

“Sustainable urban development: An integrated assessment of Kazakhstani cities”

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SUSTAINABLE URBAN DEVELOPMENT: AN INTEGRATED ASSESSMENT OF KAZAKHSTANI CITIES

Abstract

Rapid urbanization has increased pressure on urban systems, creating challenges related to resource efficiency, waste management, and environmental protection. These challenges are particularly acute for Kazakhstan, where cities differ substantially in their resource use, environmental conditions, infrastructure, and socioeconomic characteristics. This study aims to conduct a comparative assessment and identify the key characteristics of urban metabolic profiles and sustainable development in Kazakhstani cities. A simplified resource-flow assessment and a comprehensive urban sustainability assessment were conducted for 13 cities in Kazakhstan using 2021 data, the recent year with the most comprehensive and comparable city-level data for both assessment approaches. The results demonstrate substantial heterogeneity in sustainable development performance. The integral sustainability index ranges from 0.28 for Karagandy to 0.71 for Aktau. Five of the 13 cities demonstrate a moderately high level of sustainability (Aktau, Zhezkazgan, Pavlodar, Petropavl, and Taraz), while eight have a moderately low level. The environmental, infrastructure, and socioeconomic sub-indices range from 0.29 to 0.94, 0.25 to 0.75, and 0.00 to 0.86, respectively, indicating pronounced differences in environmental conditions, infrastructure, and socioeconomic capacity. The study of metabolic profiles and risks to sustainable development took into account the availability and quality of energy resources consumed, water consumption and availability, and air quality. The prevalence of precarious employment and wage levels were considered as indirect indicators of the intensity of metabolic processes. Groups of cities with limited access to cleaner thermal energy sources, industrial cities, cities with socioeconomic vulnerability, and cities with moderate water balances were identified. Based on these profiles, recommendations were formulated to support more integrated urban development.

Keywords

sustainable development, urban metabolism, resources, waste, infrastructure, ecology, Kazakhstan

JEL Classification

R00, Q01, Q50

INTRODUCTION

Urbanization is a defining phenomenon of the modern era. Its significance extends far beyond the increasing share of the population living in urban areas. Urbanization reshapes employment structures, production systems, patterns of natural resource consumption, waste generation, urban sustainability, and the role of cities as key drivers of national economic growth. At the same time, the expansion of urban systems gives rise to a range of socio-demographic, technological, and environmental challenges, while strengthening the influence of cities on broader regional and national development trajectories.

Modern cities are complex socio-economic and ecological systems characterized by a high spatial concentration of economic activity and human capital, intensive resource consumption, and substantial waste generation. The impacts of urban activities extend far beyond city boundaries, influencing entire regions. Against the backdrop

of accelerating climate change and resource depletion, achieving sustainable urban development has become a major concern for both researchers and policymakers. Accordingly, Sustainable Cities and Communities (SDG 11) has been recognized as a core United Nations Sustainable Development Goal.

Kazakhstan is a moderately urbanized country undergoing accelerated urbanization. As of June 1, 2026, the country's population reached 20,575,979, with 63.9% living in urban areas. In Kazakhstan, cities account for 85.6% of water use, while water-use efficiency is estimated at USD 10/m³ (BNS, 2025). The share of municipal solid waste that is recycled or otherwise processed is 30%, whereas only 19% of urban landfills comply with environmental and sanitary standards (BNS, 2025a).

Despite the growing importance of this process, relevant research remains fragmented. Existing literature focuses primarily on demographic dimensions or on megacities within the urban metabolism framework. Comparatively less attention has been paid to the structural development and differentiation of regional urban systems, as well as their complex interactions with surrounding socio-economic and environmental contexts.

1. LITERATURE REVIEW AND HYPOTHESIS

Research on the economic, environmental, and social dimensions of urban development is underpinned by several fundamental concepts that have shaped integrated approaches to the analysis of urban systems. Urban metabolism (UM), introduced by Wolman (1965), conceptualizes the city as an open system that consumes resources, transforms them through economic and social activity, accumulates stocks, and generates wastes and emissions. Subsequent research broadened this interpretation. Kennedy et al. (2011), in their comprehensive review, showed that urban metabolism can provide information relevant to sustainability, including energy efficiency, material recycling, waste management, and infrastructure, while Broto et al. (2012) emphasized the dynamic and interdisciplinary character of flows of energy, materials, food, waste, and social resources within urban systems. This interpretation reflects the complex interaction of environmental, social, economic, and infrastructural factors within urban systems, as well as the methodological limitations faced by urban metabolism research.

Regional and territorial metabolism is an emerging field of research. Verger et al. (2018) define territorial metabolism as the flows and stocks of material and energy that sustain human activity within a territory, connecting consumption to sustainable development and its local and global environmental impacts. Similarly, Ferretto et al.

(2024) approach territorial metabolism by analyzing material flows and quantifying the environmental trade-offs of waste transformation. Silva et al. (2020) highlight the critical role of cities in global sustainability, arguing that assessment must extend beyond the urban scale. They identify key methodological limitations in urban metabolism that currently hinder the practical implementation of the theory. These include a lack of a unified methodology, limited availability of city-level data, and insufficiently detailed classifications of material types, flows, stocks, and imported and exported materials. The expansion from urban to territorial metabolism therefore reflects an important shift in literature: resource flows are increasingly considered in relation to the wider territories, supply chains, and socioeconomic systems on which cities depend.

Sustainable development provides a complementary framework centered on the long-term balance between economic development, social well-being, and environmental constraints. Since the publication of the Brundtland Commission report, the concept has been applied at national, regional, and urban scales (Lützkendorf & Balouktsi, 2017). According to the United Nations (UN, 2015), although urban areas occupy only 3% of the Earth's land surface, they generate approximately 60% of global GDP, account for around 75% of global CO₂ emissions, consume nearly 80% of the world's energy, and use more than 60% of global resources. Sustainable development is generally understood as a continuous process grounded in intergenera-

tional equity and the balance between socio-economic objectives and environmental constraints (Xu et al., 2018). This framework provides a methodological basis for developing sustainability indicators and assessing long-term urban development trajectories.

Urban resilience is a related but distinct concept that refers to a city's capacity to maintain essential functions and public well-being amid external and internal shocks through adaptation, flexibility, and a balance between autonomy and connectivity (ARUP, 2019; Allan & Bryant, 2011; Singh, 2024). Unlike approaches focused on individual hazards, resilience emphasizes the ability of urban systems to function under multiple and uncertain risks by reducing vulnerability and strengthening adaptive capacity. In this sense, urban resilience is an important component of, rather than a synonym for, long-term urban sustainability.

The circular economy adds a resource-management perspective to this framework. Although the concept of the circular economy emerged in the 1960s, no universally accepted definition exists. Nonetheless, its core principles, centered on resource circulation, recovery, and reuse, align closely with urban metabolism (Reike et al., 2018). Murray et al. (2017) argue that the circular economy primarily focuses on redesigning production and consumption systems to maintain material flows. However, they also note key limitations, particularly the insufficient integration of the social dimension, which is fundamental to sustainable development. Similar constraints persist within urban metabolism models.

Since the early 2000s, the literature has increasingly integrated these concepts. Sviden and Jonsson (2001) and Barles (2009, 2010) linked urban metabolism to sustainable urban development and emphasized that cities should be examined in relation to their surrounding regions and external supply areas. Bahers et al. (2020) demonstrated the importance of metabolic relationships between cities and their hinterlands, while Talandier and Donsimoni (2022) connected material and energy flows with territorial economics, employment dynamics, and industrial development. Pakina and Mukhamedina (2023) and Brüning-González et al. (2025) identify urban metabolism as a framework

for sustainable urban planning and policy. Taken together, these studies suggest that urban metabolism is most informative for sustainability assessment when physical resource flows are interpreted alongside environmental pressures, infrastructure conditions, and socio-economic characteristics rather than treated as an isolated accounting exercise.

Recent urban research increasingly integrates sustainability with urban metabolism, extending metabolic analysis beyond city boundaries to regional and territorial scales. This spatial and conceptual expansion strengthens the methodological foundation of urban metabolism by mitigating data fragmentation, opacity, and lack of standardization. Merging circular economy principles and urban metabolism tools with the core dimensions of sustainable development provides a robust framework for holistic and adaptable urban assessment.

The literature reveals two main groups of assessment approaches. The first comprises composite urban assessment frameworks integrating environmental, social, economic, and infrastructural dimensions. Examples include the Green City Index (Siemens, 2012), the UN SDG 11 framework (UN-Habitat, 2020), and OECD urban sustainability metrics (OECD, 2022). These approaches support comparative analysis, the identification of spatial and sectoral imbalances, and the establishment of policy priorities. Composite indices are also widely used to assess specific dimensions of urban performance, including quality of life and the capacity of urban systems to respond to risks and crises (Narieswari et al., 2019; Kim et al., 2023). However, their application depends strongly on the availability, comparability, and standardization of city-level data. Within this group, the SDEWES Index provides a more resource- and energy-oriented assessment of urban sustainability across seven domains, ranging from energy and climate to social welfare and policy innovation (Pakina & Mukhamedina, 2023). Its particular strength lies in linking environmental and energy-related indicators with socio-economic dimensions of urban development.

The second group is metabolic assessment frameworks and methods. Material Flow Analysis (MFA) remains the cornerstone of urban metabo-

lism research, accounting for physical mass/energy flows and stocks within defined spatial boundaries (Brunner & Rechberger, 2016; Zhang, 2013). Standardized MFA protocols facilitate transparent cross-border comparative analysis (Eurostat, 2018; OECD, 2022; IRP, 2020). Beyond MFA, urban metabolism research uses complementary approaches that assess specific substances, environmental impacts, resource-conversion efficiency, or ecological carrying capacity. However, these methods often require detailed and spatially consistent datasets, which limits their application in comparative city-level studies under conditions of data scarcity. Although MFA scales effectively from municipal to territorial levels (Roemers, 2024; Deng et al., 2023), García-Guaita et al. (2018) note its limitations in directly measuring environmental impacts despite mass-balance accuracy. To address these data-intensive requirements, García-Guaita et al. (2018) propose a simplified MFA approach for data-scarce contexts, enabling comparative environmental profiling and informed decision-making.

Empirical metabolic research in Kazakhstan focuses predominantly on major metropolises due to administrative statistical availability, whereas secondary cities face acute data constraints. Key developments include the initial application of the SDEWES Index to Astana (Pakina & Mukhamedina, 2023), assessments of construction-driven resource consumption (Atakhanova & Baigaliyeva, 2025), and Almaty's circular economy baseline assessment led by an international consortium including UNDP, UNEP, ADB, and EBRD (Hoogzaad, 2019). Given limited localized data, combining urban metabolic tools with broader multidimensional sustainability frameworks offers a pragmatic strategy for regional urban evaluations.

This study aims to conduct a comparative assessment and identify key characteristics of urban metabolic profiles and sustainable development in Kazakhstani cities. The study hypothesizes that

H1: Under conditions of data scarcity, combining a simplified resource-flow assessment with a comprehensive sustainability evaluation can reveal differences in metabolic patterns and sustainable development risks across Kazakhstan's cities.

2. METHOD

Informed by current urban sustainability and metabolism literature, this study integrates two complementary methodologies to compare urban sustainability performance across Kazakhstan. The sample comprises 13 regional administrative centers, with the urban administration serving as the statistical unit. Empirical data were drawn from regional branches of the National Bureau of Statistics for 2021, representing the latest period with consistent municipal-level accounting for energy generation, fuel consumption, and environmental metrics.

Empirical data were drawn from regional branches of the National Bureau of Statistics for 2021. This year was selected because it represents the most recent period for which a sufficiently complete and comparable set of city-level indicators was available across all 13 regional administrative centers and for both assessment approaches. More recent data are fragmented, unavailable for some cities, or reported only at the regional or national level, which would reduce cross-city comparability. The use of a single reference year therefore ensured methodological consistency between the simplified resource-flow assessment and the Urban Sustainability Index.

To overcome statistical data gaps, we constructed a simplified resource-flow framework based on MFA. The model integrates urban structural parameters (land area, population size, total housing stock, and housing development rate), input flows (electricity, thermal energy, motor fuel, liquefied gas, and food supply), and output flows (wastewater volume, municipal solid waste, and point-source air emissions). All flow metrics were standardized to ensure cross-city comparability (Table 1), offering a data-lean strategy for mapping metabolic profiles and defining strategic directions for urban transformation.

The second methodology evaluates multidimensional urban performance via a composite Urban Sustainability Index. To preserve methodological alignment, the index relies on identical 2021 statistical baseline data. The overall index aggregates three structural sub-indices (Table 2): (1) an Environmental sub-index, accounting

for metabolic environmental pressures; (2) an Infrastructure sub-index, assessing utility and engineering grid coverage; and (3) a Socio-economic sub-index, capturing demographic and economic drivers of metabolic throughput.

An equal-weighting scheme was applied across sub-indices to mitigate weighting subjectivity and ensure robust benchmarking. The mathematical formulation of the composite index is as follows:

$$USI_i = \frac{1}{3} \sum_{k=1}^3 SI_{ik}, \quad (1)$$

where USI_i is the urban sustainability index i ; SI_{ik} is the subindex k of the analytical block for the region; 3 is the number of analytical blocks. Range: $0 \leq USI_i \leq 1$.

Since no universally accepted threshold values exist for composite urban sustainability indices, the normalized composite index was interpreted using equal-width intervals across [0, 1]. Designed exclusively for descriptive and comparative purposes, these categories do not represent absolute sustainability benchmarks. The classification system was structured as follows:

- 0.00 to 0.25 – low level of metabolic and socio-economic sustainability, characterized by

high resource load with limited socio-economic results;

- 0.26 to 0.50 – moderately low level, reflecting structural imbalances between resource consumption and the quality of urban development;
- 0.51 to 0.75 – moderately high level, indicating relatively efficient use of resources and favorable socio-economic conditions;
- 0.76 to 1.00 – high level of sustainability characterized by a balanced combination of resource efficiency and socio-economic outcomes.

To ensure cross-city comparability, all indicators underwent min-max normalization, bounding values within the [0, 1] range. Positive indicators (where higher values represent preferable outcomes) were rescaled using linear normalization via Equation (2), whereas negative indicators (where lower values are desirable) were transformed using inverse normalization via Equation (3):

$$x_{ij}^* = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}, \quad (2)$$

Table 1. Data for comparative resource-flow profile of Kazakhstani cities

Source: Our compilation based on data from regional departments of the Bureau of National Statistics.

Cities	Drivers				Inputs				Outputs		
	City area, km ²	Population, people	Housing stock, thousand m ²	Housing construction, thousand m ²	Water, tons	Food, tons	Thermal and electrical energy, TJ	Fuel (gasoline, diesel, propane) total, tons	Waste, tons	Wastewater, tons	Stationary source emissions, tons
Aktau	298	209742	6550	640	63412300	175746	33897	121083	60387	13431300	19300
Aktobe	2338	518335	11593	906	26903400	556385	28096	258045	212965	18749100	31463
Atyrau	3500	369951	9467	669	17461000	299120	25017	318605	165423	9831300	27917
Zhezkazgan	8589	91781	1816	26	16864200	78747	8914	28235	16824	15046200	58400
Karagandy	499	502030	11637	413	58771200	420348	28385	258265	222888	22808600	49800
Kostanay	281	325100	5968	118	15519200	304016	7015	230081	93485	13081400	15970
Kyzylorda	2400	343 200	7575	397	15756000	66092	7689	146755	37068	8308800	17229
Pavlodar	633	361765	7991	192	78489600	361961	48682	176222	347947	31072100	190600
Petropavl	225	219634	4755	220	12978000	177576	17468	73452	61398	21679000	30272
Semey	27500	350584	6318	224	16735300	282242	10477	97166	54150	13078900	24000
Taraz	188	365529	7395	336	20224000	355371	11384	106323	75947	18021400	29200
Oral	731	320726	7386	411	21157300	314191	5685	304680	103472	9773600	8233
Oskemen	540	349838	7206	205	37166800	346630	27167	387574	66648	36377900	54000

Table 2. Indicators of the Urban Sustainability Index (USI)

Source: Our compilation based on data from regional departments of the Bureau of National Statistics.

Cities, indicator characteristics	Environmental subindex			Infrastructure subindex			Socio-economic subindex	
	Average annual concentration of suspended particles PM- 2.5 in atmospheric air (mg/m3)	Air Pollution Index (API), units	Deviation of the annual average air temperature from the 1961–1990 baseline, +C°	Housing stock, m ² /person	Available groundwater reserves, cubic meters per day per capita	Quality of available energy resources for household heat generation (CO ₂ equivalent, tons per year per capita)	Vulnerable employment, %	Average nominal wage per employee (USD)
Code	B1	B2	B3	B4	B5	B6	B7	B8
Type	negative	negative	negative	Positive	positive	negative	negative	positive
Max	0.152	11	2.6	31.2	5.21	6	31.7	936
Min	0.0013	2	0.9	18.0	0.39	1	0.10	460
Aktau	0.010	6	2	31.2	0.54	1.1	0.10	806
Aktobe	0.126	7	2.1	22.4	2.14	0.9	13.6	510
Atyrau	0.088	7	2.6	25.6	0.40	1.4	17.5	936
Zhezkazgan	0.011	6	1.1	19.8	2.47	1.2	7.3	664
Karagandy	0.152	11	1.1	23.2	2.11	6.1	15.7	513
Kostanay	0.100	4	1.6	18.4	1.72	1.1	27.8	477
Kyzylorda	0.001	3	2.3	22.1	1.30	1.4	20.1	516
Pavlodar	0.010	3	0.9	22.1	5.21	1.0	10.1	502
Petropavl	0.002	3	1	21.6	0.39	1.7	13.7	503
Semey	0.010	2	1.2	18.0	5.14	5.3	31.7	460
Taraz	0.030	5	1.6	20.2	4.12	0.7	22.6	628
Oral	0.004	2	2.5	23.0	0.51	1.3	17.5	476
Oskemen	0.025	7	1.2	20.6	4.45	5.8	13.1	575

$$x_{ij}^* = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}, \quad (3)$$

$$\sum_{j=1}^{m_k} w_{jk} = 1. \quad (5)$$

where x_{ij} is the actual value of the indicator j for the region i , $\min(x_j)$, $\max(x_j)$ are the minimum and maximum values of the indicator j in the sample; x_{ij}^* is the normalized value of the indicator, $0 \leq x_{ij}^* \leq 1$. To construct sub-indices for each analytical domain, normalized indicators were aggregated applying an equal-weighting scheme, calculated via the arithmetic average in Equation (4):

$$SI_{ik} = \frac{1}{m_k} \sum_{j=1}^{m_k} x_{ij}^*, \quad (4)$$

where SI_{ik} represents the aggregate sub-index value for analytical dimension k in city i ; x_{ij}^* denotes the normalized score of indicator j for city i , w_{jk} signifies the weighting factor assigned to indicator j within dimension k , m_k is the total count of indicators comprising dimension k ; the weighting vectors satisfy the normalization constraint:

Equal weighting was adopted due to the lack of consensus in theoretical and empirical literature regarding differential component prioritization across Kazakhstani regions. This approach aligns with the OECD Handbook on Constructing Composite Indicators, which endorses equal weighting as a transparent baseline when no definitive theoretical rationale exists for alternative weighting schemes (OECD, 2008). Equivalent schemes are broadly applied in urban planning (Desogus et al., 2024) and composite sustainability indexing (Murphy et al., 2023; Blancas & Contreras, 2025; Guo et al., 2024). Despite the availability of complex weighting techniques, equal weighting offers distinct advantages in transparency, mathematical reproducibility, and mitigation of investigator bias.

Integrating these two complementary frameworks enables a more holistic urban evaluation, effec-

tively bridging traditional sustainability metrics with metabolic throughput analysis.

3. RESULTS

The simplified resource-flow assessment highlights pronounced spatial disparities in metabolic profiles (Table 3). These variations emerge across both total resource throughput and normalized flow metrics, driven by regional climatic conditions, local economic specialization, and demographic dynamics.

To gain a deeper understanding of current urban metabolic profiles, it is necessary to examine key indicators representing environmental quality, ecological impacts of resource throughput and emissions, natural resource reserves, and energy infrastructure capacity. To this end, the selected indicators were incorporated into the comprehensive assessment framework (Table 2).

The normalized indicators are presented in Table 4, while the calculated sub-indices and composite index values are summarized in Table 5. The composite sustainability index reveals that the evaluated cities fall within the range of moderately low to moderately high sustainability levels. Indicators B3, B5, and B6 highlight key environmental challenges faced by cities, particularly under climate change impacts, water scarcity, and national decarbonization commitments. Importantly, the relevance of these metrics extends beyond municipal

administrative boundaries. Cities are inherently embedded in regional metabolic systems, where baseline environmental conditions constrain local metabolism and define the operational framework for executing sustainable urban policies.

Indicator B3 measures regional mean annual temperature anomalies relative to the 1961–1990 baseline. Spatially heterogeneous warming patterns may trigger climatic migration, with the sharpest thermal increases concentrated in hydrocarbon-producing western regions (encompassing Aktau, Atyrau, Aktobe, Kyzylorda, and Oral). As World Bank assessments highlight, regional warming, exceeding global average rates, combines with freshwater depletion and extreme weather events to pose major systemic threats to national sustainability (World Bank, 2021). Accelerating hydrological shifts are expected to temporarily heighten flood risks before causing sustained reductions in river flow. At the same time, increased mudflow frequency risks destabilizing infrastructure across more than 150 Kazakhstani urban and rural communities (World Bank, 2021).

Access to water resources, both present and future, serves as a critical determinant of regional and urban development prospects across Kazakhstan. Because groundwater reserves are unevenly distributed nationwide, localized access to aquifers provides distinct comparative advantages for urban growth.

Among the examined municipal centers, Aktau, Pavlodar, and Zhezkazgan exhibit the highest per

Table 3. Comparative resource-flow assessments of Kazakhstani cities

Cities	Housing stock, m ² /person	Housing construction, m ² /person	Water, m ³ /person	Energy, GJ/person	Fuel, kg/person	Waste, kg/person	Wastewater, m ³ /person	Emissions, kg/person
Aktau	31.23	3.05	302.33	161.61	577.30	287.91	64.04	92.02
Aktobe	22.37	1.75	51.90	54.20	497.83	410.86	36.17	60.70
Atyrau	25.59	1.81	47.20	67.62	861.21	447.15	26.57	75.46
Zhezkazgan	19.79	0.29	183.74	97.13	307.63	183.31	163.94	636.30
Karagandy	23.18	0.82	117.07	56.54	514.44	443.97	45.43	99.20
Kostanay	18.36	0.36	47.74	21.58	707.72	287.56	40.24	49.12
Kyzylorda	22.07	1.16	45.91	22.40	427.61	108.01	24.21	50.20
Pavlodar	22.09	0.53	216.96	134.57	487.12	961.80	85.89	526.86
Petropavl	21.65	1.00	59.09	79.53	334.43	279.55	98.71	137.83
Semey	18.02	0.64	47.74	29.89	277.15	154.46	37.31	68.46
Taraz	20.23	0.92	55.33	31.14	290.87	207.77	49.30	79.88
Oral	23.03	1.28	65.97	17.73	949.97	322.62	30.47	25.67
Oskemen	20.60	0.59	106.24	77.66	1 107.87	190.51	103.98	154.36

Table 4. Normalized indicators of the Urban Sustainability Index

Cities	Environmental subindex			Infrastructure subindex			Socio-economic subindex	
	Average annual concentration of suspended particles PM-2.5 in atmospheric air (mg/m ³)	Air Pollution Index (API), units	Deviation of the annual average air temperature from the 1961–1990 baseline, +°C	Housing stock, m ² /person	Available groundwater reserves, cubic meters per day per capita	Quality of available energy resources for household heat generation (CO ₂ equivalent, tons per year per capita)	Vulnerable employment, %	Average nominal wage per employee (USD)
Code	B1	B2	B3	B4	B5	B6	B7	B8
Aktau	0.94	0.56	0.35	1.00	0.03	0.93	1.0	0.73
Aktobe	0.17	0.44	0.29	0.33	0.36	0.96	0.6	0.10
Atyrau	0.42	0.44	0.00	0.57	0.00	0.86	0.4	1.00
Zhezkazgan	0.94	0.56	0.88	0.13	0.43	0.91	0.8	0.43
Karagandy	0.00	0.00	0.88	0.39	0.36	0.00	0.5	0.11
Kostanay	0.35	0.78	0.59	0.03	0.28	0.92	0.1	0.03
Kyzylorda	1.00	0.89	0.18	0.31	0.19	0.87	0.4	0.12
Pavlodar	0.94	0.89	1.00	0.31	1.00	0.94	0.7	0.09
Petropavl	1.00	0.89	0.94	0.27	0.00	0.81	0.6	0.09
Semey	0.94	1.00	0.82	0.00	0.99	0.13	0.0	0.00
Taraz	0.81	0.67	0.59	0.17	0.77	1.00	0.3	0.35
Oral	0.98	1.00	0.06	0.38	0.02	0.89	0.4	0.03
Oskemen	0.84	0.44	0.82	0.20	0.84	0.04	0.6	0.24

Table 5. Comprehensive assessment of urban sustainability

Cities	Sub-indices			USI	Levels of sustainability	Metabolic features and risks of sustainable development
	SI _{env}	SI _{infr}	SI _{socecon}			
Aktau	0.62	0.65	0.86	0.71	moderately high level	Low water availability. High energy intensity of water desalination. Temperature increase
Aktobe	0.30	0.55	0.34	0.40	moderately low level	High levels of air pollution. Rising temperatures. Risks of contamination of the freshwater fields by the oil and gas industry
Atyrau	0.29	0.48	0.72	0.50	moderately low level	Fuel flow dominance. High air pollution. High emissions from stationary sources. Temperature increase
Zhezkazgan	0.79	0.49	0.60	0.63	moderately high level	High per capita and absolute emissions from stationary sources and water losses. No access to clean thermal energy sources. Large water losses
Karagandy	0.29	0.25	0.31	0.28	moderately low level	High CO ₂ emissions. High air pollution. No access to clean thermal energy sources. Urban metabolism is determined by coal generation. Vulnerable water balance
Kostanay	0.57	0.41	0.08	0.35	moderately low level	Fuel flow dominance Low access to quality jobs and high levels of precarious employment
Kyzylorda	0.69	0.46	0.24	0.46	moderately low level	Temperature increase. Water resource shortage
Pavlodar	0.94	0.75	0.39	0.69	moderately high level	High per capita and absolute emissions from stationary sources and water losses. No access to clean thermal energy sources
Petropavl	0.94	0.36	0.33	0.54	moderately high level	Mixed metabolic profile. High CO ₂ emissions. No access to clean thermal energy sources
Semey	0.92	0.37	0.00	0.43	moderately low level	No access to clean thermal energy sources. Low access to quality jobs and high levels of precarious employment

Table 5 (cont.). Comprehensive assessment of urban sustainability

Cities	Sub-indices			USI	Levels of sustainability	Metabolic features and risks of sustainable development
	SI _{env}	SI _{infr}	SI _{socioecon}			
Taraz	0.69	0.65	0.32	0.55	moderately high level	Relatively low metabolic rate. Air and water pollution risks associated with the chemical industry. Temperature increase. Dependence on transboundary rivers. Risks of pollution of the Merke freshwater reservoir by industry
Oral	0.68	0.43	0.24	0.45	moderately low level	Fuel flow dominance. Temperature increase
Oskemen	0.70	0.36	0.41	0.49	moderately low level	Metabolic profile is shaped by the metallurgical industry, air pollution, and water pollution. No access to clean thermal energy sources. High air pollution

capita water consumption. Aktau suffers from acute freshwater scarcity. Located in an arid desert climate with mean annual precipitation of approximately 150 mm and summer temperatures reaching +42°C, the city has no natural surface freshwater sources. Groundwater resources remain underutilized because they are remote from major urban centers such as Aktau and Zhanaozen and lack water-supply pipelines. Deep mineral and geothermal groundwater sources occur at depths of up to 1,000 meters. As a result, the pressure on desalination facilities increases sharply, particularly during the summer months.

Consequently, Aktau relies entirely on Caspian Sea desalination plants and long-distance groundwater transfers. These geographical constraints shape Aktau's metabolic profile: high energy intensity driven by desalination requirements, low baseline hydrological availability, and heavy pressures on atmospheric and soil systems. Despite these constraints, per capita water consumption remains exceptionally high, driven by rapid housing construction and Aktau's emerging role as an international tourism gateway. Aktau's urban metabolism can thus be characterized as highly resource- and energy-intensive.

Conversely, elevated water throughput in Pavlodar and Zhezkazgan stems primarily from aging municipal utility infrastructure and industrial specialization rather than demographic growth. In Pavlodar, water supply network decay rates reach approximately 85%, resulting in extensive conveyance losses, exacerbated by some of the lowest water tariffs in the country. A similar pattern occurs in Zhezkazgan, where high per capita consumption is driven by distribution losses across degraded networks, coupled with a 90% degradation rate

at municipal water treatment facilities. Facility reconstruction has dragged on for over a decade, largely because design capacities were repeatedly revised downward due to sustained population outmigration.

Cities remain strongly influenced by external regional energy topologies. Kazakhstan's municipal centers access energy flows through regional grids, where the lack of a unified national natural gas pipeline constrains decarbonization efforts. While Aktau and Atyrau depend exclusively on natural gas, six cities (Semey, Karagandy, Pavlodar, Petropavl, Zhezkazgan, and Oskemen) rely solely on hard coal, and five cities use a dual coal-gas mix. Because of these infrastructure bottlenecks, municipalities remain locked into carbon-intensive energy structures. For comparative evaluation, natural gas and hard coal throughput data were converted into standard CO₂ emission equivalents. Natural gas distribution shows marked spatial disparities: western and southern regions have more modern gas infrastructure, while northern and central cities face structural energy constraints, driving higher consumption of liquefied petroleum gases (propane and butane).

Urban metabolic dynamics are closely intertwined with socio-economic conditions. Accordingly, housing provision per capita was incorporated as a core sustainability indicator, with 30 m² of living space per person used as a reference value (R. Anker & M. Anker, 2017). While several Kazakhstani cities have achieved this reference value, Semey and Zhezkazgan lag, historically impacted by the revocation of their regional administrative status in 1997, which triggered population outflows and infrastructure stagnation. Similarly, Petropavl, Pavlodar, and Kostanay show low resi-

dential construction rates. Suppressed construction activity reflects broader deceleration in metabolic throughput and economic velocity.

Furthermore, SDG-aligned metrics such as vulnerable employment (measured via self-employment rates) reflect economic resource demand. High self-employment levels in Semey, Kostanay, Taraz, and Kyzylorda indicate lower metabolic intensity within the local formal economy. Semey has the lowest socio-economic sub-index value in the sample ($SI_{soecon} = 0.00$), reflecting its unfavorable relative position in terms of vulnerable employment and average nominal wages.

Overall, composite sustainability index calculations place the studied cities within the moderately low to moderately high sustainability performance tiers. Aktau achieved the highest overall score (0.71), driven by socio-economic performance, specifically formal employment dominance, higher wage levels, robust residential construction, and transition toward cleaner and renewable energy sources.

4. DISCUSSION

The integrated assessment demonstrates that the sustainability of Kazakhstan's cities depends not only on their socio-economic characteristics but also on the interaction between urban systems and regional resource conditions. Comparing the simplified resource-flow assessment with the Urban Sustainability Index (USI) indicates that cities with comparable socio-economic performance may show substantially different patterns of resource consumption and environmental pressures. This finding supports the systems approach to urban sustainability, according to which cities should be considered as open socio-ecological systems exchanging energy, materials, and waste with surrounding regions (Kennedy et al., 2007; Barles, 2009).

One key finding concerns the spatial heterogeneity of climate-related risks. The analysis revealed that western Kazakhstan, including Aktau, Atyrau, Aktobe, Kyzylorda, and Oral, experienced the largest increase in average annual temperature. These results are consistent with data from

the World Bank (2021), which identified Western Kazakhstan as one of the country's most vulnerable regions because of increasing aridity, water scarcity, and extreme weather events. Our findings extend these observations by demonstrating that regional climatic conditions are directly reflected in the metabolic characteristics and sustainability profiles of individual cities.

The assessment of water consumption also revealed substantial differences among cities. Aktau exhibited the highest resource intensity because of its dependence on seawater desalination and limited freshwater availability, whereas elevated water consumption in Pavlodar and Zhezkazgan appears to be associated mainly with aging infrastructure and water supply costs. Similar conclusions have been reported by García-Guaita et al. (2018), who showed that urban water metabolism depends not only on natural resource availability but also on infrastructure efficiency and regional water supply systems. Unlike previous studies that focused primarily on individual cities, our analysis provides a comparative assessment across multiple cities within a single national context, revealing significant regional variation in urban metabolic patterns.

The results further indicate that regional energy infrastructure significantly influences urban sustainability. Cities with greater access to natural gas tend to experience lower environmental pressures than cities that rely primarily on coal. This observation is consistent with the findings of Kerimray et al. (2018), who reported marked regional differences in energy availability and carbon intensity in Kazakhstan. At the same time, our results indicate that differences in energy efficiency are determined not only by fuel mix but also by the effectiveness of regional infrastructure and resource consumption intensity, factors often overlooked in traditional sustainability assessments.

The social dimension of the Urban Sustainability Index highlights the importance of housing conditions and labor market characteristics for sustainable urban development. Cities such as Semey and Zhezkazgan continue to experience lower housing provision and weaker infrastructure development, while Semey, Kostanay, Taraz, and Kyzylorda display relatively high shares of vulnerable employ-

ment. The zero value of the socio-economic sub-index for Semey should be interpreted as a relative minimum within the study sample rather than as an absolute absence of socio-economic sustainability. It highlights the city's particularly vulnerable position in the labor market and income dimensions compared with the other regional centers. These findings are consistent with the broader literature emphasizing that social infrastructure and employment quality are essential components of urban sustainability (UN-Habitat, 2020; OECD, 2020). However, unlike previous studies that analyze these indicators separately, the proposed framework integrates them with environmental and resource-flow indicators, providing a more comprehensive assessment of urban sustainability.

Research on urban sustainability and assessment tools still needs development. At the global level, UN SDG 11 "Sustainable Cities and Human Settlements Indicators" includes 10 targets and 15 global indicators (UN, 2026). It should be noted that these indicators reflect the broader spatial context of urban sustainability, due to the influence of cities well beyond their borders. There are different-sized spatial units and indicators present here, which does not make them less applicable for understanding sustainability. Global indicators are subject to adjustments in national sustainable development strategies. For example, in Kazakhstan's Monitoring the Sustainable Development Goals until 2030 dashboard, SDG 11 reflects five targets, which include seven alternative national indicators, most of which cover the urban population or urban settlements as a whole. For individual cities, only the modified global emissions indicator for PM_{2.5} and PM₁₀ is presented. In addition, countries use different standards for emission levels.

A comparison of the simplified resource-flow assessment and the Urban Sustainability Index provides additional insights into the multidimensional nature of sustainable urban development. Aktau achieved the highest overall sustainability score because of favorable socio-economic conditions, despite severe environmental constraints related to water scarcity and climate vulnerability. Conversely, Kostanay demonstrated relatively favorable environmental characteristics but lower socio-economic performance.

These findings align with previous studies showing that the economic, social, and environmental dimensions of urban sustainability do not necessarily evolve simultaneously and therefore require integrated assessment frameworks rather than reliance on single composite indicators (Kennedy et al., 2007; Muñoz & Navia, 2018). This study confirms this finding for Kazakhstan and underscores the importance of combining metabolic and sustainability-based approaches.

Overall, the findings indicate that neither conventional sustainability indicators nor urban metabolism metrics alone are sufficient for assessing the complexity of urban systems. Their combined application provides a more comprehensive understanding of the interactions between resource consumption, environmental impacts, and socio-economic development. This integrated approach may support evidence-based urban planning and contribute to developing differentiated sustainability policies for Kazakhstan's cities.

Research on urban sustainable development and urban metabolism in Kazakhstan faces several limitations stemming from the current framework of national and regional statistical data collection. First, the cross-sectional nature of the study, based on a single-year baseline (2021), precludes longitudinal trend tracking. Second, four cities were excluded from the sample due to persistent data gaps. Furthermore, data scarcity prevented the calculation of a complete input-stock-output material flow balance. Most indicators within the national SDG 2030 monitoring framework remain aggregated at the national or regional level; material balances for key commodity groups are compiled exclusively nationwide, whereas energy balances are disaggregated by sector only at national and regional scales. Crucially, the absence of city-level data on economic activity in both physical and monetary terms restrict formal evaluations of urban economic diversification, technological adaptation, and growth dynamics. Finally, data collection was highly labor-intensive because regional statistics are fragmented across separate departmental portals, predominantly published in non-machine-readable formats, and subject to periodic classification changes across reporting cycles.

CONCLUSION

This study aims to conduct a comparative assessment and identify key characteristics of urban metabolic profiles and sustainable development in Kazakhstani cities. The research hypothesis was confirmed. The analysis revealed substantial intra-national variation across Kazakhstani cities in resource availability, consumption intensity, and associated environmental pressures, enabling the identification of key urban metabolic profiles and systemic vulnerabilities.

As ongoing urbanization reinforces the pivotal role of cities in national development, establishing a standardized national urban data infrastructure becomes critical. Capitalizing on digital transformation, urban data protocols should be standardized to monitor localized material balances (including water, energy vectors, food, and construction materials), alongside open-access emissions and waste registers. To maximize utility for spatial planning and policy-making, these data must be rendered machine-readable and centralized within a unified digital database.

For cities facing structural access limits to low-carbon thermal energy (Karaganda, Pavlodar, Petropavl, Semey, Zhezkazgan, and Oskemen), priority should be given to decarbonizing district heating networks. Recommended interventions include regional gasification and deep thermal retrofitting of building stock. These measures should consider not only environmental gains but also their broader contributions to demographic stability and national spatial connectivity.

In heavily industrialized centers with high stationary air emissions, specifically Karaganda, Pavlodar, and Oskemen, modernizing thermal power infrastructure and upgrading industrial emissions controls are urgently required. For Pavlodar and Zhezkazgan, rehabilitating degraded water conveyance networks and treatment facilities remains paramount.

In socio-economically vulnerable cities (Kostanay, Kyzylorda, Semey, and Taraz), policy should target formal job creation and employment stability through industrial modernization and the expansion of ecosystem services. Finally, for cities facing severe hydrological stress (Aktau and Kyzylorda) alongside rapid thermal anomalies (Aktau, Kyzylorda, Oral, and Atyrau), priorities must focus on reducing distribution grid losses, expanding desalination capacity, and scaling infrastructure for industrial water reclamation and reuse.

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