

Urban Sustainability Indexing and GIS Mapping: A Reproducible Framework and Intertemporal Comparability (Kazakhstan, 2000–2022)

Nyussupova, G.,¹ Aidarkhanova, G.,^{2*} Tazhiyeva, D.,³ Kenespayeva, L.,⁴ Kelinbayeva, R.,⁵ Aubakirova, G.,⁶ Kairanbayeva, G.,⁷ Zhakypbek, A.,⁸ and Zhumagulov, C.⁹

Al-Farabi Kazakh National University, 71 al-Farabi Ave., Almaty, Republic of Kazakhstan

E-mail: gulnara.nyussupova@gmail.com,^{1*} <https://orcid.org/0000-0001-5294-2671>,^{1*}

gaukhar.aidarkhanova@gmail.com,² <https://orcid.org/0000-0001-7280-7071>,²

damira.tazhiyeva@gmail.com,³ <https://orcid.org/0000-0001-6824-5600>,³ laura.kenespaeva81@gmail.com,⁴

<https://orcid.org/0000-0001-5734-1947>,⁴ zhar80@mail.ru,⁵ <https://orcid.org/0000-0001-5294-2671>,⁵

gauhara_91@mail.ru,⁶ <https://orcid.org/0000-0002-5806-5638>,⁶ gaukhar_new@mail.ru,⁷

<https://orcid.org/0000-0002-0250-3184>,⁷ bzikasd@gmail.com,⁸ <https://orcid.org/0000-0003-2538-1287>,⁸

c.zhumagulov@gmail.com,⁹ <https://orcid.org/0009-0007-3147-4945>⁹

*Corresponding Author

DOI: <https://doi.org/10.52939/ijg.v21i12.4655>

Abstract

This study develops a reproducible GIS-based framework for assessing urban sustainability and applies it to Kazakhstan's cities over the period 2000–2022. A composite Urban Sustainability Index (USI) is constructed from 29 objective indicators grouped into five thematic sub-indices: economic development, urban infrastructure, demography, social infrastructure, and environmental sustainability. The methodology combines min–max normalization, expert-based weighting, and standardized aggregation, ensuring intertemporal comparability and transparency of calculations. GIS is employed to visualize spatial differentiation and reveal territorial patterns of sustainability trajectories. A key methodological innovation of the study lies in ensuring long-term intertemporal consistency of the assessment while maintaining spatial interpretability under conditions of heterogeneous and partially constrained statistical data. Empirical results demonstrate moderate overall progress without convergence. A stable core of cities (Atyrau, Almaty, Astana, Pavlodar) consolidates its leading position but encounters an environmental ceiling that constrains further advancement. A transitional group exhibits incremental improvement limited by one or two structurally weak components, while a peripheral cluster remains locked in low sustainability due to a thin economic base and insufficient social provision. The findings confirm that isolated improvements in infrastructure or economic performance do not translate into higher sustainability outcomes without balanced development across all dimensions. Methodologically, the paper contributes a scalable and reproducible architecture for urban sustainability assessment that is suitable for integration into GIS-based monitoring systems and SDG 11 dashboards. The proposed framework is transferable to other national contexts with comparable data availability and provides a foundation for future extensions incorporating Earth observation data, subjective well-being indicators, and spatial–causal analysis.

Keywords: Composite Index, GIS Mapping, Intertemporal Comparability, Kazakhstan, SDG 11, Spatial Heterogeneity, Urban Sustainability

1. Introduction

Sustainable urban development is currently one of the key topics on the global scientific and policy agenda. Cities concentrate the majority of the population and economic activity while simultaneously facing mounting pressures from environmental, social, and infrastructure challenges

[1]. United Nations documents, including Sustainable Development Goal 11 and the New Urban Agenda, emphasize the need for a comprehensive assessment of urban sustainability grounded in objective indicators and spatial analysis [2].

In this context, international organizations are actively advancing approaches to index-based assessment and cartographic visualization to strengthen the evidence base for decision-making [3] and [4].

Contemporary research practice demonstrates a shift toward reproducible analytical models that ensure transparency of calculations and intertemporal comparability [5]. Combining composite indices with GIS-based cartographic methods makes it possible to identify spatial regularities in socio-economic and environmental development, as well as to delineate risk zones and growth poles [6]. These approaches provide a methodological foundation for multidimensional analysis of urban systems and for monitoring the trajectories of their sustainability. For Kazakhstan, the objective assessment of urban sustainability is particularly salient given ongoing urbanization, socio-economic transformation, and pronounced spatial differentiation in the quality of the urban environment [7]. Despite the institutional entrenchment of sustainable development principles, comprehensive studies that provide time-comparable analyses of urban sustainability remain limited.

In recent decades, urban sustainability research has increasingly emphasized the role of land use patterns and environmental conditions as key determinants of long-term urban development. The spatial configuration of residential, industrial, and green areas directly shapes resource consumption, environmental pressure, accessibility of services, and exposure to ecological risks. In rapidly urbanizing and transition-economy contexts, inefficient land use, urban sprawl, and concentration of polluting activities often amplify environmental degradation and reduce the effectiveness of infrastructure investments. Consequently, sustainability assessment frameworks increasingly recognize the need to integrate environmental indicators and spatial perspectives in order to capture how land use dynamics and environmental constraints interact with economic and social development. This research need is particularly relevant for cities where historical planning legacies and uneven modernization processes have produced pronounced spatial heterogeneity in environmental quality and land use efficiency.

The aim of this study is to develop a reproducible methodology for indexing and GIS-based mapping of urban sustainability in Kazakhstan's large cities over the period 2000–2022. The methodology entails constructing a composite index from key economic, social, and environmental indicators and applying GIS to identify spatial patterns. The proposed approach is designed for subsequent adaptation at

both the national and international levels. To operationalize this aim, the study addresses four sub-objectives:

- 1) to construct a composite Urban Sustainability Index from a stable set of 29 objective indicators grouped into five thematic sub-indices;
- 2) to ensure intertemporal comparability of the assessment by applying consistent normalization, weighting, and aggregation procedures across all temporal slices (2000–2022);
- 3) to identify spatial differentiation and temporal dynamics of urban sustainability trajectories using GIS-based visualization and typological classification;
- 4) to interpret the dominant drivers and constraints of sustainability across city groups (core, transitional belt, and periphery of risk) to support analytical monitoring.

The working hypothesis is that Kazakhstan's cities exhibit persistent geographic differences in sustainability levels, driven by a combination of demographic, economic, and environmental factors identifiable through composite indexing and GIS mapping. Accordingly, the proposed reproducible indexing and GIS-mapping framework will reveal intertemporal dynamics and pronounced spatial heterogeneity in the development of Kazakhstan's large cities. The results provide an analytical basis for integrating sustainability indicators into urban policy monitoring systems and for assessing progress toward SDG 11.

Despite the extensive international literature on urban sustainability assessment, several methodological gaps remain relevant for transition and post-Soviet contexts. Many widely used global indices rely on proprietary data, non-transparent weighting schemes, or single-time snapshots, which limits their reproducibility and applicability for longitudinal monitoring. At the national level, existing studies on urban sustainability in Kazakhstan and comparable countries are predominantly indicator-specific or descriptive and rarely ensure intertemporal comparability across long time horizons. In addition, GIS is often employed as an auxiliary visualization tool rather than as an integrated component of analytical frameworks for sustainability assessment. As a result, there is a lack of reproducible, GIS-oriented methodologies that combine multidimensional indexing, temporal consistency, and spatial interpretability under conditions of constrained and heterogeneous statistical data. This study addresses this gap by proposing and applying a transparent

Urban Sustainability Index framework designed explicitly for intertemporal analysis and GIS-based mapping of urban development trajectories.

2. Literature Review

2.1 International Frameworks and Indicators of Urban Sustainability

Global challenges of urbanization—including inequality in access to infrastructure, pollution, degradation of natural resources, and increasing vulnerability to climate threats—have necessitated the development of universal criteria for assessing the sustainable development of cities. One of the key international reference points is the United Nations Sustainable Development Goal 11 (SDG 11), aimed at ensuring inclusive, safe, sustainable, and smart cities [1]. In parallel, specialized standards for urban sustainability are being developed, such as ISO 37120, ISO 37122, and ISO 37123, which focus respectively on quality-of-life indicators, digitalization, and climate resilience [8]. OECD standards on territorial sustainability likewise contribute to harmonizing approaches to the measurement and comparative analysis of regional and urban indices [9]. These international frameworks underscore the importance of integrating spatial, social, and economic information into comparable and reproducible assessments. However, their successful implementation requires adapting indicators to the regional context and developing reproducible monitoring methodologies, especially in countries with limited statistical and technical capacities.

2.2 Methodological Approaches to Sustainability Indexing

The quantitative assessment of sustainability is based on the method of composite indices, which makes it possible to aggregate heterogeneous indicators into a composite measure. The OECD–JRC Handbook [10] provides a detailed discussion of the stages of constructing such indices—from normalization and weighting to sensitivity analysis. Three types of sustainability—environmental, economic, and social—emphasizing the importance of a balanced representation of each component [11]. An adaptive weighting methodology that minimizes distortions when new indicators are incorporated was proposed by [12]. The expert-based calibration and the transparency of the aggregation procedure was highlighted by [4]. Recent studies emphasize that ensuring an index's reproducibility over time requires the selection of stable, accessible, and regularly updated indicators. This is particularly important when working with time series, where any

methodological adjustment can affect the intertemporal comparability of results [13].

2.3 Ensuring Intertemporal Comparability

Intertemporal comparability is a critical prerequisite for assessing the dynamics of urban sustainability. It encompasses not only the technical repeatability of calculations but also the maintenance of consistent spatial boundaries, the harmonization of statistical series, and the standardization of aggregates. For example, studies by [14] and [15] demonstrate approaches to unifying indicators of urban greenness and land use through matching algorithms and machine-learning models. The synchronizing data across different cities is possible only with ontological rigor and the availability of intertemporal data layers [16]. One effective instrument is the deployment of open platforms and ontologies, as implemented in [17], which applies a spatio-temporal ontology to unify and update urban indicators.

2.4 GIS as a Tool for Visualization and Analysis: Contemporary Directions

Geographic information systems play an important role not only in analyzing spatial characteristics but also in visualizing indexing results. In particular, the use of ArcGIS makes it possible to integrate tabular data and cartographic objects, as well as to apply classification methods (Jenks, quantile, equal intervals) and cartographic design tools (ColorBrewer, CartoCSS) to enhance map readability [18]. Despite the availability of more sophisticated spatial-analytical models in the contemporary literature, the use of GIS even at the visualization stage remains a powerful tool for popularizing results, supporting decision-making, and drawing attention to territorial differentiation. Current studies advance the idea of intelligent indexing and dynamic monitoring. Thus, within the smart-city concept, an ontologically grounded structure for real-time sustainability assessment was proposed by [19]. The work of [20] combines GIS, DEA, and scenario modeling, which makes it possible to evaluate regional efficiency in terms of sustainability. The integration between market indicators (land price) and spatial data were integrated to assess sustainability, demonstrating alternative approaches [21]. However, most of these solutions require significant resources—both institutional and technical. In the context of developing countries, it is important to design methodologies that combine reproducibility, accessibility, and applicability.

2.5 Kazakhstan Context: Availability, Gaps, and Prospects

In Kazakhstani academic and analytical practice, issues of urban sustainability are still represented predominantly at the level of individual indicators or qualitative assessments. The assessment of quality of life, spatial inequality, and socio-demographic sustainability were addressed in [22] and [23]; however, systematic sustainability indexing using reproducible methodologies and GIS visualization remains limited. Moreover, most existing assessments lack intertemporal comparability, which complicates the analysis of dynamics and the development of long-term solutions. The absence of unified indices and cartographic visualization prevents the integration of the obtained results into national systems of monitoring and strategic planning. Against this background, the methodology for indexing the sustainability of Kazakhstan's cities proposed in this article, followed by visualization in the ArcGIS environment, addresses several gaps at once: it ensures the reproducibility of calculations over a multi-year period (2000–2022), demonstrates pronounced territorial differentiation, and provides a tool for visual support of regional sustainable development policy. Unlike advanced but resource-intensive approaches, the proposed solution is oriented toward practical applicability, institutional compatibility, and flexible scaling within the national context.

3. Methods and Materials

This study covers all officially recognized cities of the Republic of Kazakhstan within the administrative boundaries as of 2022. The analysis spans 2000–2022, which makes it possible to assess the dynamics of urban sustainability on an intertemporal basis. The spatial framework for the index assessment is the system of cities within 17 regions and three cities of republican significance. Administrative data were aggregated at the level of first-order cities, ensuring comparability and continuity of analysis over more than two decades.

The main sources of statistical information are the Bureau of National Statistics of the Republic of Kazakhstan (<https://stat.gov.kz/>), territorial socio-economic development programs, akimat reports, and archival data of the Ministry of National Economy. All indicators were preliminarily checked for comparability in terms of format, measurement units, and geographic referencing. To preserve intertemporal integrity, manual harmonization of coding and the correction of data gaps were applied. In addition, international standards and methodological guidelines were used in developing the index architecture and normalization procedures:

ISO 37120:2018 [8], the OECD Handbook on Constructing Composite Indicators [9], as well as UN-Habitat approaches [1]. This ensured compatibility of the assessment with global sustainability frameworks and aligned the indicators with the SDG targets. To enhance the transparency and reproducibility of the methodological design, the analytical sequence underlying the urban sustainability assessment is presented in a schematic form. The framework integrates data preparation, composite index development, intertemporal standardization, and GIS-based visualization into a coherent analytical structure (Figure 1).

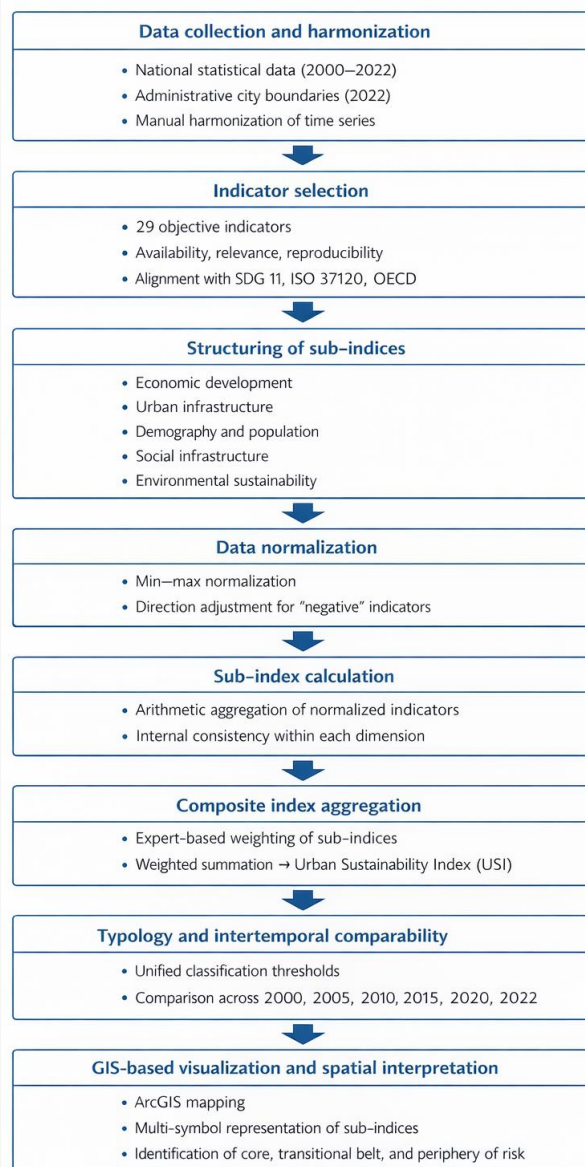


Figure 1: Analytical framework for urban sustainability assessment

The proposed framework follows a stepwise logic that links statistical data harmonization with composite index aggregation and spatial interpretation. Consistent normalization and weighting procedures are applied across all temporal slices, ensuring the intertemporal comparability of the results. The separation between index computation and GIS-based visualization preserves analytical robustness while strengthening spatial interpretability. Such a structure allows the methodology to be replicated in other territorial contexts characterized by heterogeneous but comparable data sources.

3.1 Concept of the Urban Sustainability Index

The methodological basis of the integrated Urban Sustainability Index rests on the concept of systemic sustainability, according to which the development of an urban territory is evaluated by a combination of demographic, infrastructural, environmental, and economic parameters [11] and [13]. In this study, the Index is structured into five sub-indices, each assigned a weight based on expert calibration [4]:

- Economic development (weight 0.2) captures employment conditions, fixed capital investment, production activity, and household income, reflecting the economic base and investment capacity of urban systems.
- Urban infrastructure (weight 0.2) reflects the provision and functional quality of utilities, transport networks, and housing stock, which determine accessibility and reliability of urban services.
- Demography and population (weight 0.1) characterizes population size, migration trends, and natural increase, indicating demographic sustainability and labor-force renewal.
- Social infrastructure (weight 0.3) encompasses access to healthcare, education, and social services, representing the human and social dimension of urban sustainability.
- Environmental sustainability (weight 0.2) incorporates pollutant emissions, investments in environmental protection, and urban greening, capturing environmental pressures and mitigation efforts within cities.

In total, 29 quantitative indicators were used in the calculations. Indicator selection followed the criteria of availability, reproducibility, theoretical relevance, and policy relevance [9] and [10]. The use of a fixed set of 29 objective indicators represents a deliberate methodological choice. Indicator selection prioritized long-term availability, statistical consistency, and relevance to internationally

recognized urban sustainability frameworks, which is essential for ensuring intertemporal comparability over extended time horizons. By relying on a stable and transparent indicator system, the index avoids structural breaks associated with frequent indicator substitution and supports consistent tracking of urban sustainability dynamics across cities and years.

The relative importance of the five thematic sub-indices was determined using a structured expert judgment approach. An expert panel consisting of specialists with academic and applied expertise in urban studies, regional development, spatial planning, and environmental assessment evaluated the contribution of each sustainability dimension to long-term urban sustainability.

Experts evaluated the relative contribution of each sustainability dimension (economic development, urban infrastructure, demography, social infrastructure, and environmental sustainability) to long-term urban sustainability. Individual assessments were aggregated using an averaging procedure, and the resulting weights were applied consistently across all cities and time periods to maintain intertemporal comparability. This weighting strategy supports methodological transparency and stability of the index structure under heterogeneous data conditions, while avoiding excessive sensitivity to statistically driven or context-specific fluctuations.

3.2 Data Normalization and Aggregation

All quantitative indicators were rescaled to a dimensionless scale using min–max normalization as defined in Equation 1:

$$X_{norm} = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

Equation 1

Where X_i is the value of the indicator for a given city, and X_{min} and X_{max} are the minimum and maximum values across the entire set of cities, respectively. For indicators where an increase in the value is interpreted as a deterioration (e.g., pollution level), a reverse transformation was applied. After normalization, the sub-indices were calculated as the arithmetic mean of their constituent indicators, and the final index as the weighted sum of the sub-indices is defined in Equation 2:

$$USI = \sum_{i=1}^n w_i S_i$$

Equation 2

Where w_i is the weight of sub-index i , and S_i is its value.

The selection of analytical tools and procedures in this study was guided by the principles of transparency, reproducibility, and intertemporal consistency. Min–max normalization was adopted because it preserves relative differences between cities while enabling the integration of indicators measured in different units and scales, which is essential for long-term comparative analysis. Expert-based weighting was applied to reflect the multidimensional nature of urban sustainability and to avoid overemphasizing statistically dominant but conceptually narrow indicators. In data-constrained and heterogeneous statistical environments, such as those characteristics of transition economies, expert calibration provides greater interpretability and methodological stability than purely data-driven weighting techniques. The use of GIS was deliberately limited to visualization and spatial interpretation rather than index computation, ensuring analytical clarity while enhancing the spatial readability and policy relevance of the results.

3.3 Typology of Sustainability and Intertemporal Comparability

Based on the computed values of the USI, a typology of urban sustainability was developed. The class intervals were designed with regard to the empirical distribution of values and the classification logic employed in comparable studies [12]. Seven sustainability categories are distinguished—from “crisis level” (< 0.150) to “high sustainability” (> 0.900). This gradation provides a robust platform for monitoring and for intertemporal and interterritorial comparison (Table 1). Using a unified system of indicators and a consistent normalization methodology across all temporal slices (2000, 2005, 2010, 2015, 2020, 2022) guarantees comparability of values between years. This makes it possible to interpret not only the current state but also development trajectories, including cities’ transitions between sustainability types.

3.4 Role of GIS and Visualization

Although geographic information systems (GIS) are not used in this study to calculate the sub-indices or the composite USI, they play a key role in visualizing the results and conducting spatial analysis. The use of ArcGIS software made it possible to present index estimates in the form of thematic maps, providing an intuitive display of intercity differences and revealing resilient and vulnerable territories.

The GIS implementation was based on vector spatial data and attribute tables rather than raster datasets. Administrative boundaries of the Republic of Kazakhstan and point layers representing city locations were used as the primary spatial layers. Attribute data containing the calculated sub-index and composite index values were linked to spatial features through unique identifiers. No raster-based remote sensing data were employed in this stage of the analysis, as GIS was used for visualization and spatial interpretation of the index results. Given the specifics of the source data—the values of the sub-indices and the Index calculated for 20 cities (17 regional capitals and 3 cities of republican significance)—special attention was paid to choosing appropriate symbols and the graphic structure of the maps. Standard choropleth mapping proved ineffective due to the small area at scales covering the entire territory of Kazakhstan. Therefore, preference was given to proportional point mapping methods that ensure clarity and data comparability. Implemented a multi-symbol visualization concept, in which each city is represented by a set of five triangular symbols corresponding to the five sub-indices. The size of each triangle varies proportionally to the value of the respective sub-index, while the color scheme is fixed according to the thematic dimensions. The integrated index is additionally visualized using a bar chart placed next to the city marker, with the bar height proportional to the aggregated index value.

Table 1: Sustainability level classification

Types by Sustainability Level	Range of Composite Index Values	Subtypes by Sustainability Level
Sustainable	$\geq 0,900$	High sustainability
	$0,750 \leq X < 0,900$	Sustainable level of development
Moderately sustainable	$0,600 \leq X < 0,750$	Near-sustainable level of development
	$0,450 \leq X < 0,600$	Average level of sustainability
	$0,300 \leq X < 0,450$	Development level exhibiting signs of instability
Unsustainable	$0,150 \leq X < 0,300$	Unsustainable level of development
	$< 0,150$	Crisis level of development

This approach enables simultaneous representation of both the multi-component profile of urban sustainability and the final evaluation within a single map, maintaining readability and high analytical value of the visualization. To display the final composite index, an additional map was used with circles of proportional size and a color gradation corresponding to five sustainability levels: from “very low” to “high.” The geographic locations of the features were rendered with high accuracy based on official coordinates of settlements obtained from the territorial reference directories of the Republic of Kazakhstan.

Visualization was carried out using core ArcGIS tools, including the Symbology module for managing sizes and colors and the Layout View for final map composition. Thus, GIS visualization in this study serves not only as a means of presenting results but also as a tool for interpreting the spatial structure of urban sustainability, contributing to more substantiated conclusions and the formulation of targeted recommendations for regional policy.

3.5 Limitations and Reproducibility Potential

The research methodology was developed in accordance with the principles of transparency, modularity, and scalability. Every step—from data collection to index computation is formalized and documented, making the method suitable for replication in other countries or regions. At the same time, it should be noted that the quality of the calculations depends on the completeness of statistical information, especially in small and rapidly growing cities.

3.6 Validation of Results

The validity of the Urban Sustainability Index was assessed through a combination of intertemporal consistency checks, internal coherence analysis, and external benchmarking. Given the composite and multidimensional nature of the index, validation focused on the stability, interpretability, and analytical robustness of the results rather than on predictive performance.

First, intertemporal validation was performed by examining the persistence of relative city positions and sustainability typologies across the reference years 2007, 2017, and 2022. Despite overall growth in index values, the spatial configuration of leading, transitional, and lagging cities remained largely stable, indicating that the index captures structural differences rather than short-term fluctuations or random variation.

Second, internal coherence was evaluated by analyzing the relationships between sub-indices and the composite index. Cities characterized by strong economic and infrastructural performance but weak environmental indicators consistently failed to achieve high composite sustainability scores. This pattern confirms the non-substitutability of sustainability dimensions and supports the conceptual assumption that balanced development across economic, social, and environmental components is required to attain higher sustainability levels.

Third, external validation was conducted through qualitative comparison with independent international assessments, including UN-Habitat reports and the Arcadis Sustainable Cities Index. The identification of major agglomerations as development leaders constrained by environmental pressures is consistent with these external benchmarks, lending further credibility to the observed spatial patterns.

Taken together, these validation procedures indicate that the proposed framework provides a reliable and analytically sound basis for intertemporal and spatial assessment of urban sustainability under conditions of heterogeneous and partially constrained statistical data.

4. Results

4.1 Dynamics of the Composite Index (2007–2022)

The analysis of the composite USI shows a moderate increase in values over 2007–2022; however, gaps between cities persist. In the study’s baseline year (2007), the leaders were Aktau (0.672), Atyrau (0.613), and Astana (0.593), whereas Shymkent (0.397), Taldykorgan (0.407), and Turkestan (0.413) were in the lowest-sustainability zone. The high starting scores in the Caspian cities were driven by the oil-and-gas boom and infrastructure improvements, while the low values in the south reflected a legacy of peripherality and a weak industrial base. By the midpoint of the period (2017), a marked leveling occurred: owing to government programs for infrastructure modernization and investments in the social sector, Almaty, Atyrau, Astana, and Pavlodar moved into the “near-sustainable” category (0.611–0.651). The improvement is associated with the construction of new utility networks, an upswing in regional economies, and inflows of migrants. However, by 2022 the growth rate had slowed: Aktau and Astana showed slight declines (from 0.609 to 0.585 and from 0.651 to 0.621, respectively) (Figure 2). This reflects intensive infrastructure projects reaching saturation

toward the late 2010s, while environmental pressures and transport congestion began to constrain further gains.

Overall, over the twelve years under review, no city crossed the sustainable development threshold (0.75). The leaders—Atyrau (0.667), Almaty (0.635), and Astana/Astana (0.621)—consolidated their positions at the top of the ranking but still remain below the sustainable level. At the opposite pole,

Turkestan (0.450), Shymkent (0.490), and Taldykorgan (0.486) are economically and infrastructurally weak centers where demographic pressure and an insufficient social base keep the index low. Thus, the dynamics of the Urban Sustainability Index confirm the thesis of growth without convergence: the gap between leaders and laggards is narrowing slowly, which leads to the need to unpack the internal structure of the index.

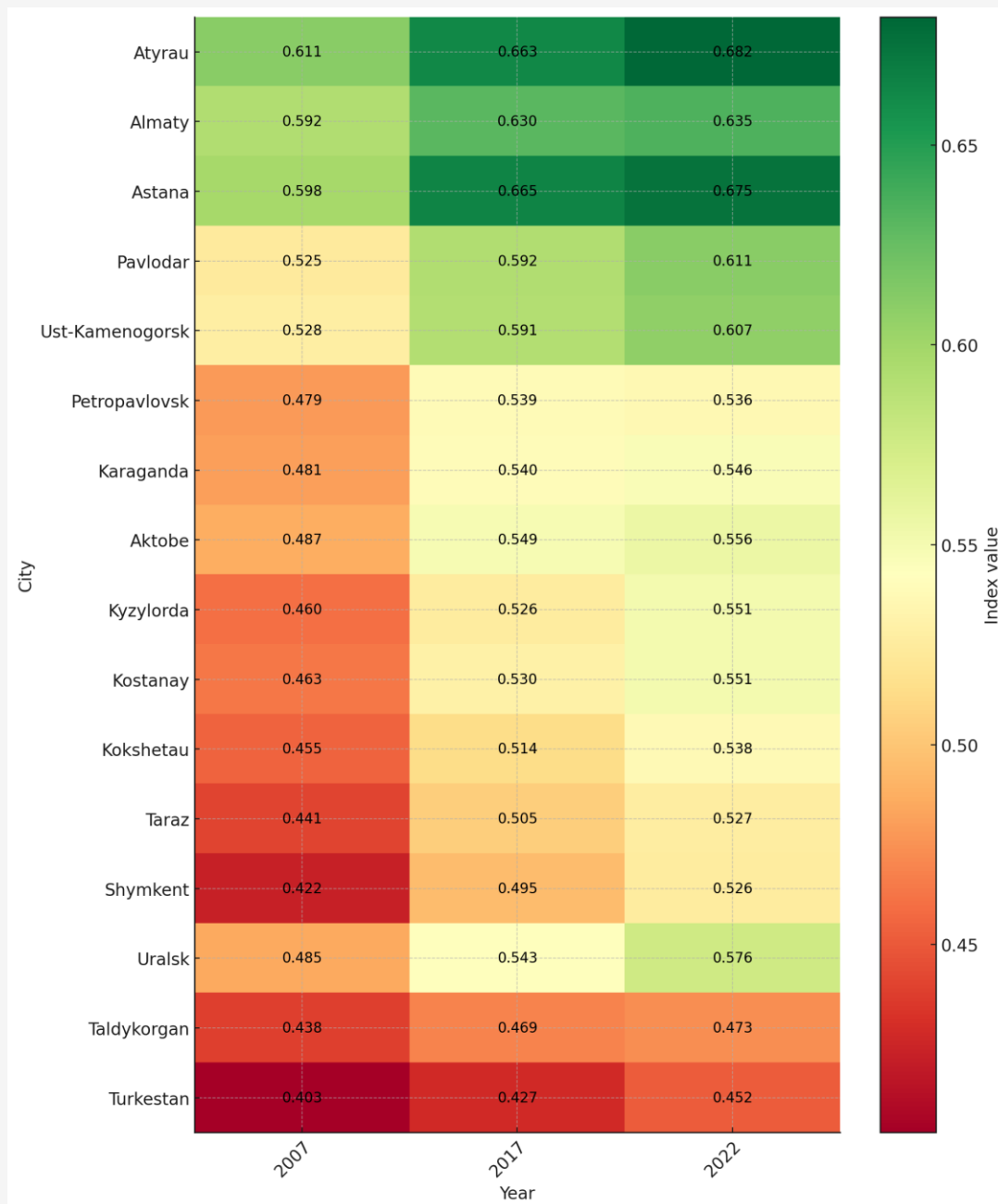


Figure 2: Dynamics of the composite Urban Sustainability Index for Kazakhstan's cities in 2007, 2017, and 2022

4.2 Thematic Structure of the Sub-Indices: Drivers and Constraints

Economic development. In 2022, the highest values for the “Economy” block were recorded in Aktau (0.613), Atyrau (0.588), and Almaty (0.564). These cities rely on the resource-export sector, a growing service economy, and diversified labor markets, which ensure steady income inflows and investment attractiveness. At the same time, Turkestan (0.345), Taldykorgan (0.420), and Taraz (0.423) show structural weakness (Figure 3): the absence of large industries and an underdeveloped small-business sector prevent them from building economic potential. It is the economic lag that explains why, even with infrastructure improvements, these cities’ composite index remains low. Urban infrastructure. The “Infrastructure” component was the main growth driver in the first half of the period: in Aktau, Astana, and Almaty the sub-index rose from 0.65–0.66 to 0.77–0.85 thanks to large-scale investments in transport, energy, and utility networks. However, by 2022 several cities experienced a slowdown or decline (for example, Astana: from 0.849 in 2017 to 0.716 in 2022), indicating infrastructure overstretch—the network no longer keeps up with population

growth and motorization. In peripheral centers such as Turkestan and Taldykorgan, even after improvements the indicators remain at 0.53–0.61, pointing to a chronic shortage of engineering capacity.

Demography and population. The demographic sub-index shows how young and mobile the city’s population is. In 2022, the leaders were Astana (0.701), Shymkent (0.637), and Almaty (0.638). These cities attract youth migration and have positive natural increase, which supports the labor market and consumer demand. In the northern and eastern centers—Kokshetau (0.545), Kostanay (0.548), Karaganda (0.566)—the demographic resource is constrained by population aging and out-migration. Where demographics are unfavorable, even strong economic indicators do not yield a substantial increase in the composite index.

Social infrastructure. The “Social infrastructure” indicator reflects the availability and quality of education, healthcare, and social protection. Almaty (0.902), Astana (0.825), and Oral/Ural'sk (0.684) demonstrate strong positions; the presence of universities, clinics, and cultural institutions underpins high human potential.

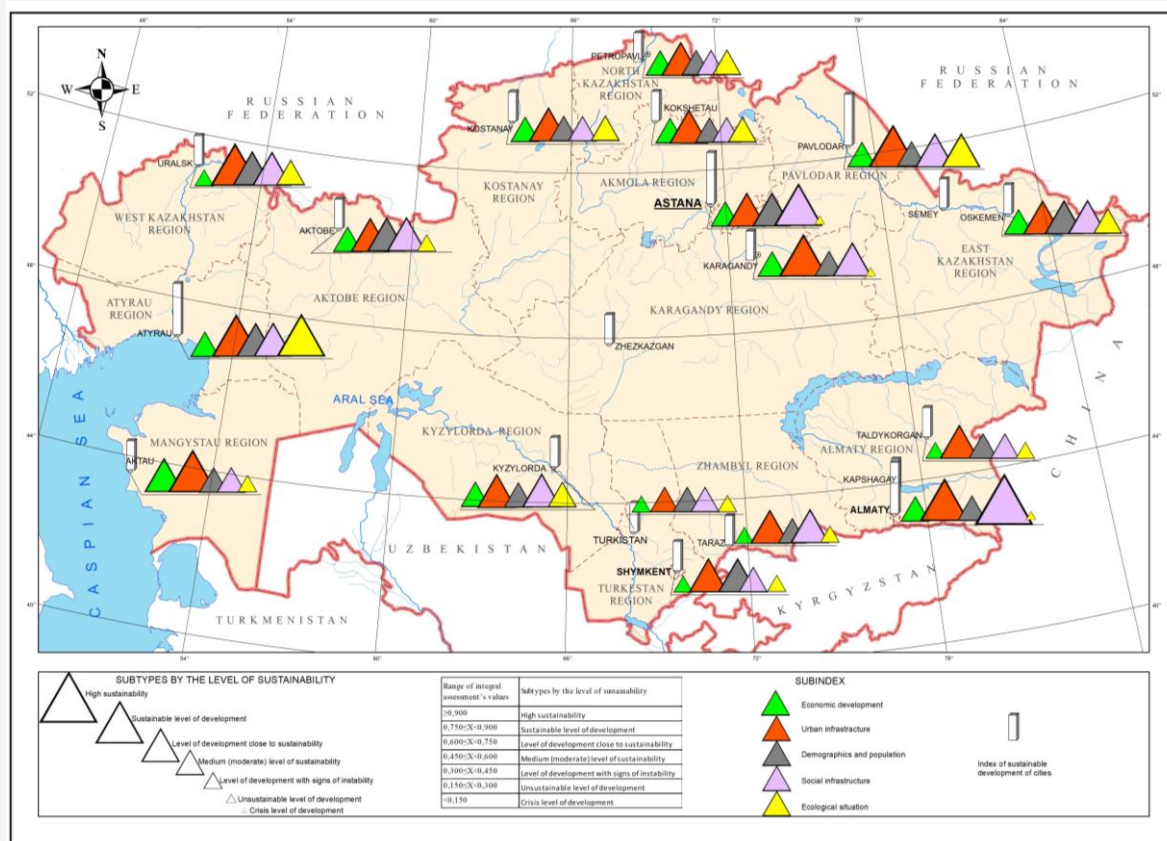


Figure 3: Spatial differentiation of the five urban sustainability sub-indices (2022)

In peripheral cities—Aktau (0.597), Kostanay (0.575), and Kokshetau (0.584)—the sub-index remains in the 0.57–0.60 range (Figure 2), indicating a shortage of social services. In practice, a combination of high physical infrastructure with low social indicators leads to the outflow of qualified population. Environmental situation. The environmental sub-index revealed the main “bottleneck” of development.

In 2022 only Atyrau (0.834) and Pavlodar (0.661) had high values, whereas Almaty (0.247) and Astana (0.276) suffer from chronic pollution and low greening levels. Even resource centers like Aktau lost ground (declined from 0.827 to 0.411) due to degradation of the marine ecosystem. The environmental component effectively “erodes” gains from other sub-indices: in large agglomerations, further sustainability growth is impossible without green technologies and environmental protection measures.

Sustainable development is achieved only when all five sub-indices are balanced: an economic base, advanced infrastructure, favorable demography, and social support cannot compensate for environmental deficits. The analysis shows that leading cities succeed by combining strong economy, infrastructure, and social sphere, but run up against environmental and demographic constraints; laggards, in turn, fail to move into the “sustainability zone” due to cumulative underperformance across several components.

4.3 Spatial Distribution of Sustainability: Core, Transitional Belt, and Periphery of Risk

The calculations indicate that, taken together, the five sub-indices clearly group cities into several stable clusters: in one case, favorable economic and social infrastructure indicators are offset by environmental costs; in another, specific strengths coexist with weaknesses; and a third group is characterized by comprehensive vulnerability. This contrast underscores the need for targeted strategies for each type. Stable core. The leaders in the composite sustainability index include several major centers that best combine a strong economic base with developed infrastructure and social services. In 2022 this group included Atyrau (0.667), Almaty (0.635), Astana (0.621), and Pavlodar (0.612), with composite index values ranging from 0.612 to 0.667. Each of these agglomerations has seen intensive growth driven by large investment projects and strong human and financial attraction; however, environmental constraints are precisely what currently prevent them from moving into the sustainable-development category.

Transitional belt. Ust-Kamenogorsk (0.594), Oral/Uralsk (0.565), Aktobe (0.556), Kyzylorda (0.538), Petropavlovsk (0.532), Kostanay (0.527), Kokshetau (0.521), Taraz (0.506), and Shymkent (0.490) are territories with moderate sustainability and mixed profiles. They typically feature one or two strong sub-indices (more often infrastructure and demography), but a weak link (the social sphere or environment) prevents them from crossing the 0.6 threshold. They require targeted programs aimed at balancing weak components; otherwise, the effect of investments will dissipate.

Periphery of risk. Turkestan (0.450) and Taldykorgan (0.486) are cities where the economic base, social infrastructure, and demography reinforce vulnerability. Here, infrastructure projects often do not lead to increased sustainability due to a shortage of human resources and low urban-environment quality. To exit the risk zone, major institutional and financial injections are needed; otherwise, the gap with leading centers will only widen.

Spatial analysis confirms that modernization efforts in 2007–2017 raised the sustainability level of most cities but did not resolve territorial polarization. Developing infrastructure and the economy without simultaneously improving environmental quality, the social sphere, and demographic potential leads the composite Urban Sustainability Index to hit a plateau. These results provide the basis for the “Discussion” section, which will examine the alignment of national strategies and international frameworks with the identified patterns and propose specific directions for targeted policy

5. Discussions

Assessment of Kazakhstan’s USI for 2007, 2017, and 2022 revealed pronounced spatial and temporal differences that reflect uneven progress toward achieving the SDGs. The results indicate both upward trajectories in a number of key cities and persistent vulnerability of urban systems on the periphery, despite strategic intentions enshrined in national documents and international commitments. Cities such as Astana, Almaty, and Atyrau demonstrate steady growth and movement of index values toward the sustainability thresholds. These centers aggregate economic, infrastructural, and managerial resources, which is consistent with the findings of global comparative studies such as the Arcadis Sustainable Cities Index [3], emphasizing the role of administrative and financial hubs in advancing sustainable transformations. This also accords with the conclusions of UN-Habitat (2020), according to which cities with diversified economies and targeted investments perform better in composite sustainability indices.

By contrast, the cities of Shymkent, Taraz, and Turkestan maintain relatively low USI values. Despite elevated administrative status and the implementation of regional development programs (e.g., the “Program for the Development of Turkestan Region for 2020–2025”), they are characterized by infrastructure overload, demographic pressure, and insufficient economic diversification. Similar results are reflected in international studies documenting the gap between urbanization and infrastructure development in developing countries [24], as well as in the conclusions of [17] which stress the need to account for spatio-temporal variability in urban sustainability indexing, especially in a transition-economy context. An intermediate position is occupied by cities such as Pavlodar, Ust-Kamenogorsk, and Oral. The observed positive dynamics of the index may be associated with the implementation of industrialization programs and investments in human capital. These processes corroborate the study about the potential of secondary cities to serve as growth poles of regional sustainability, provided effective territorial governance is in place [25].

The spatial asymmetry visualized on the maps confirms the hypothesis of pronounced territorial differentiation in the sustainability of Kazakhstan’s cities. This points to the limitations of universal governance approaches in the context of high geodemographic heterogeneity. Such observations are consistent with international critiques of standardized approaches to urban planning [26] and reinforce arguments in favor of adaptive, context-sensitive management.

From a public policy perspective, Kazakhstan declares its commitment to sustainable development in strategic documents such as “Kazakhstan-2050,” the “Concept for Territorial Development to 2025,” and the national localization of the SDGs. However, practical implementation remains fragmented, especially in cities with limited institutional capacity and low investment attractiveness. This underscores the need to transition to more flexible, data-driven governance systems integrating GIS and indicator-based monitoring. The slowdown in USI growth in 2017–2022 may indicate that the previous toolkit has reached a “ceiling” of effectiveness and requires re-evaluation. As OECD country experience shows, sustained progress requires not only initial investments but also innovations in governance systems, citizen engagement, and digital monitoring [4]. The index and cartographic tools developed in this study can form the basis for such solutions, particularly in developing early-warning indicators and city-level sustainability dashboards.

Thus, Kazakhstan’s urban trajectory is at a strategic crossroads. The presence of an institutional base and political will creates favorable preconditions for sustainable transformations; however, their success will depend on the capacity to conduct territorially differentiated and adaptive policy based on evidence. The USI presented in this work can serve as an analytical foundation for setting priorities, monitoring the effectiveness of measures, and integrating the index into a unified architecture of sustainable urban planning.

6. Limitations

In closing, we note the limits to interpreting the results, which define the scope for generalization and subsequent policy.

1. *Data and periodicity*: The empirical base includes three reference points (2007, 2017, 2022). Such stepwise discretization constrains the capture of short-term fluctuations and shocks (e.g., the impact of specific reforms or episodes of air-quality deterioration).
2. *Normalization and weights*: Min–max normalization and expert weights were applied across the five sub-indices. This enhances transparency but preserves sensitivity to outliers and to the choice of weights; alternative (robust or non-compensatory) schemes may partially change city rankings.
3. *Boundaries of analysis and scales*: The assessment is tied to administrative boundaries; agglomeration effects, commuting, and suburban zones are only partially reflected, which is especially important for major centers.
4. *Indicator composition*: The index is based on a fixed set of 29 objective indicators selected to ensure statistical stability, transparency, and intertemporal comparability. While this design choice strengthens longitudinal analysis, it does not capture certain subjective dimensions of urban sustainability, such as perceived quality of life or environmental comfort, which may be addressed in future extensions of the framework.
5. *Spatial and causal analytics*: This version does not perform tests of spatial autocorrelation or quasi-experimental evaluations of causal effects of urban policy; therefore, causal inferences are analytic-interpretive in nature.

6. *External validity*: The method is portable and reproducible; however, direct comparisons with foreign indices require careful calibration due to differences in statistics and institutional contexts.

These limitations do not negate the identified patterns (growth without convergence, the “environmental ceiling” among leaders, and the “thin” economic base on the periphery) but set priorities for fine-tuning monitoring and refining policy measures.

Policy Implications:

Given the above limitations, implications are formulated to strengthen cities’ advantages and address the “bottlenecks” of the sub-indices.

National Level:

- Shift from uniform approaches to cluster-based targeting: use the three groups (“core,” “transitional belt,” “periphery of risk”) as a framework for differentiating instruments and target KPIs.
- Institutionalize a sustainability dashboard: annual updates of sub-indices and the USI, public cartographic visualization, and “early warnings” when specific components decline.
- Deploy a green agenda as a prerequisite for growth in megacities (Astana, Almaty): air quality, green infrastructure, waste management, building energy efficiency, and clean transport as keys to overcoming the “environmental ceiling.”
- Introduce multicriteria impact scoring for investment projects (covering all five sub-indices) and “green” public-procurement standards.

Regional Level (by Clusters):

- Stable core (Atyrau, Almaty, Astana, Pavlodar). Focus: ecological modernization and integration of transport and land use (TOD) to cross the 0.75 threshold without sacrificing quality of life.
- Transitional belt (Ust-Kamenogorsk, Oral/Ural'sk, Aktobe, Kyzylorda, Petropavlovsk, Kostanay, Kokshetau, Taraz, Shymkent). Focus: leveling the weak link (typically the environment or social infrastructure) based on existing strengths (infrastructure, demography). Instruments: modernization of district heating and public transport, development of the primary health-and-social network, workforce training.

- Periphery of risk (Turkestan, Taldykorgan). Focus: “anchoring” the economy (industrial and logistics parks, SME clusters) plus basic social services and municipal engineering. Without this, infrastructure investments will not convert into USI gains.

Regional Level:

- Introduce data-driven management cycles: quarterly/annual sub-index updates, public reporting, and program adjustments based on actual progress.
- Expand resident participation (surveys; citizen science for air/noise) to integrate subjective metrics.
- Establish urban sustainability labs to pilot green and social solutions with subsequent scalability.

The implications are deliberately tied to each cluster’s profile: where the environment is the constraint, green-modernization measures take priority; where the social sphere is “thin,” index growth will stall without strengthening basic services.

6. Conclusion

The study proposed a reproducible architecture for a composite assessment of urban sustainability (USI) based on five sub-indices, together with its GIS visualization for Kazakhstan’s cities. By integrating composite index construction, ensured intertemporal comparability, and GIS-based spatial interpretation within a single reproducible framework, the study addresses key methodological limitations of existing urban sustainability assessments, particularly in data-constrained and transition-economy contexts. The results for 2007, 2017, and 2022 show growth without convergence: the core (Atyrau, Almaty, Astana, Pavlodar) consolidates its position but runs into environmental constraints; the “transitional belt” advances slowly due to one or two weak links; and the “periphery of risk” requires an economic anchor and basic social investments. Methodologically, the work ensures transparent normalization, weighting, and intertemporal comparability, while the cartographic products enhance the managerial applicability of the results.

References

- [1] United Nations Human Settlements Programme (UN-Habitat). (2020). *World Cities Report 2020: The value of sustainable urbanization*. <https://doi.org/10.18356/27bc31a5-en>.

- [2] United Nations. (2017). *The New Urban Agenda*. [Online]. Available: <https://habitat3.org/the-new-urban-agenda>. [Accessed: Oct. 26, 2025].
- [3] Arcadis. (2022). The Arcadis Sustainable Cities Index 2022: Prosperity Beyond Profit. [Online]. Available: <https://media.arcadis.com/-/media/project/arcadiscom/com/perspectives/global/sci-2024/sustainable-cities-index-2022.pdf>. [Accessed: Oct. 26, 2025].
- [4] Organisation for Economic Co-operation and Development (OECD). (2020). *Decarbonising Urban Mobility with Land Use and Transport Policies: The case of Auckland, New Zealand*. <https://doi.org/10.1787/095848a3-en>.
- [5] Gan, X., Fernandez, I. C., Guo J., Wilson, M. and Zhao, Y., (2017). When to Use What: Methods for Weighting and Aggregating Sustainability Indicators. *Ecological Indicators*, Vol. 81, 491–502. <https://doi.org/10.1016/j.ecolind.2017.05.068>.
- [6] Ahmad, A. and Anwar, S., (2023). A Composite Index for Sustainable Development: Measurement and Development Status of Selected Countries. *Journal of Economic Impact*, Vol. 5(1), 1–14. <https://doi.org/10.5223/jei5012301>.
- [7] Aidarkhanova, G., Zhumagulov, C., Nyussupova, G. and Kholina, V., (2025). Assessing the Impact of Demographic Growth on the Educational Infrastructure for Sustainable Regional Development: Forecasting Demand for Preschool and Primary School Enrollment in Kazakhstan. *Sustainability*, Vol. 17(9). <https://doi.org/10.3390/su17094212>.
- [8] International Organization for Standardization. (2018). Sustainable Cities and Communities—Indicators for City Services and Quality of Life (ISO 37120:2018). [Online]. Available: <https://www.iso.org/standard/68498.html>. [Accessed: Oct. 26, 2025].
- [9] OECD. (2020). *A Territorial Approach to the Sustainable Development Goals: Synthesis Report*. <https://doi.org/10.1787/e86fa715-en>.
- [10] OECD/European Union/EC-JRC. (2008). *Handbook on Constructing Composite Indicators: Methodology and User Guide*. OECD Publishing, Paris. <https://doi.org/10.1787/79789264043466-en>.
- [11] Mori K. and Christodoulou, A., (2012). Review of Sustainability Indices and Indicators: Towards a New City Sustainability Index (CSI). *Environmental Impact Assessment Review*, Vol. 32(1), 94–106. <https://doi.org/10.1016/j.eiar.2011.06.001>.
- [12] Mazziotta, M. and Pareto, A., (2016). Methods for Constructing Non-Compensatory Composite Indices: A Comparative Study. *Forum for Social Economics*, Vol. 45(2–3), 213–229. <https://doi.org/10.1080/07360932.2014.996912>.
- [13] Greco, S., Ishizaka, A., Tasiou, M. and Torrisi, G., (2019). On the Methodological Framework of Composite Indices: A Review of the Issues of Weighting, Aggregation, and Robustness. *Social Indicators Research*, Vol. 141(1), 61–94. <https://doi.org/10.1007/s11205-017-1832-9>.
- [14] Mahajan, S., (2024). greenR: An Open-Source Framework for Quantifying Urban Greenness. *Ecological Indicators*, Vol. 163. <https://doi.org/10.1016/j.ecolind.2024.112108>.
- [15] Ding, X., Wang, Y., Wang, H., Jiang, Y. and Wu, Y., (2025). Adaptive and Differentiated Land Governance for Sustainability: The spatiotemporal Dynamics and Explainable Machine Learning Analysis of Land Use Intensity in the Guanzhong Plain Urban Agglomeration. *Land*, Vol. 14(9). <https://doi.org/10.3390/land14091883>.
- [16] Higgs, C., Alderton, A., Rozek, J., Adlakha, D., Badland, H., Boeing, G., Both, A., Cerin, E., Chandrabose, M., De Gruyter, C., De Livera, A., Gunn, L., Hinckson, E., Liu, S., Mavoa, S., Sallis, J. F., Simons, K. and Giles-Corti, B., (2022). Policy-relevant Spatial Indicators of Urban Liveability and Sustainability: Scaling from Local to Global. *Urban Policy and Research*, Vol. 40(4), 321–334. <https://doi.org/10.1080/08111146.2022.2076215>.
- [17] Sica, F., De Paola, P., Tajani, F. and Doko, E., (2025). Spatial–Temporal Ontology of Indicators for Urban Landscapes. *Land*, Vol. 14(1). <https://doi.org/10.3390/land14010072>.
- [18] Liakos L. and Panagos, P., (2022). Challenges in the Geo-Processing of Big Soil Spatial Data. *Land*, Vol. 11(12). <https://doi.org/10.3390/land11122287>.
- [19] Kuster, C., (2019). *A Real Time Urban Sustainability Assessment Framework for the Smart City Paradigm (Doctoral Dissertation)*. ORCA–Cardiff University Institutional Repository, Cardiff University. [Online]. Available: <https://orca.cardiff.ac.uk/id/eprint/126015/>. [Accessed Oct. 26, 2025].

- [20] Aungkulanon, P., Montemanni, R., Nanphang, A. and Luangpaiboon, P., (2025). A Data-Driven Informatics Framework for Regional Sustainability: Integrating Twin Mean-Variance Two-Stage DEA with Decision Analytics. *Informatics*, Vol. 12(3). <https://doi.org/10.3390/informatics12030092>.
- [21] Xu, Z. and Li, Q., (2014). Integrating the Empirical Models of Benchmark Land Price and GIS Technology for Sustainability Analysis of Urban Residential Development. *Habitat International*, Vol. 44, 79–92. <https://doi.org/10.1016/j.habitatint.2014.04.012>.
- [22] Nyussupova, G., Aidarkhanova, G., Kenespayeva, L. and Kelinbayeva, R., (2023). Gender Features of the Kazakhstan Labour Market in the Context of Sustainable Development. *Hungarian Geographical Bulletin*, Vol. 72(1), 59–74. <https://doi.org/10.15201/hungeobull.72.1.4>.
- [23] Bektemyssova, G., Bykov, A., Moldagulova, A., Omarov, S., Shaikemelev, G., Nuralykyzy, S. and Umutkulov, D., (2025). Analysis of Spatial Aggregation and Activity of the Urban Population of Almaty Based on Cluster Analysis. *Sustainability*, Vol. 17(7). <https://doi.org/10.3390/su17073243>.
- [24] United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP). (2023). *Geospatial Solutions for Sustainable Development*. [Online]. Available: <https://www.unescap.org/blog/geospatial-solutions-sustainable-development>. [Accessed Oct. 26, 2025].
- [25] Abreu, I., Nunes, J. M. and Mesias, F. J., (2019). Can Rural Development Be Measured? Design and Application of a Synthetic Index to Portuguese Municipalities. *Social Indicators Research*, Vol. 145(3), 1107–1123. <https://doi.org/10.1007/s11205-019-02124-w>.
- [26] Alberti, M., (2017). Grand Challenges in Urban Science. *Frontiers in Built Environment*, Vol. 3. <https://doi.org/10.3389/fbuil.2017.00006>.