Universidade do Contestado | www.unc.br/periodicos ISSNe: 2237-9029
DRd | Desenvolvimento Regional em debate
Revista eletrônica do Programa de Mestrado em Desenvolvimento Regional da Universidade do Contestado

AVALIANDO A SUSTENTABILIDADE URBANA ATRAVÉS DO NEXO ÁGUA-ENERGIA-ALIMENTOS: O CASO DE CURITIBA – PR

ASSESSING URBAN SUSTAINABILITY THROUGH THE WATER-ENERGY-FOOD NEXUS: THE CASE OF CURITIBA – PR

EVALUACIÓN DE LA SOSTENIBILIDAD URBANA A TRAVÉS DEL NEXO AGUA-ENERGÍA-ALIMENTOS: EL CASO DE CURITIBA – PR

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RESUMO

Diante da crescente preocupação global com a segurança hídrica, energética e alimentar, este estudo tem como objetivo propor um índice capaz de avaliar de forma integrada as inter-relações entre esses três setores no município de Curitiba, Paraná. Para isso, foram analisados 470 artigos publicados entre 2018 e 2023, dos quais se extraíram os indicadores mais relevantes relacionados ao nexo água-energia-alimento (AEA). Os dados foram coletados em plataformas oficiais como IBGE, COPEL, INMET e da Prefeitura de Curitiba. A metodologia adotada combina Programação por Compromisso com a distância de Mahalanobis e os limiares de Pareto, permitindo uma análise geométrica e normalizada da sustentabilidade urbana. A construção do índice visa não apenas quantificar a situação atual da cidade, mas também evidenciar os pontos críticos que comprometem sua autonomia. Os resultados demonstram que Curitiba apresenta baixa sustentabilidade nos três setores, revelando forte dependência de recursos externos para abastecimento hídrico, energético e alimentar. A conclusão aponta que, apesar dos reconhecimentos em sustentabilidade, o município enfrenta limitações estruturais significativas, o que compromete seu funcionamento diante de crises futuras. O índice proposto se mostra como uma ferramenta estratégica para apoiar o planejamento urbano integrado e a formulação de políticas públicas mais eficientes.

Palavras-chave: nexo; AEA; indicador; sustentabilidade.

ABSTRACT

In view of the growing global concern about water, energy, and food security, this study aims to propose an index capable of assessing in an integrated manner the interrelationships between these three sectors in the city of Curitiba, Paraná. To this end, 470 articles published between 2018 and 2023 were analyzed, from which the most relevant indicators related to the water-

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energy-food (WEF) nexus were extracted. The data were collected from official platforms such as IBGE, COPEL, INMET, and the City of Curitiba. The methodology adopted combines Commitment Programming with the Mahalanobis distance and Pareto thresholds, allowing a geometric and normalized analysis of urban sustainability. The construction of the index aims not only to quantify the current situation of the city, but also to highlight the critical points that compromise its autonomy. The results demonstrate that Curitiba has low sustainability in the three sectors, revealing a strong dependence on external resources for water, energy, and food supply. The conclusion indicates that, despite the recognition of sustainability, the municipality faces significant structural limitations, which compromise its functioning in the face of future crises. The proposed index appears to be a strategic tool to support integrated urban planning and the formulation of more efficient public policies.

Keywords: nexus; WEF; indicator; sustainability.

RESUMEN

Ante la creciente preocupación mundial con la seguridad hídrica, energética y alimentaria, este estudio pretende proponer un índice capaz de evaluar de forma integrada las interrelaciones entre estos tres sectores en la ciudad de Curitiba, Paraná. Para ello, se analizaron 470 artículos publicados entre 2018 y 2023, de los cuales se extrajeron los indicadores más relevantes relacionados con el nexo agua-energía-alimentos (AEA). Los datos fueron recolectados de plataformas oficiales como IBGE, COPEL, INMET y la Ciudad de Curitiba. La metodología adoptada combina la Programación de Compromiso con la distancia de Mahalanobis y los umbrales de Pareto, permitiendo un análisis geométrico y normalizado de la sostenibilidad urbana. La construcción del índice pretende no sólo cuantificar la situación actual de la ciudad, sino también destacar los puntos críticos que comprometen su autonomía. Los resultados muestran que Curitiba presenta baja sostenibilidad en los tres sectores, revelando fuerte dependencia de recursos externos para el suministro de agua, energía y alimentos. La conclusión indica que, a pesar del reconocimiento de la sostenibilidad, el municipio enfrenta importantes limitaciones estructurales, lo que compromete su funcionamiento ante futuras crisis. El índice propuesto es una herramienta estratégica para apoyar la planificación urbana integrada y la formulación de políticas públicas más eficientes.

Palabras clave: nexo; AEA; indicador; sostenibilidad.

Como citar este artigo: SANTOS, Francielle da Rocha; BOLLMANN, Harry Alberto; PAGIORO, Thomaz Aurélio. Avaliando a sustentabilidade urbana através do nexo água-energia-alimentos: o caso de Curitiba – PR. **DRd – Desenvolvimento Regional em debate**, v. 15, p. 687-710, 03 jul. 2025. Doi: https://doi.org/10.24302/drd.v15.5813.

Artigo recebido em: 02/02/2025
Artigo aprovado em: 21/04/2025
Artigo publicado em: 03/07/2025

1 INTRODUCION

Despite the significant economic development that has occurred in the last century, the consumption of natural resources has increased rapidly, especially in developing countries. In this context, water scarcity has become an urgent global challenge, especially given that the agricultural sector accounts for the majority of this consumption (Unesco, 2014). It is estimated that global demand for water will increase by 40% by 2030 and by 55% by 2050, with around 40% of the world's population living in regions under water stress (Unesco, 2014). The water crisis also impacts the energy sector, which is responsible for using 10% of global freshwater to generate energy, in addition to consuming 4% of the energy produced for the treatment and transportation of water itself (Unesco, 2020). In light of this scenario, the need for integrated and efficient management of natural resources is growing, with emphasis on the water-energy-food (WEF) nexus, whose strategic relevance was highlighted in events such as the Bonn Conference (Hoff, 2011) and publications by the World Economic Forum (2011). The articulation between SDGs 2, 6 and 7 shows that the nexus is essential to achieving sustainability (Simpson; Jewitt, 2019). However, authors such as Galaitsi and Huber-Lee (2018) highlight the scarcity of empirical evidence proving the practical effectiveness of nexus approaches, which reinforces the need to move from "nexus thinking" to "nexus action" (Mcgrane et al., 2018).

Based on this panorama, this study proposes the development of a matrix of environmental indicators to assess the sustainability of the city of Curitiba from the WEF-WEF nexus perspective. The proposal aims to understand whether the city, recognized for its sustainable vocation, actually meets the environmental safety criteria when analyzed under an integrated approach. The analysis of the indicators will allow a concrete visualization of the availability and vulnerability of resources essential for subsistence, considering the interactions between society and the environment, influenced by factors such as urbanization, climate change and population growth (Newman, 2020; Kok, 2016). In this way, the study seeks to contribute to the strengthening of public policies and urban planning, with a focus on the resilience and sustainability of Curitiba.

2 LITERATURE REVIEW

2.1 NEXUS WATER, ENERGY AND FOOD

The concept of the WEF nexus has gained increasing visibility and has been integrated into sustainable development. When the term “sustainable development” was introduced at the UN, it was emphasized that population growth, food security, energy, environment and urban development “are interconnected and cannot be treated in isolation” (Brundtland, 1987).

The WEF nexus gained attention in 2008 during the World Economic Forum, when water was designated as “the link between economic growth and the environment” (World Economic Forum, 2011). Since then, its interpretation has varied globally, reflecting geopolitical and regional differences (Ringler *et al*., 2013; Biba, 2016). According to FAO (2014), the nexus describes the interrelated nature of global resource systems to achieve social, economic and environmental objectives.

The prioritization of the nexus components varies according to the perspective of the sectors involved (Wichelns, 2017; Liu et al., 2018). Studies on the nexus indicate that 71% of freshwater and 30% of global energy are used in agriculture, but one third of food is lost, resulting in wasted water and energy (Mohtar; Daher, 2012; FAO, 2014).

The UN relates the nexus to the SDGs, such as food security (SDG 2), clean water (SDG 6), affordable energy (SDG 7) and climate action (SDG 13) (Salam et al., 2017).

Despite the progress, the nexus faces implementation challenges due to the lack of coordination between dimensions (DEL BORGHI et al., 2020). For sustainable development to occur, integrated management between sectors is crucial (Scott Andrew, 2017; Weitz Nina, 2017).

2.2 WATER-ENERGY-FOOD NEXUS IN THE CITY OF CURITIBA

Curitiba is recognized as a Model City in Brazil, standing out for its urban innovations and commitment to sustainability. Awarded as a "Model City of Sustainability" in 2010, its BRT public transportation system, bike paths, parks and green areas are examples of sustainable solutions. Integrated urban management and planning promote a high quality of life, consolidating the city as an international reference since the administrations of Jaime Lerner.

Curitiba has received awards such as “ONU-Habitat” (2008), “Cidade Verde” (2010), “Cidades Sustentáveis” (2012), among others, for initiatives in public transportation, waste management, renewable energy and promotion of a smart city. However, it faces challenges in water, energy and food sustainability. Despite adequate infrastructure and awareness programs, periods of drought can cause water shortages. Local energy generation is low and local food production does not fully meet demand, requiring imports from other regions, which impacts sustainability.

Curitiba's urban development has historically been associated with an integrated vision of planning, which seeks to balance economic growth, quality of life and environmental sustainability. However, the city faces new challenges related to regional development and the governance of urban policies, especially in the context of contemporary demands for water, energy and food resources. Despite adequate infrastructure and awareness programs, periods of drought can cause water shortages. Local energy generation is low and local food production does not fully meet demand, requiring imports from other regions, which impacts sustainability.

Regional development has historically been driven by its strategic geographic position and by public policies that prioritized industrialization and urban innovation (RIBEIRO, 2020). However, Curitiba's centrality in the regional context has generated inequalities between the municipality and the cities of the Metropolitan Region. Thus, metropolitan integration and intermunicipal cooperation emerge as fundamental strategies to ensure balanced and sustainable development in the region (Brandão, 2020).

The 1966 Master Plan laid out a basis for urban development guided by transport axes and rationalized land use, consolidating a logic of linear and controlled growth (Macedo, 2013). However, in recent decades, the city has faced emerging pressure from horizontal expansion, which has resulted in the occupation of environmentally sensitive areas, such as river basins and valley bottoms. Instruments such as Ecological-Economic Zoning and integrated management of river basins are recommended strategies to reverse this situation and promote more sustainable urban development.

With regard to the governance of urban policies, the city has stood out for its capacity to mobilize resources and for dialogue between the public and private sectors. However, the integration of policies related to the water, energy, and food nexus still presents significant challenges. Therefore, coordination between the municipal, state, and metropolitan governments is essential to address structural problems, such as the management of urban rivers, water supply, and food security.

2.3 SUSTAINABILITY INDEXES AND INDICATORS

The distinction between an index and an indicator is essential for measuring specific characteristics. An indicator reflects a specific aspect of a reality, such as a literacy rate, while an index aggregates multiple indicators into a synthetic metric to facilitate comparisons (SICHE et al., 2007). Indicators are tools that simplify and communicate complex information, and are essential for assessing trends and identifying critical points (Warhurst, 2002).

Most of the studies analyzed brought indicators of sustainability, accessibility and availability, based on the current situation of the location of their studies. The selection of indicators depends on the objectives and interests for sustainable development and can be extremely broad (Pupphachai; Zuidema, 2017). However, the emphasis on sustainable development can vary according to the interpretation of the sustainability index (Guimarães; Feichas, 2009).

In the last five years, of the various articles examined, only one of them explored the Commitment Programming technique in the context of sustainability indicators. Despite being an old method, known for its simplicity and efficiency, it has been underutilized when it comes to indicators related to the concept of nexus. This trend suggests a significant gap in the application of this method in contexts that address the interconnections between water, energy and food. Due to its efficiency, this method will be used in the work.

2.4 NEXUS MEASUREMENT UNITS

Water is typically measured in cubic meters, energy is recorded in kilowatt-hours, while food is analyzed in a variety of ways, such as calories, nutritional content, and more. In addition, it is crucial to consider the different assessment scales, which can range from the national level to cities, provinces, regions, and river basins.

To ensure accurate and detailed analysis, it is necessary to standardize all these indicators by converting them to a neutral scale. This practice is vital in the development of composite indicators, since, in addition to varying units of measurement, the eigenvalues can present substantial differences (Simpson et al., 2020).

This allows different indicators, with different units of measurement and scales of variation, to be integrated in a logical and cohesive manner. This practice contributes to creating a single metric that facilitates the analysis and interpretation of performance, whether in the resources sector or in any other area of study.

By giving equal weight to the three pillars, it is understood that SDGs 2, 6 and 7 are equally essential.

2.5 USING MULTI-OBJECTIVE COMMITMENT PROGRAMMING

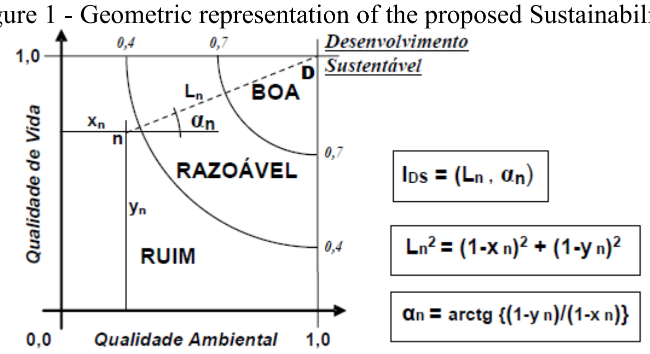
Sustainability analysis can integrate qualitative and quantitative indicators through multi-criteria and multi-objective methods, allowing the evaluation of alternatives and the search for ideal scenarios (Wang et al., 2016). These methods, applied to complex systems, involve the optimization of one or more objective functions, considering specific criteria of the problem (Bollmann, 2006).

Commitment Programming (PCMO) is based on the concept of "ideal point", representing maximum development with minimum environmental impact, and uses geometric metrics to approximate reference solutions, even if unattainable due to conflicting objectives (Zeleny, 2011). Choosing the appropriate metric is essential for assessing distances and searching for solutions. Decision-making in these methods can occur in two ways: by consolidating the objectives of the problem into a single optimization criterion, based on preference weights (Villamil, 2022), or by classifying the objectives by priority, leading to the optimal solution in stages (Hashimoto, 2004). In both cases, it is up to the decision-maker to select the alternative that best suits their needs.

The Pareto Efficient Method, introduced by Vilfredo Pareto at the beginning of the 20th century, establishes that an allocation of resources is efficient when it is not possible to improve the situation of one agent without worsening the situation of another. This concept is widely used in economic theory and in multicriteria decision-making. In one study, Pareto efficiency was combined with PCMO, applying scale normalization, where the least favorable condition receives a value of zero (0.0) and the ideal, one (1.1). This method allowed the optimization of environmental and quality of life indicators in a limited Cartesian space, facilitating multi-objective analysis (Bollmann, 2006).

In the Figure presented by Bollmann (2006), the process begins with the determination of the normalized values that represent the environmental quality and quality of life of a given planning unit, represented by the coordinates xn and yn (Figure 1).

Figure 1 - Geometric representation of the proposed Sustainability Indicator



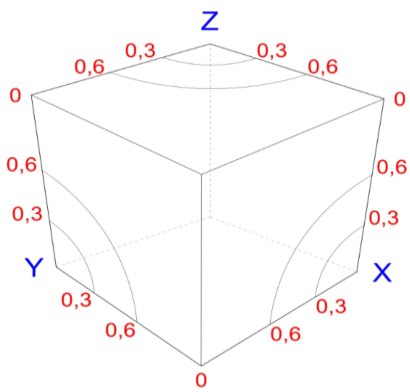
Fonte: Bollmann, 2006

Sustainability can be assessed based on the value of Ln: if it is less than 0.3, it indicates high sustainability; between 0.3 and 0.6, moderate sustainability; and above 0.6, low sustainability. The angle α is also an important indicator: when it is equal to 45°, there is a balance between quality of life and environmental preservation. If it is less than 45°, quality of life predominates over preservation; if it is greater, the opposite occurs (Bollmann, 2006).

To describe the sustainability of an area N, polar coordinates (Ln, αn) are used instead of Cartesian coordinates (Xn, Yn). This approach measures the geometric distance between point N and the ideal point D, in addition to the angle of the vector nD. If the compromise solutions satisfy the decision maker, the process ends; if not, the weights or ideal solutions are adjusted and the algorithm is re-executed (Bollmann, 2006).

Pareto optimality is widely used in the search for solutions that reconcile multiple objectives without compromising one criterion to the detriment of another. The Mahalanobis formula complements this approach by calculating the distance between points, considering scales and correlations between variables. This metric is useful when variables have distinct units or complex relationships. Unlike the Euclidean distance, the Mahalanobis distance adjusts for differences between variables and allows the selection of Pareto-optimal solutions closest to the mean of the set analyzed. The integration of commitment programming and this metric provides an effective method for balancing conflicting objectives. In the study, three dimensions (X, Y and Z) were considered, and the distance to point L (Figure 2) determined the sustainability levels.

Figure 2 - 3-dimensional representation of the Sustainability Indicator



Using the Mahalanobis formula, if $0 < L \leq 0.43$, sustainability is considered high. If $0.43 < L \leq 0.86$, sustainability is moderate. And if $0.86 < L \leq 1.44$, sustainability is low.

3 METHODOLOGY

3.1 THE SEARCH FOR RELEVANT INDICATORS

To assess the security of the water, energy, and food (WEF) nexus, the study was developed in five stages:

1. Selection of the unit of analysis: The city of Curitiba (PR) was selected as a case study. With an estimated population of 1,773,718 inhabitants and a population density of 4,078 inhabitants/km², the municipality has mild summers and occasional frost (IBGE, 2024).

2. Selection of indicators: The main indicators used in the literature to assess water, energy, and food security were defined.

3. Data collection: The data corresponding to the indicators were collected. When not available, the indicators were discarded.

4. Standardization of variables: The data were standardized to allow comparison between different indicators.

5. Application of commitment programming: The standardized indicators were integrated through this methodology, allowing the identification of optimized solutions for the WEF nexus.

To identify relevant indicators, a search was conducted on the Scopus platform using the string ("water" AND "energy" AND "food" AND "nexus") AND (("parameter" OR "parametre*") OR ("index*" OR "indice*") OR ("indicator*"))*. A total of 518 articles were found up to 2023, which were reduced to 470 by filtering English-language texts published between 2018 and 2023.

The most cited indicators in the literature and selected for this study include accessibility and availability, related to environmental, water, energy and food security. Articles that did not address the three sectors (water, energy and food) or that mentioned "nexus" without specific indicators were excluded.

The selection of indicators considered relevance, data availability and reliability, excluding possible redundancies. The selected indicators are based on three pillars – water, energy and food – and include sub-pillars such as access (equitable distribution of resources) and availability (sufficient supply to meet demand), both essential for environmental security.

Although there is no standardized method for integrated resource management using the WEF nexus, the approach should be adapted to the specificities of each context, considering the scale and characteristics of the environment. The creation of specific indicators for Curitiba can serve as a basis for future research and the development of more effective methodologies.

3.2 USING COMMITMENT PROGRAMMING

This research uses a combination of Commitment Programming, Pareto Threshold Theory and Mahalanobis Distance to assess the water, energy and food (WEF) nexus in Curitiba. The choice of these methods is based on the search for an innovative and consistent approach, given that such methodologies have not yet been widely applied in this type of integrated analysis.

Commitment Programming was used to deal with the multiplicity of criteria involved in the WEF nexus analysis, allowing the achievement of solutions that seek a balance between different dimensions (water, energy and food). This method offers an effective approach to multicriteria decision problems, especially when there is no single ideal solution, but rather a set of alternatives that will be evaluated according to the trade-offs between the criteria (Zeleny, 1982).

Pareto Threshold Theory was used to identify critical sustainability points in the regional analysis. The use of this concept offers a clear and visual interpretation of the results, facilitating the identification of regions that are close to or far from the sustainability limits (Pareto, 1906).

The data normalization process began using Excel software. For each variable, a trend line was constructed, the adequacy of which was verified using the coefficient of determination (R^2), seeking values as close to 1 as possible, in order to ensure greater accuracy in the adjustment. From each graph, a representative equation was obtained, in which the values of the independent variable (x) were replaced by the empirical data collected.

In the next step, the geometric mean (Equation 1) was applied to the normalized data. This approach was adopted to minimize distortions caused by extreme values — a recurring problem when using the arithmetic mean. The geometric mean is especially appropriate for positive variables that present variations on a logarithmic scale, ensuring a more balanced representation of the data set.

$$XG= \sqrt[n]{X1.X2.X3\ldots Xn} \qquad \text{Equation 1}$$

To measure the distance between points, the Mahalanobis metric (Equation 2) was used, which considers the correlation between variables and adjusts the data scale, making it more accurate than the Euclidean distance in multivariate analysis (Maesschalck, 2000). While the Euclidean distance measures the linear difference between two points, the Mahalanobis distance adjusts this measure using a covariance matrix of the variables.

$$D(x)^n = (1-\mu_1)^n + (1-\mu_2)^n + (1-\mu_n)^n \qquad \text{Equation 2}$$

Where n is the number of variables.

With this calculation, it was possible to determine the position of the points in the three main dimensions (x, y, z), which represent the levels of sustainability in relation to water, energy and food.

This three-dimensional model allows visualizing the balance between the three sectors and classifying each point as high, moderate or low sustainability. In addition, the analysis facilitates the identification of critical areas and the targeting of more effective policies, in line with studies that emphasize the importance of holistic approaches to sustainability (Toth; SZIGETI, 2016).

4 RESULTS AND DISCUSSION

The results involved the selection of 470 articles (2018-2023) and the definition of indicators for Curitiba, based on the literature and calculations of the security of the water-energy-food nexus using the PCMO method.

The most cited indicators are linked to the environmental security of the nexus, with emphasis on access and availability, as well as production and consumption, which are part of the Brazilian SDG indicators because they connect the three sectors.

To quantify the accessibility of resources, the relationship between population, demand and the need for imports was considered, seeking to optimize allocation and increase the security of the nexus. In addition to the indicators in the literature, the Curitiba matrix incorporated those listed in the SDGs and the city's available data.

The details of each indicator evaluated, as well as the justification for its inclusion or exclusion in the matrix, are presented in Table 1.

Table 1 - Indicators found in the literature

Nº	SECTOR	INDICATOR	DATA AVAILABILITY	INCLUDE/EXCLUDE
1	Water **	Percentage of people using at least basic drinking water services	IBGE (PNAD)	Include; has data, and the indicator is relevant to SDG 6.
2	Water	Water resources per capita	__	Exclude; values were not found at the municipal level
3	Water	Annual freshwater withdrawal	__	Exclude; it is an indicator of SDG 6.4.2, but values were not found at the municipal level
4	Water	Annual precipitation	INMET	Include; this indicator impacts the availability of water, energy and food.
5	Water	Groundwater abstraction	__	Exclude, although there is some data, there is no precision of all water used
6	Water	Total water consumption	IBGE	Include, there is data available and it is part of SDG 6.
7	Water	Water consumption in the industrial sector	__	Exclude, lack of data

8	Water	Water consumption in the agricultural sector	__	Exclude, lack of data
9	Water	Water quality in water bodies (WQI)	IAT	Include. It is a measure that is in SDG 6.3.2. It impacts water treatment.
10	Water	Degree of implementation of integrated water resources management	BRAZIL LEVEL	Delete. Data is only for Brazil.
11	Water		__	Delete. The use of this resource is incipient
12	Water	Water reuse	__	Delete. No data available. Although there is a law in the city for collecting rainwater in properties larger than 300 m².
13	Water	Rainwater harvesting	IBGE	Include; has data and is relevant for determining the portion of water lost
14	Water	Loss index	__	Delete. Unaccounted data
	Water	Virtual water footprint	SMSC	Include; has data and is relevant for water security
15	Water	Population affected by waterborne disease: leptospirosis	City of Curitiba - Department of Water Resources	Delete. Data exists, but with the IQA values, the water pollution index data becomes redundant.
16	Water	Water pollution index	INMET	Exclude. Not relevant for this research.
17	Water	Evaporation	IBGE	Include. Part of SDG 6.1.1
18	Energy	Supply capacity	IBGE	Include; data available and part of SDG 7.1.1.
19	Energy	Access to electricity	COPEL	Include; corresponds to SDG 7.2.1. Data available
20	Energy**	Electricity consumption	ABRAPCH	Include; considers only electricity. Important to understand how much is produced and consumed
21	Energy	Electricity production	__	Exclude; this indicator represents all GHGs.
22	Energy	Carbon footprint	__	Exclude. Lack of data.
23	Energy	CO2 emissions	__	Delete. The city of Curitiba does not import energy
24	Energy	Energy imports	COPEL	Include; has data
25	Energy	Total energy consumption	__	Delete. The data is for rural energy and not just for irrigation.
26	Energy	Energy consumption for irrigation	COPEL	Delete. Not relevant. But has data
27	Energy	Industrial energy consumption	__	Delete. Despite being part of SDG 12, there is no data available
28	Food	Amount of fossil fuel subsidies per unit of GDP (production and consumption)	__	Delete; although it is part of SDG 2, there is no data.
29	Food	Children under 5 years of age who are stunted	DECREE Nº 2453 (PREFECTURE)	Include; part of SDG 2
30	Food	Children under 5 years of age who are stunted age affected by malnutrition	__	Exclude. No data found for the Municipality

31	Food	Dietary energy supply	__	Exclude. No data found for the Municipality
32	Food	Average protein supply	DECREE Nº 2453 (PREFECTURE)	Include. It is an essential indicator for determining access
33	Food	Obesity in adult population (>18 years)	__	to food.
34	Food	Food produced per water consumption	BRAZIL LEVEL	Exclude. Despite being an indicator that promotes the link between water and food, this data is not available.
35	Food	Amount of food used to generate energy	__	Exclude; no data is available
36	Food	Average income of farmers	IBGE	Include; Has data
37	Food	Cost of harvesting	STATE LEVEL	Exclude; Data is not available
38	Food	Pesticide demand	STATE LEVEL	Exclude; Data is not available
39	Food	Fertilizer consumption	IBGE	Delete; has data but is an irrelevant indicator for determining food sustainability
40	Food**	Average yield	IBGE POF	Include. Essential for determining food sustainability. Knowing how much is produced and how much is consumed.
41	Food	Food consumption	IBGE	Include, data is available.
42	Food	Food production	__	Exclude. SDG 12 indicator. No data available
43	Food	Food loss rate	__	Exclude. No data
44	Food	Percentage of food imports	IBGE	Exclude. Not relevant. Data is available
45	Food	Cultivated area	__	Exclude. Lack of data. However, it would be a good indicator for food security
46	Food	Pest control	IBGE	Include; data is available

** Approximate data

The data for this study were obtained mainly from the IBGE (PNAD and POF), although they have limitations because they do not capture the entire complexity of the population.

The Water Quality Index (WQI) was analyzed for the Atuba, Barigui and Belém rivers, based on the Alto Iguaçu Report (2010-2018). Initially, the geometric mean of each point was calculated, resulting in 0.66 for the Barigui River, 0.94 for the Atuba River and 0.93 for the Belém River. These values were then applied to the Mahalanobis formula, reaching a final value of 0.92, classifying the waters as polluted.

The incidence of waterborne diseases was analyzed with a focus on leptospirosis, which had 93 cases in 2016. This indicator helps to highlight the impact of poor sanitation conditions and water pollution on public health. When there are cases of the disease, it is likely that there are areas with water contaminated by sewage or garbage, which compromises water quality.

Regarding electricity production, Curitiba has initiatives such as the Nicolau Klüppel PCH (21.6 MWh) and the Caximba Solar Pyramid (2048 MWh), contributing to energy diversification.

Food consumption was estimated based on the POF (2008), providing approximate values for Curitiba and the metropolitan region.

The survey uses the most recent data available, most of which come from official sources such as the Brazilian Institute of Geography and Statistics (IBGE). The IBGE collects census data every ten years, with occasional updates in specific surveys, such as the Continuous National Household Sample Survey (PNAD continuous). Although this ensures reliability and comprehensiveness of the information, the long interval between censuses may represent a time limitation for surveys that require more recent data.

After including and excluding indicators, of the initial 46, 15 indicators remained. The AEA nexus matrix for the city of Curitiba, with the latest recorded data, is described in Table 2.

Table 2 - WEF nexus matrix for the municipality of Curitiba

Nº	SECTOR	YEAR	INDICATOR	LATEST CATALOGED DATA	UNIT OF MEASUREMENT
1	Water	2018	People using basic drinking water services	99,6	%
2	Water	1991-2020	Average annual rainfall	1630,7	mm/year
3	Water	2017	Total water consumption	0,171	m³/d/inhab
4	Water	2017	Loss rate	38,3	%
5	Water	2016	Population affected by waterborne disease: leptospirosis	93	People
6	Water	2022	Supply capacity	99,89	%
7	Water	2013-2017	Water Quality Index	0,92	Normalized
8	Energy	2022	Access to energy	99,9	%
9	Energy	2022	Energy consumption	4.651.845	Mwh
10	Energy	2020	Energy production	2069	Mwh
11	Food	2019	Children under 5 years of age affected by malnutrition	4,51	%
12	Food	2023	Obesity in the adult population (>18 years)	24,50	%
13	Food	2008	Food consumption	0,818	Kg/inhab/d
14	Food	2022	Food production	0.001377	Kg/inhab/d
15	Food	2022	Per capita production of pigs, cattle and sheep	1954	heads

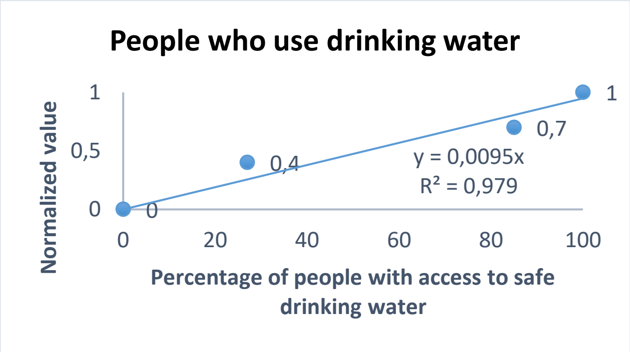
4.1 STANDARDIZATION OF INDICATORS

To normalize the data, Excel software was used, initially analyzing each indicator individually and then comparing them.

The graphs generated in Excel visually represented the normalized data, helping in evidence-based decision-making. The analysis was performed for the Water, Energy and Food indicators.

Currently, 84.9% of the Brazilian population has access to treated water, leaving 30 million people without access, which is represented in the graph as a transitional situation, neither ideal nor totally unfavorable. In addition, approximately 27% of the world's population does not have access to safe drinking water, a critical situation highlighted in Figure (3).

Figure 3 – Percentage of people using basic drinking water services (%)



In Figure 4, the ideal precipitation value corresponds to 1,790 mm/year, corresponding to the most productive city in Brazil, Sorriso, located in the state of Mato Grosso. On the other hand, the area considered poor in the graph corresponds to some cities in the states of Alagoas and Pernambuco, where the annual precipitation is approximately 300 mm, characterizing long periods of drought. In the city of Curitiba, it has approximately 1,630 mm/year, which would correspond to the optimum zone in the graph.

Figure 4- Precipitation (mm/year)

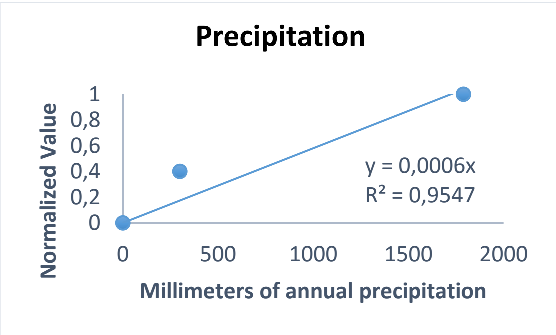


Figure 5 shows the ideal drinking water consumption. The São Paulo Sanitation Company estimates that the consumption required to meet basic needs is 110 liters per person per day, representing the ideal point on the graph. According to the UN, satisfactory consumption should vary between 50 and 100 liters per person per day, with 50 liters being considered reasonable.

In Curitiba, according to the IBGE, the treated consumption was 240 liters per inhabitant per day in 2017, but due to losses in the supply system, the actual consumption was reduced to 170 liters per inhabitant per day. Although the ideal value is 110 liters, values above this are considered acceptable.

Figure 5 – Water consumption L/hab/d

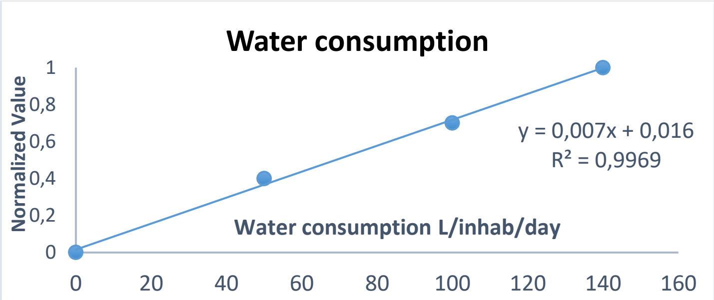


Figure 6 shows the range considered acceptable for water losses in supply systems, as established by the United Nations, generally varying between 15% and 25%. In the graph, the value of 15% is situated in the range considered satisfactory.

According to the National Sanitation Information System (SNIS), in 2018, Brazil had a water loss rate of 38.4%. This value is represented in the graph in the category considered inadequate. In the city of Curitiba, the rates are similar to the national ones, approaching 38.3%, corresponding to the unfavorable zone of the graph.

Figure 6 - Normalized value of the water loss index (%)

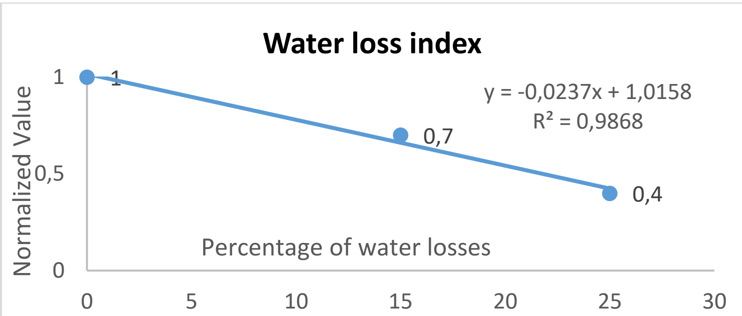
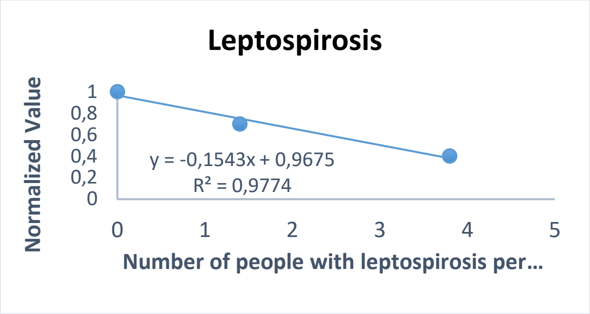


Figure 7 shows the rates of leptospirosis, a disease transmitted by contaminated water. The WHO does not define a universally acceptable rate, as the incidence varies according to local conditions, and is monitored as cases per 100,000 inhabitants, with higher rates in endemic areas. Ideally, the absence of cases would be desirable.

In Brazil, in 2016, there were 3,065 cases, with a rate of 1.4 cases per 100,000 inhabitants, considered moderate. In the state of Paraná, the rate was 3.8 cases per 100,000 inhabitants, classified as unfavorable. In Curitiba, 93 cases were recorded, with a rate of 5.4 cases per 100,000 inhabitants, also classified as unfavorable.

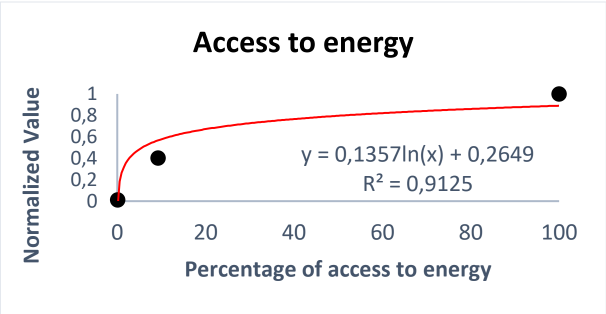
Figure 7 - Leptospirosis (number of people)



Access to energy (Figure 8) is considered a fundamental right and is included in the UN Sustainable Development Goals (SDGs), specifically SDG 7, which aims to ensure reliable, sustainable and affordable access for all.

In an ideal scenario, access to energy would be 100% for all. In Brazil, the southern region, where Curitiba is located, has 99.3% access. However, the International Energy Agency (IEA) (2023) indicates that 9.3% of the global population still lacks access to electricity, representing an unfavorable condition.

Figure 8 – Access to energy (%)



As previously mentioned, the electricity distribution network in Brazil is integrated into the National Interconnected System (SIN). In recent years, the incorporation of photovoltaic energy and small hydroelectric plants has resulted in an increase in the energy generated and distributed locally. In Table 2, the energy consumption values in the municipality are 4,651,845 MWh, while energy production is approximately 2,069 MWh. Figure 18 illustrates energy consumption in the city of Curitiba, demonstrating that local production is less than 1% (Figure 9) of the total consumed.

Figure 9 - Consumption x production

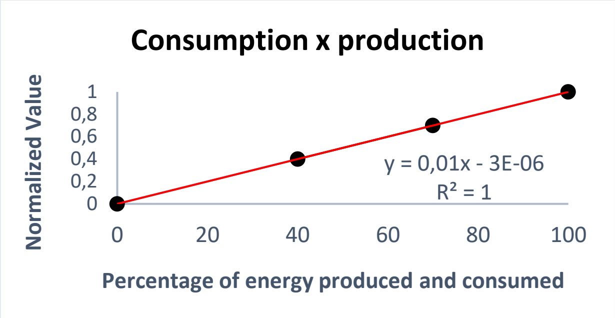
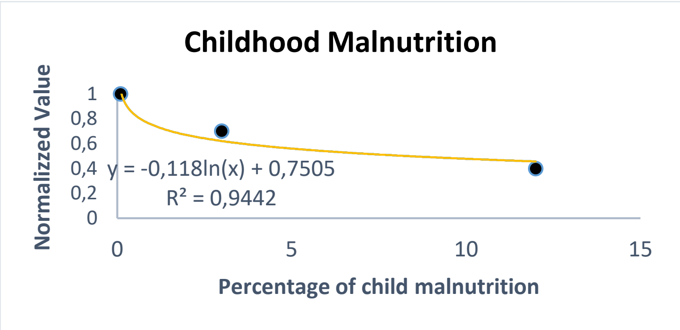


Figure 10 shows child malnutrition rates. The ideal global goal is to minimize the number of children under 5 who are malnourished. Japan has one of the lowest child malnutrition rates in the world, around 3%, reflecting an advanced health system and high socioeconomic levels. In contrast, Brazil has approximately 12% of children affected by malnutrition, which is a concern. In Curitiba, the rate is 4.5%, characterizing a moderate level of malnutrition.

In the graph, the ideal value is zero malnutrition, with Japan classified as favorable, Brazil as low, and Curitiba as fair.

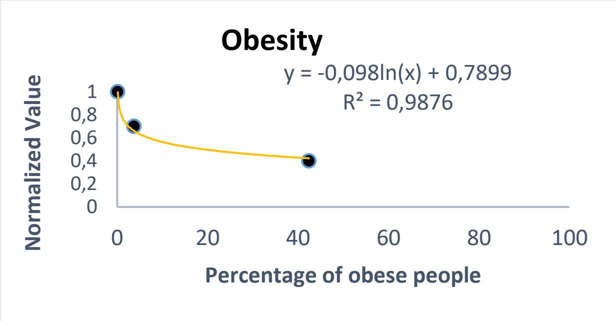
Figure 10 – Malnutrition



In 2020, obesity in the United States affected 42.4% of adults, an increase of 26% since 2008. This rate is one of the highest in the world. In contrast, Japan has less than 4% of the obese population, which is considered favorable in the graph (Figure 11), since the ideal value for obesity is zero.

In Brazil, according to Abeso, in 2019, 19.8% of the adult population was obese, which is classified in the graph as moderate. In Curitiba, the obesity rate in 2023 was 24.5%, which characterizes a more worrying situation.

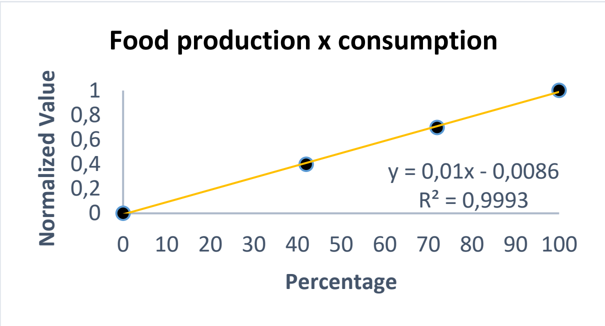
Figure 11 – Obesity (%)



Determining the ideal amount of food production and consumption varies according to factors such as demographics, nutritional needs, natural resources and food security policies. There is no universal value, as each country has its own particularities.

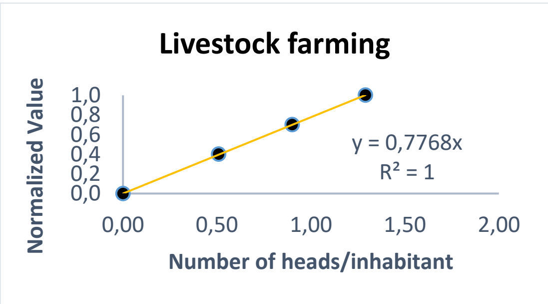
In the case of Curitiba, which depends heavily on external food, local production serves less than 1% of the population (Figure 12), highlighting the need for imports to meet the city's food demands.

Figure 12 - Food production and consumption



Just like agricultural production, livestock farming is also relatively low, with values lower than 0.1% of Brazilian production, which is due to the city's more urban than rural nature. If we compare the number of cattle in the state of Paraná (15,498,188) with the number of inhabitants of the state (approximately 12 million), we will obtain a favorable situation in the graph, with a little more than one steer per inhabitant. However, when performing the same calculation for the city of Curitiba, the resulting value will be close to zero (Figure 13).

Figure 13 - Livestock farming



For a better fit of the trend line, the polynomial equation was more suitable than the linear, logarithmic and power equations in most graphs. Each trend line was checked and adjusted using the coefficient of determination R^2. Each graph presented the most suitable formula based on the values of x and y, aiming for an R^2 as close as possible to 1. Then, the x values were replaced by data from the city of Curitiba, allowing the normalization of each indicator. Table 3 shows all the normalized data.

Table 3 – Standardized Indicators

Nº	INDICATOR	ÍNDEX	NORMALIZED VALUE
1	People using basic drinking water services	99,6	0,948
2	Average annual precipitation	1630,7	0,978
3	Total water consumption	0,171	1,206
4	Loss rate	38,3	0,108
5	Population affected by waterborne disease: Leptospirosis	93	0,134
6	Water Quality Index	0,92	0,92
7	Energy access	99,9	0,887
8	Energy consumption vs. production	4.651.845/2069	- 0,001
9	Children under 5 years of age affected by malnutrition	4,51	0,573
10	Obesity in the adult population (>18 years)	24,50	0,476
11	Food consumption vs. production	0,818/0.001377	0,0086
12	Per capita production of pigs, cattle and sheep	1954	- 0,0008

Values must be in the range of 0 to 1. The closer to zero, the more unfavorable the scenario. Values closer to 1 are considered closer to the ideal. Therefore, values that were below zero were rounded to zero and, later, to 0.1 for a better assessment of the geometric mean. Values that exceeded 1.0 were rounded to 1.0, as it is understood that the ideal situation is represented by the value 1 and above this point.

4.2 APPLICATION OF COMMITMENT PROGRAMMING

With the indicators standardized, the final step consisted of defining the sustainability index for the city of Curitiba. For each indicator, the geometric mean was calculated. The geometric mean for the water indicator resulted in 0.435, for the energy indicator it was 0.297 and for the food indicator it was 0.123. With these results, the Mahalanobis formula was used for a more precise assessment.

According to the methodology adopted, values between 0 and 0.43 are considered excellent in terms of sustainability. Values between 0.43 and 0.86 are classified as moderate, while values above 0.86 to 1.44 are indicative of low sustainability. The value obtained by applying the equation was 1.06, demonstrating that Curitiba is in the low sustainability range.

By identifying solutions that are close to the Pareto frontier, managers can ensure that resources are being used in a balanced manner, maximizing overall sustainability.

As mentioned previously, Curitiba has received several sustainability awards in recent decades. One of the main reasons for its recognition as the most sustainable city in Brazil was its implementation of actions aimed at reducing car use, encouraging the generation and use of renewable energy, promoting food security, reducing social inequality, reducing waste sent to landfills and encouraging urban agriculture. These initiatives have promoted the socioeconomic development of the city in line with sustainability principles.

However, when analyzing the sustainability indicators presented in this paper, it can be seen that Curitiba faces significant challenges regarding the sustainability of fundamental resources such as water, energy and food. With regard to the food indicator, the city presents a notable imbalance, as consumption is much higher than its local production, which is practically insignificant. The same can be observed in the energy sector, where internal production is low and the city depends heavily on the national interconnected system to ensure the supply of almost 100% of the population.

These data reveal that, despite achievements in several areas, Curitiba still faces challenges in terms of self-sufficiency and sustainability in critical natural resource sectors, requiring greater attention and investment in local solutions to improve these indicators in the long term.

5 FINAL CONSIDERATIONS

Although Curitiba has been widely recognized for its sustainability initiatives, it still faces significant challenges regarding the nexus between water, energy and food. Despite its advances, the city relies heavily on external resources, which compromises its status as a truly sustainable city.

Energy: Curitiba relies heavily on the national interconnected system, which limits its local energy generation capacity and creates external dependency. This conflicts with the principles of self-sufficiency and resilience, which are essential for sustainability.

Food: The city also lacks significant local agricultural production, relying on food imported from other regions, which increases the ecological footprint related to transportation and can generate vulnerabilities in relation to food security.

Water: The quality of the city's rivers is a concern, with water pollution and basic sanitation problems that directly affect public health, such as in the case of leptospirosis. This situation goes against the image of a sustainable city.

In addition, urbanization and population growth increase pressures on natural resources, which requires greater investment in local solutions, such as energy generation, food production and water treatment.

The creation of a matrix of indicators enabled the integrated analysis of three fundamental sectors for systemic functioning and urban sustainability.

The methodology adopted to assess sustainability indicators was effective in integrating different variables, such as water, energy and food, considering urban and environmental challenges. The analysis used tools such as commitment programming, Pareto and Mahalanobis analyses, as well as geometric normalization techniques, which allowed for an equitable comparison of data, despite the differences in scale between the indicators.

One of the challenges observed is the institutional fragmentation in Brazil, with separate laws for the management of water, energy and food, which makes it difficult to implement integrated public policies. The lack of coordination between these sectors prevents a systemic and efficient approach to the water-energy-food nexus, which is crucial for building real sustainability.

The research also faced difficulties in obtaining accurate data, especially from state and municipal agencies, which reflect a lack of transparency and integration between information. This impacts the creation of effective public policies.

The nexus WEF highlights the critical interdependence between these three systems, and is a key concept for formulating public policies that promote sustainable development and urban resilience. In the context of cities such as Curitiba, these interactions are fundamental for territorial planning, natural resource management, and the promotion of socio-environmental justice. Cities are both major consumers and managers of these resources, and integrated urban planning must take into account existing interconnections and vulnerabilities. Incorporating the nexus WEF into urban planning allows for a more systemic and cross-cutting approach to public policies. Measures such as the creation of management protection zones, the promotion of renewable energy technologies, and the implementation of community urban gardens are examples of policies that integrate these three dimensions.

In summary, the results of this study indicate that, although Curitiba has made progress in areas such as public transport and green areas, the city faces significant challenges in the management of its water, energy and food resources. Dependence on external sources and the lack of local production put the city’s autonomy and adaptability at risk, especially in the face of future climate and economic challenges. Therefore, it is essential that Curitiba develop public policies focused on improving energy efficiency, encouraging local food production and implementing sustainable water management.

Collaboration between different sectors of society will be essential to address these challenges and align Curitiba with the Sustainable Development Goals (SDGs), ensuring a more sustainable future for the city.

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