite incremental growth, governance and planning research remains comparatively underrepresented across all phases. While several studies recommend sustainable planning strategies (Hanoon, 2023; Karimi et al., 2023), empirical evaluation of policy effectiveness remains limited. Thus, Figure 5 not only demonstrates thematic diversification but also highlights a persistent imbalance between technical modeling capacity and governance translation. Overall, the temporal trajectory captured in Figure 5 reflects intellectual maturation: the field has evolved from methodological establishment to morphological analysis and, more recently, to sustainability integration. However, the continued dominance of modeling research suggests that future scholarship must strengthen institutional and policy-oriented dimensions to achieve more holistic urban resilience frameworks (Koko, 2021; J. Luo, 2008; Y. H. Zhang, 2021).

Figure 6 presents an integrated conceptual synthesis derived from thematic coding, quantitative comparison, and bibliometric structure. The figure presents a conceptual framework illustrating the integrated structure of urban growth and spatial analysis within the domains of remote sensing and GIS. At the core, the framework positions urban expansion analysis as a multidisciplinary process supported by five interrelated components, methodologies and classification techniques, statistical and spatial modeling approaches, geospatial data sources, urban growth dynamics, and environmental as well as socio-ecological impacts (Fenta, 2017; Franci, 2015; Megahed, 2015; Shrestha, 2025). The methodological layer highlights widely used classification and machine learning approaches, including Maximum Likelihood Classification, Random Forest, k-Nearest Neighbors (kNN), and Artificial Neural Networks (ANN), which enable accurate extraction of built-up information from satellite imagery (de Voorde, 2016; Gilbert, 2024; Kara, 2021; Marzialetti, 2023). These techniques are complemented by advanced spatial and predictive modeling tools such as Geographically Weighted Regression (GWR), Cellular Automata (CA), and Markov Chain models, which are employed to simulate spatial transitions and forecast urban expansion patterns (Lu, 2023; Torres, 2024).

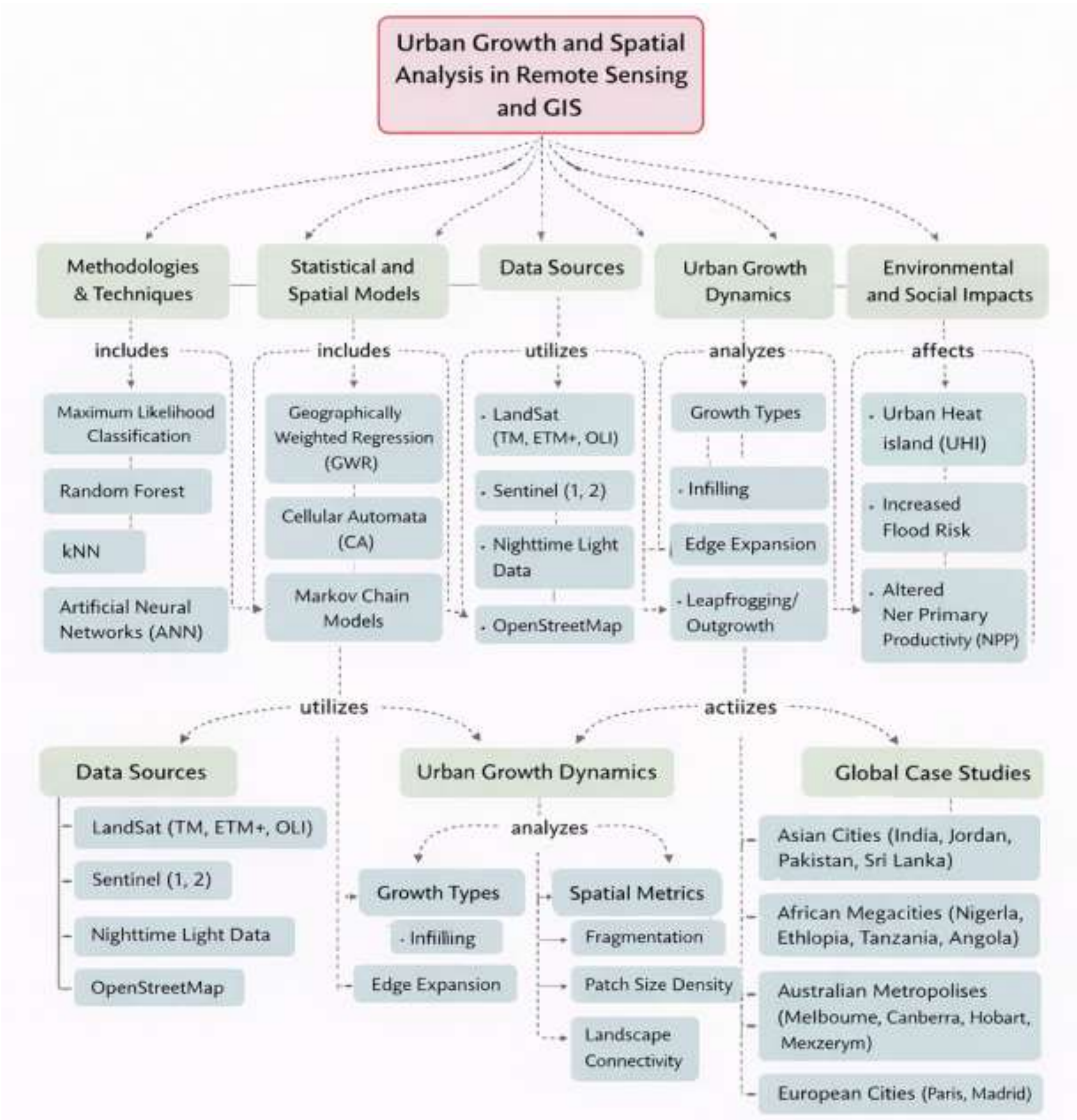

Figure 6. Conceptual Framework of Urban Growth and Spatial Analysis in Remote Sensing and GIS.

The analytical framework relies heavily on multi-source geospatial datasets, including Landsat series (TM, ETM+, OLI), Sentinel missions, nighttime light data, and OpenStreetMap, reflecting the increasing integration of multi-temporal and multi-resolution data environments (Aqdas, 2025; Ngolo, 2023; Niang, 2020). Using these datasets, studies examine urban growth dynamics through typological characterization of spatial expansion processes, primarily infilling, edge expansion, and leapfrogging or outgrowth. These growth forms are further evaluated using landscape-based spatial metrics such as fragmentation, patch size density, and landscape connectivity, which provide quantitative insights into urban form and spatial structure.

Beyond spatial characterization, the framework links urban expansion patterns to broader environmental and social consequences (Shaw, 2018; Ul Din, 2021; Zubair, 2019). Key impacts include the intensification of the UHI effect, increased urban flood risk due to land surface modification, and alterations in ecosystem productivity, particularly Net Primary Productivity (NPP) (Q. Ding, 2022; MacLachlan, 2017; Prakash, 2023). The figure also emphasizes the global applicability of these analytical approaches through representative case study regions, including rapidly growing Asian cities (e.g., India, Pakistan, Sri Lanka, and Jordan), emerging African megacities (e.g., Nigeria, Ethiopia, Tanzania, and Angola), Australian metropolitan regions, and major European urban centers such as Paris and Madrid. Overall, the framework synthesizes the methodological, data-driven, analytical, and impact-oriented dimensions of contemporary urban sprawl research, highlighting the systematic workflow and global relevance of remote sensing–based urban growth assessment (Al-Hameedi, 2021; Kantakumar, 2019; Subasinghe, 2016; Trinder, 2020).

4. DISCUSSION

The present systematic and bibliometric synthesis reveals a technically consolidated yet structurally uneven body of scholarship on urban sprawl. By integrating PRISMA-based screening, bibliometric network visualization, and quantitative comparative analysis, this review provides a multi-layered interpretation of the field's intellectual architecture. The results demonstrate that urban sprawl research is strongly anchored in geospatial modeling, increasingly connected to environmental sustainability concerns, regionally concentrated in Asian contexts, and comparatively limited in its empirical engagement with governance effectiveness. These findings carry important theoretical, methodological, and policy implications. The quantitative patterns identified in this study should be interpreted with caution due to limited data comparability across studies. Variability in reporting formats, spatial units, and measurement approaches restricts large-scale statistical generalization. Consequently, the derived distributional metrics represent indicative trends rather than definitive global estimates.

4.1. Structural Evolution of the Field

The bibliometric structure illustrated in Figure 3 reveals a highly centralized knowledge network dominated by terms such as "urbanization," "urban expansion," "model," and "Landsat." This centralization indicates that predictive modeling and satellite-based land use classification have become the defining analytical core of the discipline. The methodological distribution summarized in Table 3 reinforces this interpretation, showing that Cellular Automata and CA–Markov modeling frameworks account for the largest proportion of empirical investigations. Studies across diverse geographic contexts—including Xining (Pan, 2024), Hawassa (Molla, 2024), and Dehradun (Gupta, 2023), illustrate how simulation-based approaches are routinely employed to quantify past growth and forecast future expansion trajectories.

The temporal progression displayed in Figure 5 further demonstrates intellectual maturation within the field. Earlier research phases were primarily concerned with spatial detection, classification accuracy, and expansion quantification. Over time, however, the thematic emphasis has gradually shifted toward environmental and climate-related consequences of sprawl (Kumar & Shukla, 2022). This evolution indicates that the research community has moved beyond descriptive mapping toward evaluative analysis of impacts. Nevertheless, governance-related scholarship remains comparatively underrepresented in both the bibliometric network and temporal trend analysis. While sustainability discourse has expanded, empirical examination of institutional interventions and regulatory performance remains limited.

The regional concentration presented in Figure 4 reveals that more than half of the selected studies originate from Asian contexts (Halder & Kumar, 2025). Rapid urban transformation in China, India, and neighboring countries has generated substantial empirical attention (Pan, 2024; Zhao, 2021). Although this concentration reflects the intensity of contemporary urbanization processes, it also shapes the global narrative of sprawl. Theoretical generalizations drawn from high-growth metropolitan regions may not fully capture dynamics in slower-growth or post-industrial urban systems. Thus, the structural evolution of the field is closely intertwined with geographic research priorities. While bibliometric analysis provides valuable insight into the structural organization of the research field, it does not, in itself, establish causal relationships between concepts or research trends. Accordingly, the interpretations presented in this study are based on an integrative approach combining bibliometric patterns with thematic and quantitative evidence.

4.2. Theoretical Implications for Urban Sprawl Research

4.2.1 Rethinking Sprawl as Systemic Land Transformation

Traditionally, urban sprawl has been conceptualized as low-density outward expansion characterized by spatial dispersion and fragmentation. Entropy-based analyses in the reviewed literature support this interpretation, as increasing entropy values indicate greater spatial disorder and diffusion (Rahman, 2016; Roy, 2021). However, the quantitative evidence compiled in Section 3.5 suggests that sprawl should be reinterpreted as a systemic land transformation process rather than merely spatial dispersion.

The heterogeneity of expansion magnitudes illustrates this complexity. Hawassa experienced a 573.65% increase in built-up area, expanding from 584.73 ha to 3,939.03 ha while converting 3,148.74 ha of agricultural land (Molla, 2024). By contrast, Irbid exhibited more moderate expansion phases of 19.22% and 8.04% (Mashagbah, 2022). Dehradun and Shimla expanded by 112.4% and 138.0%, respectively (Gupta, 2023), demonstrating rapid transformation in mountainous ecosystems. The statistical skewness of the distribution confirms that urban expansion is structurally uneven and driven by high-growth frontier cities rather than uniform global trends.

Moreover, index-based measures such as the Urban Horizontal Expansion (UHE) and Urban Vertical Expansion (UVE) indices complicate traditional definitions of sprawl. (Zhao, 2021; Zhao et al., 2021) observed modest horizontal expansion increases but significant vertical intensification in suburban areas. These findings suggest that sprawl dynamics encompass both horizontal diffusion and vertical densification, challenging binary classifications of compact versus dispersed development. Theoretically, urban growth should therefore be understood as a multidimensional restructuring of land systems involving magnitude, configuration, intensity, and functional transformation.

4.2.2 Environmental Coupling and Climate Feedback

A second major theoretical implication concerns the integration of environmental consequences into sprawl analysis. The increasing presence of climate-related keywords in Figure 3 and the temporal shift shown in Figure 5 demonstrate that environmental impact assessment has become a central research frontier. Empirical studies report significant correlations between land surface temperature and built-up density (Kanwal et al., 2026), as well as increased ecological vulnerability associated with high-altitude expansion (Castellani & Sala, 2012). Agricultural displacement in rapidly expanding cities further underscores the socio-ecological consequences of sprawl (Molla, 2024).

Despite these advances, quantitative integration of climate metrics remains incomplete. While qualitative linkages between sprawl and environmental degradation are strong, explicit numeric indicators—such as standardized temperature increases per hectare of built-up expansion—are rarely reported at the abstract level. Entropy progression values, such as the increase from 0.700 to 0.840 documented by (Rahman, 2016), illustrate morphological dispersion but do not directly quantify ecological impact. Theoretical frameworks must therefore move toward integrated socio-ecological modeling that links expansion magnitude, morphological structure, and environmental feedback loops within a unified analytical system.

4.2.3 Multi-Scale Urban Growth Dynamics

Urban sprawl operates across multiple spatial and institutional scales. Parcel-level land conversion, metropolitan expansion corridors, regional infrastructure networks, and national development policies interact dynamically to shape growth trajectories. Although Cellular Automata models effectively simulate neighborhood-level transitions, few studies explicitly integrate cross-scale causal mechanisms. (J. Luo, 2008) demonstrated that geographically weighted regression can reveal localized infrastructure-driven expansion patterns, yet such econometric approaches remain relatively rare in the broader corpus.

The conceptual framework presented in Figure 6 illustrates the layered structure of urban growth analysis, linking satellite data acquisition, spatial modeling, morphological assessment, environmental consequence evaluation, and governance translation. However, theoretical articulation of cross-scale feedback mechanisms remains underdeveloped. Bridging micro-level land conversion with macro-level institutional and economic processes constitutes a significant opportunity for future research.

4.3. Methodological Implications and Analytical Gaps

The high classification accuracies reported across multiple studies—ranging from approximately 83% to 91% (Feng, 2016)—indicate strong methodological reliability. Remote sensing archives and machine learning classification techniques have significantly enhanced temporal consistency and spatial precision. This technical maturity strengthens confidence in quantitative expansion metrics.

However, the dominance of simulation-based frameworks also reveals methodological imbalance. While CA–Markov models excel in projecting spatial patterns, they often rely on transition probabilities without fully disentangling socioeconomic drivers. The limited representation of spatial regression techniques (J. Luo, 2008) suggests that causal inference remains secondary to predictive simulation. Integrating econometric modeling, demographic analysis, and infrastructure investment data would provide deeper explanatory insight.

Another analytical gap concerns standardized environmental quantification. Although studies consistently link expansion with thermal intensification and ecological degradation (Gupta, 2023; Pan, 2024), the absence of harmonized environmental indicators restricts cross-case comparability. Full-text meta-analysis incorporating explicit temperature, carbon emission, and ecosystem service metrics would substantially strengthen quantitative synthesis.

It is important to note that the observed geographic and thematic patterns may be partially influenced by database selection and search strategy constraints. Inclusion of additional databases such as Scopus or Dimensions could potentially expand regional representation and thematic diversity. Therefore, the findings should be interpreted as reflective of a high-quality but selectively filtered corpus rather than an exhaustive global inventory.

4.4. Policy Translation and Governance Challenges

Perhaps the most significant structural gap identified in this review is the limited translation of modeling outputs into empirically validated governance strategies. Many studies conclude with recommendations for sustainable planning or smart growth frameworks (Molla, 2024; Roy, 2021), yet few evaluate the measurable effectiveness of such interventions. The bibliometric network (Figure 3) and temporal evolution (Figure 5) confirm that governance-oriented research remains peripheral relative to modeling and environmental assessment.

This diagnostic–prescriptive divide raises important policy questions. Accurate prediction of expansion trajectories does not automatically translate into effective containment strategies. Evaluating urban growth boundaries, zoning reforms, transit-oriented development, and green infrastructure policies requires integration of spatial analytics with institutional analysis. Without such integration, urban sprawl research risks remaining primarily descriptive.

Regional differentiation further complicates policy translation. High-growth frontier cities experiencing triple-digit expansion rates require distinct policy approaches compared to slower-growth or stabilized metropolitan systems. The skewed distribution of expansion magnitudes suggests that governance frameworks must be context-sensitive and adaptive rather than uniform. The limited empirical evaluation of policy effectiveness represents a structural imbalance within the current research landscape.

A comparative reading of the reviewed studies suggests that governance approaches to urban sprawl can be broadly grouped into three categories: (1) regulatory instruments (e.g., zoning, urban growth boundaries, green belts), (2) strategic planning frameworks (e.g., compact city models, polycentric development, TOD), and (3) data-driven or model-supported planning approaches. While these frameworks are widely discussed, their empirical effectiveness is rarely quantified. This reinforces the observation that urban sprawl research remains predominantly diagnostic, with limited transition toward evidence-based policy evaluation.

4.5. Future Research Directions

The findings of this review highlight several structural priorities for advancing urban sprawl scholarship. First, greater standardization of environmental indicators is required to enable cross-case comparability. Although numerous studies link expansion with thermal intensification, ecological degradation, and land conversion, harmonized metrics for land surface temperature, carbon emissions, and ecosystem service loss remain limited, constraining quantitative synthesis.

Second, methodological diversification is needed beyond simulation-based modeling. While CA–Markov frameworks dominate predictive analysis, greater incorporation of spatial econometrics and regression-based approaches would strengthen causal inference regarding socioeconomic and infrastructural drivers of expansion. Third, cross-scale analytical integration should be enhanced. Urban sprawl operates simultaneously at parcel, metropolitan, and regional scales, yet few studies explicitly link micro-level land transitions with macro-level institutional and policy dynamics. Finally, empirical evaluation of planning and governance instruments remains underdeveloped. Bridging the gap between predictive modeling and policy implementation requires systematic assessment of urban growth boundaries, zoning reforms, and transit-oriented development strategies in measurable terms.

5. CONCLUSIONS

This study provides a structured and evidence-based synthesis of global urban sprawl research through integration of PRISMA-guided screening, bibliometric mapping, quantitative comparison, and thematic analysis. From an initial pool of 183 records, 54 peer-reviewed studies were retained, forming a rigorously screened corpus for analysis. The findings reveal a technically mature yet structurally uneven field shaped by methodological consolidation, geographic concentration, and evolving sustainability integration. Geospatial modeling clearly dominates the analytical landscape. Cellular Automata and CA–Markov approaches account for 40.74% of reviewed studies, followed by remote sensing change detection (25.93%), while spatial regression techniques remain marginal (3.70%). Reported classification accuracies consistently range between 83% and 91%, confirming high technical reliability in urban land extraction and predictive simulation. However, this methodological dominance reflects a predictive orientation that often emphasizes spatial forecasting over causal or institutional explanation.

Quantitative synthesis demonstrates substantial heterogeneity in urban expansion magnitudes. Across extractable cases, mean built-up growth within the subset of comparable studies reached 119.7%, with a strongly right-skewed distribution (Sk = 1.97; K = 2.38), indicating that extreme-growth contexts disproportionately influence aggregate statistics. Reported expansion ranges from moderate increases below 20% to cases exceeding 500%, frequently accompanied by large-scale agricultural land conversion and measurable land surface temperature intensification. These findings confirm that urban sprawl operates as a context-dependent land transformation process rather than a uniform global pattern. Geographically, research output remains heavily concentrated in Asia (61.11%), particularly in China and India, limiting broader cross-regional generalization. Bibliometric overlay analysis further indicates a thematic shift toward climate change, ecosystem degradation, and environmental impacts, whereas governance-oriented research and empirical policy evaluation remain comparatively underdeveloped. From a policy perspective, the study highlights that although a variety of planning frameworks, such as compact development, transit-oriented strategies, and growth management policies—are frequently proposed, their empirical validation remains limited. Bridging this gap represents a key opportunity for advancing both research and practice. Overall, urban sprawl scholarship demonstrates strong analytical capacity in spatial detection and simulation but limited integration of cross-scale governance assessment. Advancing the field will require greater incorporation of spatial econometrics, standardized environmental indicators, and systematic evaluation of planning interventions to bridge the gap between predictive modeling and sustainable urban policy implementation.

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