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Systematic literature review on indices aimed at urban sustainability

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Revisão sistemática da literatura sobre índices voltados à sustentabilidade urbana

RESUMO

Objetivo – Apresentar um estudo bibliométrico sobre os índices voltados à sustentabilidade urbana, com ênfase na identificação dos aspectos mais relevantes para sua elaboração e aplicação.

Metodologia – Foi realizada uma análise bibliométrica de artigos científicos disponíveis nas bases de dados Web of Science e Scopus, no período de 2016 a 2020. O estudo abordou a estrutura dos índices considerando elementos como dimensões, indicadores, métodos de seleção e normalização, atribuição de pesos e técnicas de agregação.

Originalidade/relevância – A pesquisa destaca os desafios existentes na operacionalização de índices compostos por mais de 50 indicadores, devido à escassez de fontes confiáveis de dados e à ausência de padronização metodológica na construção dos índices de sustentabilidade urbana.

Resultados – Os principais achados indicam a predominância do uso do tripé tradicional da sustentabilidade (ambiental, social e econômica), com acréscimos pontuais de dimensões territoriais. Não há consenso sobre os critérios e métodos de seleção dos indicadores. Na atribuição de pesos, observa-se uma preferência por métodos objetivos que reduzem a subjetividade. Quanto aos métodos de agregação, predominam os de cálculo simples.

Contribuições teóricas/metodológicas – O estudo evidencia lacunas teóricas e metodológicas na definição e aplicação dos índices de sustentabilidade urbana, apontando a necessidade de maior rigor e clareza nos processos de construção dos indicadores e de validação das metodologias empregadas.

Contribuições sociais e ambientais – Ao apontar as dificuldades e limitações dos índices existentes, a pesquisa contribui para a formulação de indicadores mais eficazes e aplicáveis à gestão urbana, com potencial de aprimorar políticas públicas e práticas de planejamento urbano voltadas à sustentabilidade.

PALAVRAS-CHAVE: Índice. Desenvolvimento urbano. Planejamento urbano. Sustentabilidade.

Systematic literature review on indexes aimed at urban sustainability

ABSTRACT

Objective – To present a bibliometric study on indexes related to urban sustainability, with an emphasis on identifying the most relevant aspects for their development and application.

Methodology – A bibliometric analysis was conducted based on scientific articles available in the Web of Science and Scopus databases, covering the period from 2016 to 2020. The study addressed the structure of indexes considering elements such as dimensions, indicators, methods of selection and normalization, weight assignment, and aggregation techniques.

Originality/relevance – The research highlights the challenges involved in operationalizing indexes with more than 50 indicators, due to the lack of reliable data sources and the absence of methodological standardization in the construction of urban sustainability indexes.

Results – The main findings indicate the predominance of the traditional sustainability tripod (environmental, social, and economic), with occasional additions of territorial dimensions. There is no consensus regarding the criteria and methods for selecting indicators. In weight assignment, there is a tendency toward objective methods to reduce subjectivity. Regarding aggregation methods, simple calculations are the most commonly used.

Theoretical/methodological contributions – The study reveals theoretical and methodological gaps in the definition and application of urban sustainability indexes, pointing to the need for greater rigor and clarity in the processes of indicator construction and methodology validation.

Social and environmental contributions – By highlighting the difficulties and limitations of existing indexes, the research contributes to the formulation of more effective and applicable indicators for urban management, with the potential to improve public policies and urban planning practices aimed at sustainability.

KEYWORDS: Index. Urban development. Urban planning. Sustainability.

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ISSN 2318-8472, v. 13, n. 88, 2025

Revisión sistemática de la literatura sobre índices dirigidos a la sostenibilidad urbana

RESUMEN

Objetivo – Presentar un estudio bibliométrico sobre los índices orientados a la sostenibilidad urbana, con énfasis en la identificación de los aspectos más relevantes para su elaboración y aplicación.

Metodología – Se realizó un análisis bibliométrico de artículos científicos disponibles en las bases de datos Web of Science y Scopus, en el período comprendido entre 2016 y 2020. El estudio abordó la estructura de los índices considerando elementos como dimensiones, indicadores, métodos de selección y normalización, asignación de pesos y técnicas de agregación.

Originalidad/relevancia – La investigación resalta los desafíos existentes en la operacionalización de índices compuestos por más de 50 indicadores, debido a la escasez de fuentes de datos confiables y a la falta de estandarización metodológica en la construcción de índices de sostenibilidad urbana.

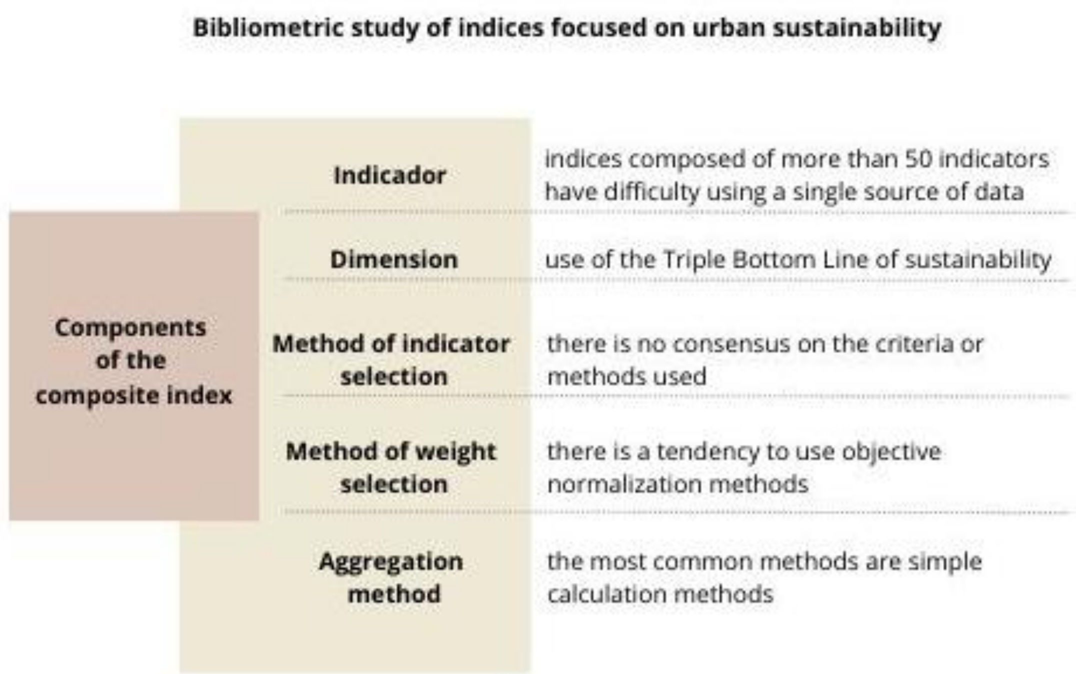
Resultados – Los principales hallazgos indican la predominancia del uso del trípode tradicional de la sostenibilidad (ambiental, social y económica), con añadidos puntuales de dimensiones territoriales. No hay consenso sobre los criterios y métodos utilizados para la selección de indicadores. En la asignación de pesos, se observa una tendencia hacia métodos objetivos que minimicen la subjetividad. En cuanto a los métodos de agregación, predominan los cálculos simples.

Contribuciones teóricas/metodológicas – El estudio evidencia lagunas teóricas y metodológicas en la definición y aplicación de índices de sostenibilidad urbana, señalando la necesidad de mayor rigor y claridad en los procesos de construcción de indicadores y validación de metodologías empleadas.

Contribuciones sociales y ambientales – Al señalar las dificultades y limitaciones de los índices existentes, la investigación contribuye a la formulación de indicadores más eficaces y aplicables a la gestión urbana, con potencial para mejorar las políticas públicas y las prácticas de planificación urbana orientadas a la sostenibilidad.

PALABRAS CLAVE: Índice. Desarrollo urbano. Planificación urbana. Sostenibilidad.

GRAPHIC SUMMARY



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1 INTRODUCTION

The continuous expansion of urban areas places the urbanization process as one of the most significant global trends of the 21st century (UN HABITAT, 2014). Over half the world's population now live in cities. With this figure expected to increase to 68 per cent by 2050, urbanization is one of the world's most transformative and challenging trends (UN HABITAT, 2019, p. 1). As the world continues to urbanize, the sustainability of urban areas must take a central stage in both science and policy arenas (HUANG, WU and YAN, 2015).

The themes "urban development" and "sustainability" have increasingly gained prominence in discussions regarding the challenges faced by contemporary cities. The growth of human settlement in urban areas positions the urbanization process as one of the most significant global trends of the 21st century. Urbanization transcends mere demographic or spatial phenomena; when effectively directed and implemented, it has the potential to address several major global challenges, including poverty, inequality, environmental degradation, climate change, fragility, and conflict (United Nations, 2014). According to Silva *et al.* (2024) territorial transformations present an ideological duality between the pursuit of development, growth and local modernity, in contrast to real city, revealing an unequal context that is inadequate to local needs.

In this context, the range of factors that can influence the development or regression towards sustainability in cities, encourage studies of increasingly precise tools adapted to the diverse realities of cities. As cities invest for competitive advantage, in the global knowledge economy there is a need to quantify, measure, compare, and rank cities based on their performance (BENCKE and PEREZ, 2018).

Therefore, there is currently a range of studies with diverse objectives in the field of urban sustainability performance. These studies address topics such as quality of life, environmental performance, well-being, ecological infrastructure, happiness, smart city, the carrying capacity of urban infrastructures, equity and social inclusion, governance and legislation, city prosperity, and others. In this scenario, rankings are usually justified as valuable tools that policymakers and planners can use to assess sustainability performance and formulate appropriate strategies to guide urbanization towards better sustainability (YANG and JIANG, 2018; ZHENG, 2018; VERNA and RAGHUBANSHI, 2018).

Several researchers have developed methodologies for measuring urban sustainability. Bibliometric review articles were consulted to identify gaps in the existing literature on the subject. Some studies focus on specific issues or engage in discussions regarding concepts integral to urban sustainability. For instance, Clifton *et al.* (2008) conducted a review of multidisciplinary approaches to urban form, while Zhang, Ghosh, and Park (2023) analyzed the relationships between urban morphology and sustainability across 89 articles using quantitative methods. Mori and Christodoulou (2012) discuss the conceptual requirements for a City Sustainability Index that can assess the external impacts (leakage effects) of cities in indoor areas. Michael *et al*. (2014) bibliometric review gathered lists of urban indicators aimed at Asian countries. Musa *et al.* (2020) evaluated 44 scientific articles to review the domains and dimensions aimed at community well-being. Additionally, Goodwin *et al.* (2021) carried out 39

ISSN 2318-8472, v. 13, n. 88, 2025

sustainability assessments of cities between 2017 and 2020 to evaluate the limits of increasing risks, including those related to carbon, water, and land use, with a particular emphasis on environmental issues.

In other studies, a focus on methodological analysis for the development of indices is evident. In 2008, Munier conducted a bibliometric review aimed at identifying the optimal set of indicators through the application of linear programming. Huang, Wu and Yan (2015) carried out the review of ten studies, providing a qualitative analysis that encompasses the primary concepts of urban sustainability, including indicators, normalization scales, weighting, and aggregation methods (such as sum, simple average and weighted average) commonly used to measure the state and progress of urban sustainability. Cohen (2017) performed a quantitative analysis to identify the most common methods used to assess urban sustainability, focusing on identifying common frameworks for assessment and categorizing indicators that measure urban sustainability. Verma and Raghubanshi (2018) qualitatively evaluated the contents of the indicator selection methodologies and indicator calculations. Kaur and Garg (2019) qualitatively analyzed 105 studies using the Prism Flow Diagram, identifying key content areas such as category/theme, indicators, weight, and performance rating scale. Sáez, Heras-Saizarbitoria and Rodríguez-Núñez (2020) conducted qualitative research to analyze and evaluate current practices from a methodological perspective based on benchmarks (BPs). Kong, Liu, and Wu (2020) undertook a systematic review, following the frameworks established by Khan *et al.* (2003) and Liberati *et al.* (2009) with the aim of summarizing "urban environment, society and sustainability research" in big data.

There are many challenges for the development of indices or indicators aimed at urban sustainability, including: the form of data collection (MAYER, 2008); gaps in the comparability of indicators (SCHIAVINA *et al.* 2019); the different spatial scales (PUTZHUBER and HASENAUER, 2010; HUANG, WU and YAN, 2015); data scarcity, weighting of indicators, lack of consensus on the concept of sustainability as well as definitions of indicators (HUANG, WU and YAN, 2015); and the complexity or excessive simplicity of measurement, along with a lack of theoretical foundations (VERNA and RAGHUBANSHI, 2018).

2 OBJECTIVE

Even though the use of indices and indicators based on urban development has been widely explored, to seek effectiveness in achieving the objectives of public policies through the use of these tools remains a necessity in this field. Having in mind the range and complexity of the analysis within the scope that involves urban reality in the pursuit of sustainable development, the objective of this article is to carry out an updated quantitative analysis to feature the indexes aimed at urban sustainability. This analysis will address the components of the index, such as: dimension, indicator, indicator selection method, normalization method, weight selection, calculation method, and aggregation method.

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 88, 2025

3 METHODOLOGY

The research was developed through a systematic literature review, using the search databases *Web of Science* and *Scopus*. The selected time frame encompassed publications from 2016 to 2020, including articles published in 2021 up to the date of the research (8/4/2021). Only peer-reviewed journal articles published in English were considered.

The search terms used were: (index or indicator) and ("sustainable urban development" or "urban sustainability") within the title, abstract or keywords. As a result, a total of 1240 documents were obtained, considering works from different agencies.

In this study, the PRISMA method was used to refine the articles. According to Meher; Liberati, Tetzlaff and Altman (2009) this method was developed in 1996 with the objective of evaluating conceptual and practical advances in the science of systematic reviews, as well as providing guidelines for conducting systematic reviews and meta-analyses. In addition, it is also useful for conducting critical evaluation of published systematic reviews.

The 1240 documents were refined in four stages: i) Identification, ii) Screening, iii) Eligibility, and iv) Inclusion. In Stage 1, a search for articles using keywords was initially carried out in the *Web of Science* and *Scopus databases,* as well as the insertion of records from other sources. Subsequently, duplicate studies were excluded. In stage 2, content analysis (screening) was carried out based on studies that included at least the triple bottom line of sustainability (social, economic and environmental) and its variations through the insertion of other dimensions such as infrastructure, sociocultural, quality of life, governance, legislation, habitability, accessibility, urbanization, health, spatial, technology, transportation and others. In the subsequent stage, documents with the application of the related indicators on the various scales were considered eligible: municipal, regional, national or international, excluding the scales of neighborhood, blocks and exclusively rural areas. Obtaining as a result Step 4 (inclusion), as shown in the PRISMA flowchart in Figure 1.

GC Revista Nacional de Gerenciamento de Cidades
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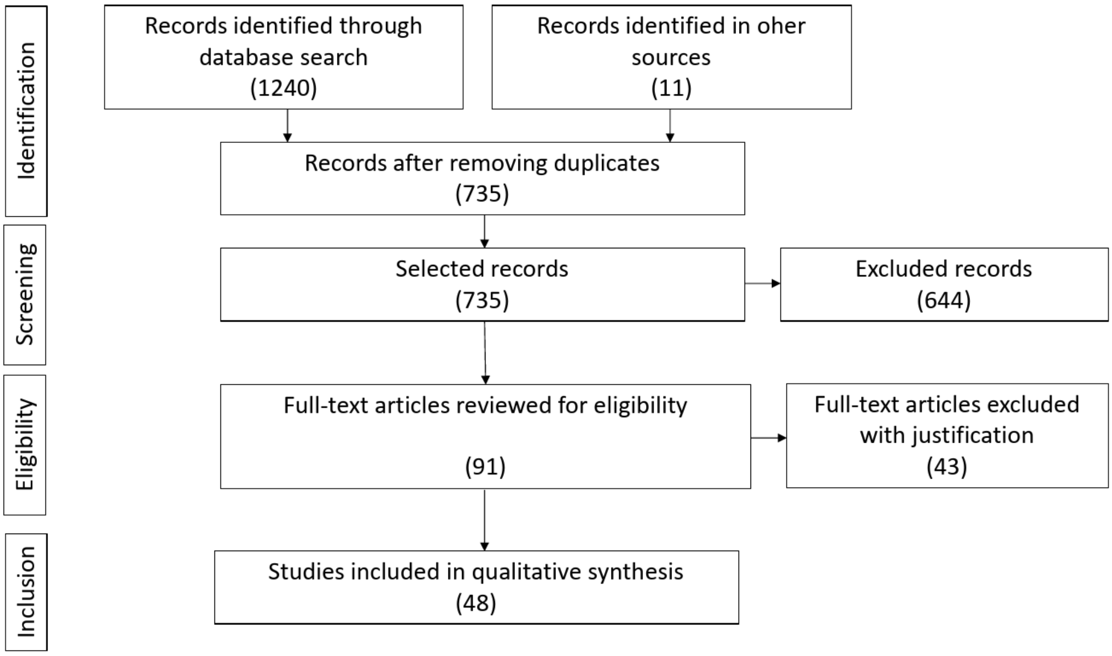
ISSN 2318-8472, v. 13, n. 88, 2025

Figure 1 - PRISMA Flowchart[1]



Source: adapted from Liberati (2009).

4 RESULTS

The results on the most relevant components of the index are presented below: dimensions, indicators, survey of indicators, method of selection of indicators, normalization of indicators, method of selection of weights and aggregation method and resulting composite index.

The selected documents, make up a total of 48 studies, listed in Table 1, where each source is also related to its respective: spatial scale, number of dimensions, number of subdimension, number of indicators, number of case studies, size of the city and country or continent where the index was applied. Several scales of case studies were observed: municipality (43), county (1), provinces (1), metropolitan region (1) and country (2); with respective relative holdings of 87.4%; 2.1%; 2.1%; 2.1%; 2.1% and 4.2%. The effort in the developing indexes focused on the municipal scale is notable. Regarding the location of the study, within the 48 documents, 20 (41.6%) were carried out in China, followed by studies with 8 multiple cities in the world (16.7%), 4 in Europe (8.3%), 2 in Hungary and India with 4.2% each and others (25%).

[1] PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was developed by experienced authors and methodologists as an evolution of the original QUOROM guidelines for systematic reviews and meta-analyses of health intervention evaluations.

GC Revista Nacional de Gerenciamento de Cidades
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Table 1 – General data of the selected documents (continue)

N.	Source (year)	Spatial scale	N. Dimension/ category	N. indicator groups	N. Indicators	N. Applied studies	City size (inhab.)	Country/ Continent
1	Jiao *et al.* (2016)[2]	Province	4	-	21	31	-	China
2	Li and Li (2017)[3]	Municipality	3	12	31	16	1 to 10 million	China
3	Alfaro-Navarro; López-Ruiz; Peña (2017)[4]	Municipality	3	10	40	158	Major cities in Europe	Europe
4	Phillis; Kouikogloua; Executioner (2017)[5]	Municipality	7	-	46	106	Capitals and megacities	Several countries
5	Sun *et al.* (2018)[6]	Municipality	3	-	22	277	Small (<1 million), medium (1-3 million), large and megal. (>3 million)	China
6	Musa *et al.* (2018)[7]	Municipality	4	2	37	1	-	Malaysia
7	Shmelev, and Shmeleva (2018)[8]	Municipality	4	-	16	57	Global Cities	Several countries
8	Yang and Jiang (2018)[9]	Municipality	6	7	20	1	-	China
9	Zheng and Bedra (2018)[10]	Municipality	8	-	51	31	-	China
10	Anisurrahman and Alshuwaikhat (2019)[11]	Municipality	5	-	92	1	1.534.731	Saudi Arabia
11	Feleki; Vlachokostas; Moussiopoulos (2019)[12]	Municipality	4	-	34	1	1.000.000	Greece
12	Founda and Elkhazendar (2019)[13]	Municipality	3	10	30	3	-	United Kingdom, Egypt and Slovakia

[2]Chongqing University
[3] Guangdong Institute of Eco-environmental Science and Technology; East China Normal University; Shanghai Key Laboratory of Urbanization and Ecological Restoration
[4] University of Castilla-La Mancha
[5] Technical University of Crete; Escuela Superior Politécnica de Chimboraz
[6] Chinese Academy of Sciences; Chinese Academy of Forest Inventory and Planning
[7] Universiti Putra Malaysia
[8] Oxford; University of St Gallen; ITMO University; Institute of Sustainable Development Strategy (ANO)
[9] Taiyuan Normal University
[10] Central South University
[11] King Fahd University of Petroleum & Minerals (KFUPM)
[12] Aristotle University
[13] Tanta University; Dar AlUloom University

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 88, 2025

13	Gong *et al.* (2019)[14]	Municipality	5	13	35	1	-	China
14	González-García *et al.* (2019)[15]	Municipality	3	-	33	64	village (<5,000), small (5,000-50,000) and medium (>50,000)	Spain
15	Hassan and Kotval-K (2019)[16]	Municipality	9	-	40	1	300.000	Iraq
16	Kotharkar; Pallapu; Bahadure (2019)[17]	Municipality	3	-	21	1	2.400.000	India
17	Tang *et al.* (2019)[18]	Municipality	3	10	39	16	>1 million	China
18	Xu; Gao; Zhang; Fu (2019)[19]	Municipality	6	-	11	26	-	China
19	Yang (2019)[20]	Municipality	6	-	20	8	1-6 million	China
20	Yi; Read; Zhang (2019)[21]	Regional	3	-	18	13	2-14 million	China
21	Yi; Dong; Li (2019)[22]	Municipality	3	-	21	17	1-12 million	China
22	Zulaica (2019)[23]	Municipality	2	16	32	1	-	Argentina
23	Buzasi and Jager (2020)[24]	Municipality	3	-	30	1	-	Hungary

[14] Sichuan University
[15] University of Santiago de Compostela; Galician Federation of Municipalities and Provinces (FEGAMP)
[16] Michigan State University; Nawroz University
[17] Visvesvaraya National Institute of Technology, Nagpur
[18] Anhui Polytechnic University; Jiangsu University of Science and Technology; The University of York; Fujian Agriculture and Forestry University
[19] Shanghai Business School; Shanghai Normal University; Chinese Academy of Sciences
[20] Chinese Academy of Sciences
[21] Northeastern University; Liaoning University
[22] Northeastern University
[23] National Council of Scientific and Technical Research (CONICET); Institute of Habitat and Environment (IHAM); National University of Mar del Plata
[24] Budapest University of Technology and Economic

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 88, 2025

Table 1 – General data of the selected documents (more)

N.	Source (year)	Spatial scale	N. Dimension/ category	N. indicator groups	N. Indicators	N. Applied studies	City size (inhab.)	Country/ Continent
24	Bhattacharya *et al.* (2020)[25]	Municipality	4	15	47	3	>1 million	India
25	Chan (2020)[26]	Municipality	3	-	18	5	100k - 2.2M	Cambodia
26	Fu *et al.* (2020)[27]	Municipality	4	15	30	1	9.9 million	China
27	Li and Yi (2020)[28]	Municipality	3	-	24	9	10-22 million	China
28	Liu *et al.* (2020)[29]	Municipality	5	-	40	6	-	China
29	Mangi *et al.* (2020)[30]	Metropolitan Region	3	-	35	34	-	China and Pakistan
30	Steiniger *et al.* (2020)[31]	Municipality	5	-	29	6	170 thousand-7.5 million	Chile
31	Wang *et al.* (2020)[32]	Municipality	11	-	92	35	Mega, large and medium-sized cities	China
32	Xia *et al.* (2020)[33]	County	3	-	6	2850 counties	-	China
33	Yang; Yang; Wang (2020)[34]	Municipality	6	-	20	13	>3 million	China
34	Buzási and Jäger (2021)[35]	Municipality	3	-	30	20	32 thousand – 1.7 million	Hungary
35	Dong *et al.* (2021)[36]	Municipality	3	-	18	26	Central cities	China
36	Li et al. (2021)[37]	Municipality	3	-	24	17	> 1 million	China
37	Sun and Zhang (2021)[38]	Municipality	5	-	51	13	>3 million	China
38	Siemens (2009)[39]	Municipality	8	8	30	30	-	Europe

[25] Kyoto University
[26] General Secretariat of the National Council for Sustainable Development; Office of Sustainable Lifestyle
[27] Shandong University; Environmental Audit Reception Center for Construction Projects in Shandong Province
[28] Northeastern University
[29] Xi'an University; Griffith University; Shaanxi Normal University; Huangshan University; Shanghai Normal University
[30] Tsinghua University; Mehran University of Engineering and Technology
[31] Pontificia Universidad Católica de Chile; Universidad de Concepción; Universidad Mayor;
[32] Chongqing University; The University of Manchester
[33] Wuhan University; Erasmus University Rotterdam; Delft University of Technology; Beijing Cstind Science and Technology Co
[34] University of Chinese Academy of Sciences; Chongqing Normal University
[35] Budapest University of Technology and Economics
[36] Nanjing University of Aeronautics and Astronautics; Chinese Academy of Sciences; University of Chinese Academy of Sciences; Guilin University of Electronic Technology
[37] North China University; Hohai University; Henan Key Laboratory of Water Environment Simulation and Treatment; Collaborative Innovation Center of Water Resources Efficient Utilization and Protection Engineering; Baoding Water Conservancy and Hydropower Survey and Design Institute
[38] Tianjin University,
[39] Economist Intelligence Unit; Siemens

ISSN 2318-8472, v. 13, n. 88, 2025

Table 1 – General data of the selected documents (conclusion)

N.	Source (year)	Spatial scale	N. Dimension/ category	N. indicator groups	N. Indicator	N. Applied studies	City size (inhab.)	Country/ Continent
39	European Commission (2012)[40]	Country	3	8	21	-	-	151 countries
40	Zoeterman et. al (2015)[41]	Municipality	3	19	87	58	>100,000	European Union
41	UNITED NATIONS (2016)[42]	Country	-	8	18	-	-	156 countries
42	UNITED NATIONS (2016)[43]	Municipality	3	20	87	145	> 40,000	E.U. and Netherlands
43	Zoeterman et. al (2016)[44]	Municipality	6	22	62	54	Developing Cities	Countries
44	ARCADIS (2018)[45]	Municipality	3	-	48	100	Major cities	All continents
45	SDSN (2018)[46]	Municipality	15	-	57	105	-	United States
46	SDSN (2019)[47]	Municipality	-	15	56	45	Large size and capital	Europe
47	IESE (2020)[48]	Municipality	9	-	101	174	79 capitals and the largest cities	80 countries
48	The Mori Memorial Foundation (2020)[49]	Municipality	6	26	70	288	Influential cities	All continents

Source: Author (2024).

Regarding the analysis of dimensions/category, indicator groups and number of indicators, there is a tendency to use four to six dimensions, with special attention to indexes with three dimensions, which corresponds to 40% of the documents reviewed. The indicator groups are present in 18 of the 48 sources analyzed, that is, 38% of the studies. Additionally, there is considerable variability in the number of indicators employed at the municipal level, ranging from 11 to 183 indicators.

[40] European Commission
[41] Tilburg University
[42] UN-Habitat
[43] Telos; Tilburg Sustainability Center
[44] UN-Habitat
[45] Arcadis
[46] Sustainable Development Solutions Network
[47] Telos; Sustainable Development Solutions Network
[48] IESE Business School University of Navarra
[49] Institute for Urban Strategies; The Mori Memorial Foundation

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 88, 2025

Among the 48 documents analyzed, it is important to highlight that only 20.0% of documents present indexes composed of more than 50 indicators, as well as the use of audited data for each indicator. Regarding the indices that are composed of 50 indicators or less, of the 38 documents, 17 (44.7%) use a single source of data for each indicator. Thus, the challenge in developing indices using a wide range of indicators is highlighted, with the objective of ensuring reliability in the use of the same methodology in data collection (Table 2).

Table 2 – Use of a single auditable or multiple sources for each indicator

Number of Indicators	Number of Documents	Single Source	Multiple Font
50 +	10	2 (20.0%)	8 (80.0%)
50 -	38	17 (44.7%)	21 (55.3%)
Grand Total	48	19 (39.6%)	29 (60.4%)

Source: Author (2024).

4.1 Survey of Dimensions

Table 3 presents an analysis of the most frequently utilized dimensions across the examined studies. From the analysis of 48 documents, it is evident that the traditional triple bottom line of sustainability predominantly shapes the dimensions of the index, with a primary focus on environmental considerations (79.2%) and economic factors (70.8%), followed by social dimensions (56.3%). Additionally, a subset of documents incorporates supplementary dimensions, including spatial urbanization (29.2%), transportation, governance/legislation, and urban infrastructure, each represented at a rate of 10.4%. It is important to note that there is a significant number of studies that do not use the dimensions (12.5%) to structure the index.

Table 3 – Summary of the dimensions of the 48 studies

N.	Dimensions Name	Observations	Percentage
1	Environment	38	79,2
2	Economical	34	70,8
3	Social	27	56,3
4	Spatial urbanization	14	29,2
5	Do not use dimension for index development	6	12,5
6	Transport	5	10,4
7	Governance and legislation	5	10,4
8	Urban infrastructure	5	10,4
9	Health	4	8,3
10	Education	4	8,3
11	Resource	4	8,3
12	Social equity	3	6,3
13	Housing	3	6,3

Source: Author (2024).

4.2 Survey of Indicators

ISSN 2318-8472, v. 13, n. 88, 2025

Evaluating improvement in urban sustainability, or the lack thereof, requires the implementation of a methodology able to assess specific aspect of reality. This assessment can be conducted through both qualitative and quantitative data.

The range of diversity of indicators can be seen in Table 1. In total, 1,538 indicators were obtained in the 48 documents analyzed. Given the substantial quantity of indicators identified, a selection was made to focus on those most frequently referenced, specifically those appearing in a minimum of seven documents. This criterion was established to provide a clearer understanding of the varied indicators associated with the concept of urban sustainability. These indicators encompass fundamental aspects such as basic sanitation, urban spatialization, energy usage, housing conditions, mobility, education, accidents, cultural initiatives, connectivity, as well as transparency and civic participation.

It is important to note that some indicators shown in Chart 1 are not universally accessible on open platforms for all Brazilian cities, regardless of their size. These indicators include the industrial effluent rate, garbage recycling rate, green space as % of the city area, green area per capita, urbanization rate, connectivity density and medical density. In that matter, another issue found is that some indicators are not part of the urban spatial reality of all Brazilian municipalities, such as: proportion of the population with access to public transportation, number of buses and trolleybuses, the percentage of non-hazardous waste, industrial solid waste rate, reuse of industrial solid waste and consumption of renewable energy.

Chart 1 - Indicators used in at least seven different documents (continue)

N	Themes	Indicators	N.	Themes	Indicators
1	Noise	Perception noise annoyance	29	Education	Number of children in early childhood education
2	Air quality	CO2 emission	30		Number of children in primary education
3		Nitrogen oxides emissions	31		Population with secondary education (%)
4		Sulfur Dioxide Emission	32		Share of the population in higher education
5		Annual levels of fine particulate matter	33	R&D	Research & Development Intensity
6		Pollution Index	34		Science and technology expenditures
7		Ozone Intensity	35	Urban spatialization	Urban population density
8		Air quality	36		Green space
9	Water supply	Drinking water consumption	37		Green area per capita
10		Water supply cover	38		Population growth rate
11		Surface and groundwater quality	39		Urbanization rate
12	Sewage/effluent	Sewer network coverage	40	Social	Average family income
13		Industrial effluent rate	41		Per capita income
14	Solid waste	Garbage production	42		Gini coefficient
15		Garbage Recycling Portion	43		Proportion of people vulnerable to poverty
16		Harmless Garbage Share	44		Unemployment rate

ISSN 2318-8472, v. 13, n. 88, 2025

17		Industrial solid waste fee	45	Economical	Employment rate
18	Solid waste	Reuse of Industrial Solid Waste	46		GDP per capita
19		Proportion of municipal solid waste with proper disposal	47		Secondary and tertiary industry GDP
20	Energy	Power Consumption	48		Per capita investment in fixed assets
21		Renewable energy consumption	49		GDP growth rate
22	Connectivity	Urban connectivity density	50	Trade/Service	Retail sales of consumer goods
23	Accidents	N. injured in accidents	51		Days to open a business
24	Telephony	Free Wi-Fi is available	52	Health	Life expectancy at birth
25	Housing	Households with a burden > 30% income from rent	53		Number of hospital beds
26	Popular participation	Participation of the population in the planning process	54		Physician Density
27	Public transport	Proportion of the population with access to public transport	55	Culture	Number of public libraries
28		Number of buses and trolleybuses	56	Safety	Crime rate

Source: Author (2024).

4.3 Indicators' selecting method

Several characteristics and methods of selecting the indicators were identified. The analysis revealed two predominant selection approaches: the participatory method and the method based on the characteristics of the indicators.

The process of a participatory method incorporates expert consultation, following different methodologies, such as the Delphi method (MUSA, *et al.*, 2018), IndSelec Strategy (FELEKI, VLACHOKOSTAS and MOUSSIOPOULOS, 2018), Matriz Leopolda (GONZÁLEZ-GARCÍA *et al.*, 2019) and AHP (CHAN, 2020).

There are several methods of selecting indicators based on the characteristics of the indicators, as shown in Table 4. The characteristics or methods of selection of the indicators that were most addressed among the selected documents were: literature review (20.0%), among the selected documents, followed by data availability (19.2%), consultation with experts (10.0%), relevance (7.7%), comprehensiveness/coverage (7.7%), measurable, and comparability (4.6%) each, among others. It is important to recognize that a single document may employ multiple criteria for the selection of indicators.

ISSN 2318-8472, v. 13, n. 88, 2025

Table 4 – Criteria for selecting indicators

Indicator selection criteria	**Observations**	**Percentage**
Literature review	26	20,0
Data availability	25	19,2
Expert consultation	13	10,0
Relevance	10	7,7
Coverage/ Scope	10	7,7
Measurable	6	4,6
Comparability	6	4,6
Representativeness	4	3,1
Analysis of local conditions	4	3,1
Valid and reliable	4	3,1
Removal of duplicate data	3	2,3
Independence	3	2,3
Understandable to the community	3	2,3
Correlation Analysis	2	1,5
Recent data	2	1,5
Other	9	7,0
	130	100,0

Source: Author (2024).

The examination of various documents has revealed a lack of consensus regarding the characteristics and methodologies employed. There are several positive and negative points of view in the use of subjective methods (participatory methods) or based on the characteristics of the indicators (objective methods). According to González-García, *et al.* (2019) there is a common misconception when selecting the set of indicators, which is due to the exclusive use of subjective methods. Thus, the selection will depend only on the knowledge of the specialists. Some studies, such as presented by the *European Commission* (2012) and SDSN (2019) bring the importance of characteristics through technically sound selection criteria. Furthermore, an alternative perspective presented by Chrysoulakis *et al.* (2011) posits that a composite set of indicators, derived from both subjective methods and the inherent characteristics of the indicators, can be beneficial.

4.4 Normalization method

Data normalization seeks to eliminate the incommensurability of the indicators that may be caused by differences in their dimensions and magnitudes (DONG, L. *et al.* 2021). Therefore, the values of the indicators are usually normalized (leaving them on the same scale, for example, transformed into values between 0 and 1) and then assigning weights.

Chart 2 shows that five types of standardization methodologies were most commonly used in the selected studies. Among the normalization methods found, 51% of the selected documents use the linear interpolation method, followed by the maximum value and minimum value method (12.2%), normalization or standardization method for a z-score (8.2%), number of indicators above the average minus the number below the average (4.1%) and simple reversal (2.0%). According to Feil (2021), each normalization method has its advantages and

GC Revista Nacional de Gerenciamento de Cidades
National Journal of City Management

ISSN 2318-8472, v. 13, n. 88, 2025

disadvantages. An important issue for the data normalization procedure is the presence of outliers, which can strongly influence the results, distort and mask reality.

Chart 2 - Methods of standardization of indicators (continue)

Normalization method	**Formula**	**Note**	**%**	**Advantage**	**Disadvantage**
Linear interpolation method	$X^{(S)} = 100\frac{X - Min(X)}{Max(X) - Min(X)}$	25	51,0	Easy handling and understanding	Outliers affect the index.
Maximum and minimum value	$P_{ij} = \frac{x_{ij}}{\max_{(xi)}}$	6	12,2	Setting thresholds and ranges are identical for all indicators (0, 1)	Outliers affect the index and distort it more than the Z-score.
Normalising or Standardizing to a z-score	$\mathrm{Zx} = \frac{\mathrm{Xi} - \mu\mathrm{x}}{\sigma\mathrm{x}}$	4	8,2	Simple and easy.	They are dependent on outliers that can reflect Errors in the input data
Number of indicators above average minus the number below the mean	$S_i = \frac{(U_i - L_i)(X_i - T_i)}{(U_i + L_i - 2T_i)X_i + U_iT_i + L_iT_i - 2U_iL_i}$	2	4,1	Simple and easy and robust against Outliers	Loss of range-level information. The Arbitrariness of the threshold level and the omission of information of absolute level.
Simple reversion	X (S) = 100– X	1	2,0	-	-
It doesn't make it clear	-	10	22,5	-	-
Total	-	**48**	**100**	-	-

Source: adapted from Feil (2021).

4.5 Method of selection and calculation of Weights

The determination of weights within the sustainability indicator system, as outlined by Jiao *et al*. (2016), can be categorized into two primary approaches: equal weight (same weight) and different weights. Founda (2019) states that the importance of using different weights is due to the complexity of developing a sustainable index and the interconnection between indicators.

The categorization of distinct weights is divided into two primary methodologies: the subjective method, which is a participatory approach that relies on the collective research experiences of the group and the guidance of subject matter experts; and the objective method, in which weights are established through mathematical calculations.

ISSN 2318-8472, v. 13, n. 88, 2025

In the bibliometric study carried out, it was possible to verify that near half of the authors used the objective category (Table 5). There was a trend towards using objective methods to select weights to ensure less subjectivity in the process of calculating the final index, making the weight more objective and reliable (Liu *et al.*, 2020), as a process to avoid errors in subjective weighting (SUN and ZHANG, 2021). Among the objective methodologies employed for weight determination, the most prevalent include the Entropy method, the DP2 de Pena approach, Principal Component Analysis (PCA), and Fuzzy methods. Having said that, only 16.7% opted for the participatory methodology.

Jiao *et al.* (2016) state that objective methods such as PCA (Principal Component Analysis) and the entropy method exhibit certain limitations when applied in practice. In these objective methods, the calculation of weights is related only to the difference in the data (the greater the difference between the performance values, the greater the weight given to the associated indicator). Consequently, there is a potential risk that the outcomes may not accurately represent the relative importance between the indicators.

Table 5 - Category and methodology for determining weight

Group	Category	Methodology for Determining Weights	Number	Percentage
Equal weight	Same weight	Weightless	14	29,2
Different weights	Goal	Entropy	9	52,1
		Distance P2 (DP2)	3	
		Principal Component Analysis (PCA)	2	
		Fuzzy Method	2	
		Other	9	
	Subjective	Participatory (does not specify the methodology)	5	16,7
		AHP	2	
		Delphi Method	1	
It doesn't say			1	2,1
Total			**48**	**100**

Source: Author (2024).

According to Misha (2009 *apud* Nayak and Mishra, 2013, p.2), "[...] synthetic indicators constructed by Principal Component Analysis (PCA), Data Envelopment Analysis (DEA) or other alternatives using non-Euclidean norms are deficient in one or another desirable property compared to the Pena method".

It is also stated that Pena's DP2 method solves a large number of problems such as the aggregation of variables expressed in different measures, arbitrary weights and duplication of information (PENA, 1977; ZARAZOSA, 1996; SOMARRIBA and PENA, 2009; MONTERO *et al.*, 2010; MARTINA and FERNÁNDEZ, 2011 *apud* NAYAK and MISHRA, 2013, p.2).

On the other hand, the Fuzzy method, according to Feil (2021) has the advantage of solving complex problems. Its the disadvantage is due to the complexity and imprecision of the data.

ISSN 2318-8472, v. 13, n. 88, 2025

Regarding subjective methods, the Delphi technique is a method that obtains opinions from different experts on complex and wide-ranging topics. This technique is characterized by iterative rounds of questionnaires and a structured feedback aimed at synthesizing data to achieve consensus among a panel of experts on a complex research issue, particularly in instances there is no precise information available (BOLGER and WRIGHT, 2011; LINSTONE & TUROFF, 2002).

According to Gonzales *et al.* (2019) the *Analytic Hierarchy Process* (AHP) methodology is considered a simple and flexible technique with the aim of assigning weights to different indicators, carried out according to the experience and opinion of experts. Unlike the Delphi method, the AHP method is a decision-making process based on the comparison of pairs of criteria, followed by the application of a process to calculate the relative importance of each criterion (SAATY, 2005).

4.6 Final aggregation method

"Aggregate of indicators assists decision makers by reducing the clutter of too much information, thereby helping to communicate information succinctly and efficiently" (FOUNDA and ELKHAZENDAR, 2019, p. 28).

There exist various methodologies for the aggregation of indicators; however, the primary challenge remains the formulation of a singular metric that represents the general dimension or index, making it possible to make comparisons between cities, districts and/or countries according to the proposed objective.

Table 6 shows that the most commonly used aggregation methods are the weighted mean (27.1%) and arithmetic with 20.8%, followed by the sum (12.5%), the degree of coupling coordination (8.3%) and the entropy, fuzzy and geometric mean methods with 4.2% each. Some authors do not perform the aggregation calculation (14.6%) and there are also authors who do not make clear the aggregation methodology used (10.4%), due to little or no information.

Table 6 - Aggregation methods of the 48 studies

Aggregation method	**Observations**	**Percentage**
Weighted average	13	27,1
Arithmetic mean	10	20,8
Does not perform the calculation	7	14,6
Sum	6	12,5
It does not make clear the method used	5	10,4
Degree of coupling coordination	4	8,3
Fuzzy method	2	4,2
Linear aggregation	2	4,2
Other	8	16,7

Source: Author (2024).

The simplest methods (arithmetic, weighted and summation average) are the most used due to their simplicity of calculation. The fuzzy, entropy and degree of coupling

ISSN 2318-8472, v. 13, n. 88, 2025

coordination methods have a more complex calculation basis. In the point of view of Pissourios (2013), the complexity in the calculations of some methods makes them impractical for real use.

The complexity in the calculation can be seen in the study conducted by Dong *et al.* (2021) for the analysis of the effects of coupling on the Economy-Society-Environment system in urban areas. The Entropy Method (EM) and the Coupling Coordination Degree Model (CCDM) to synthetically evaluate the coupling coordination degree of the ESE system. The Back-Propagation Artificial Neural Network (BPANN) was applied to explore the influencing factors of the ESE system's coupling coordination degree considering the nonlinear relationship between the various indicators and the ESE system's coupling coordination degree. (DONG *et al.* (2021, p. 1).

In addition, the incorporation of fuzzy logic into sustainability assessments provides a valuable approach to addressing the subjective issues inherent in the theme of sustainability. For example, Phillis, Grigoroudis & Kouikoglou, 2011 *apud*. NASCIMENTO, 2020, p. 17), prepared a study using the SAFE (*Sustainability Assessment by Fuzzy Evaluation*) methodology to assess the sustainability of several countries. The complexity of the calculation is also observed in the study carried out by Phillis, Kouikoglou and Verdugo (2017) who applied the SAFE method to evaluate urban sustainability and *ranking* 106 cities (capitals or historic cities). According to the authors, SAFE is a hierarchical fuzzy reasoning system in which the basic indicators are grouped according to their characteristics to produce an indicator, composed of several statistical stages and methods, and uses triangular pertinence functions and product-sum algebra.

5 CONCLUSION

The present study aimed to carry out a quantitative analysis of recent scientific production in order to verify the current trend in the use of indices aimed at urban development, by analyzing the components of the index such as: dimension, indicator, method of selection of indicators, method of normalization, method of selection and calculation of weights and method of aggregation.

It was observed in the indices composed of more than 50 indicators, a tendency to present difficulty in using a single source of data for each indicator. On the other hand, in relation to indices that are composed of 50 indicators or less, there is a significant number of studies that use a single source of data for each indicator.

Another important point noted is the considerable effort in the formulation of indices aimed at the municipal scale, for this scale there is a great variability in the number of indicators between 11 and 183 indicators.

Regarding the analysis of the index components, several trends and gaps were observed: (1) in the analysis of the dimensions, a trend was observed in the use of the traditional triple bottom line of sustainability (environmental, economic and social). Furthermore, additional dimensions pertinent to urban sustainability, such as spatial urbanization, transportation, and urban infrastructure, have been incorporated. However, complementary studies would be needed to verify the advantages and disadvantages of only considering the traditional triple bottom line is sufficient, or the importance of evaluating other themes. As well

ISSN 2318-8472, v. 13, n. 88, 2025

as the analysis of advantages and disadvantages in structuring the index without dimensions to characterize sustainable urban development; (2) In the research of indicators, in general, due to the complexity of the urban sustainability theme, it involves multidisciplinary areas; (3) There is no consensus regarding the criteria or methods used among the documents studied for the selection of indicators. There are several points of view among the studies analyzed: (3a) selection of indicators through subjective knowledge through specialists, (3b) the characteristics of indicator selection and (3c) joint selection between the characteristics of the indicators and the participatory (subjective) method, and further studies are needed in relation to the form of selection of indicators to ensure their effectiveness in portraying the observed reality; (4) A trend has been observed towards the adoption of objective methods for determining weights, aimed at minimizing subjectivity in the calculation of the final index. Nonetheless, critiques arise concerning the practicality of implementing complex calculations, which may render them unsuitable for real-world applications. Consequently, a comparative study examining the practicality and accuracy of these objective methods versus more straightforward methodologies is essential; (5) The most commonly used aggregation methods are simple calculations, as already discussed in the weight selection method. It is important to carry out further studies to verify the advantages and disadvantages of using methods with more simplistic complex dimension aggregation calculation or general index.

Consequently, there remain unresolved issues pertaining to the formulation of indices focused on urban sustainability. It is recommended that subsequent research endeavors reflect on the topics discussed within this document, and that, given the limitation of the study, bibliometric analyses focused on sustainable urban development can incorporate the analysis of reference values, contributing to a discussion of the effectiveness and efficiency for the comparative analysis of the indicators.

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