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Evaluating the sustainability performance of Turkish provinces with fuzzy logic

Sustainability is the balance of social, economic, and environmental factors. Evolving from history to the present, the goal of this concept is for humanity to live in harmony with nature. Sustainable development, on the other hand, encompasses achieving urban goals for the future while increasing prosperity and efficiently passing resources to future generations. Sustainability indicators are utilized to guide policymaking and monitor progress. Indicators introduced by various institutions vary by country. In developing economies like Turkey, which this study focuses on, there are a limited number of works on measuring sustainability performance. Hence, this study evaluates urban sustainability levels using the fuzzy logic method. Another objective is to develop a measurable and replicable numerical model to analyse the sustainability performance of cities in Turkey. The study employs a measurement set consisting of twenty-seven indicators from the main ecological, economic, and social components, and it assesses the sustainability levels of cities using fuzzy logic rules. Based on the results obtained, all eighty-one provinces of Turkey are classified into quantile groups and mapped. This analytical approach can guide urban planners, policymakers, and decision-makers. This study contributes to enhancing knowledge and understanding sustainability.

Keywords: sustainability, sustainable cities, fuzzy logic, Turkey

1 Introduction

In today's world, the effects of COVID-19, population growth, climate change, environmental degradation, inadequate housing, and uncertainties related to the nexus of water, food, and energy are subjects of intense debate among academics, urban planners, and policymakers (Dumane et al., 2019; Son et al., 2023). The urbanization dynamic experienced since the Industrial Revolution has led to the rapid consumption of global resources by the human population. It is projected that by 2050 approximately 70% of the world's population, or 6.9 billion people, will live in cities (UNDP, 2020; Bharani & Ramesh, 2022). Ensuring the sustainability of life and cities and providing wellbeing for future generations require wise utilization of natural resources today. Alongside issues such as global warming, ozone layer depletion, housing, health, and the environment, policymakers need to strive for sustainable development in cities (Dumane et al., 2019).

Sustainability can be thought of as the fundamental goal of people living in harmony with nature (Robati & Rezaei, 2022). Sustainability, in a general sense, involves striking an appropriate balance among social, economic, and environmental factors (Dumane et al., 2019). The concept of sustainability has evolved from the past to the present with increasing inclusivity and continuous development. Etymologically, it comes from Latin *sustinere* 'to stand, endure' (Alptekin & Saraç, 2017). Sustainability is a long-term concept (Kusakci et al., 2022). It holds significant implications for both the private and public sectors. For businesses, it signifies adaptability to the competitive market and gaining a competitive advantage, whereas in the public sector it serves objectives such as cost efficiency, positive environmental outputs, directing the private sector toward sustainable technologies, and fostering consumer awareness about environmental and ecological issues (Akçakaya, 2016).

Sustainable development is defined as sustainable economic growth and ecological renewal. The concept of sustainable development has been pushed to the forefront of urban policy debates with the hope of constructing a desirable urban future It promises to achieve urban goals without compromising the welfare of society, quality of life, and the environment (Son et al., 2023). Sustainable development indicators are used as a source of information for crafting strategic documents and development programs. They aid in setting priorities, monitoring the success of solutions to problems, and gauging the success or failure of interventions related to environmental, social, and economic issues. The aim is to integrate the public into the decision-making process by designing, selecting, and evaluating indicators collaboratively (Michalina et al., 2021). Indicators provide information to the public, researchers, and policymakers.

One method that can be employed to measure the sustainability performance of cities is the fuzzy logic method. Fuzzy logic converts expressions conveyed in natural language into mathematical concepts, and it constructs a logical structure tailored to a specific problem (Robati & Rezaei, 2022). This structure reduces uncertainty and complexity within the system and provides clearer results. The fuzzy logic method allows for the representation of a city's sustainability level not in sharp terms such as good or bad, but in degrees of goodness or badness. The hypothesis of this study is "The fuzzy logic method can serve as an effective tool for evaluating the sustainability levels of cities using a measurement set encompassing various sustainability components and indicators." This hypothesis is based on the ability to categorize cities in Turkey according to their sustainability performance levels into quartile groups using the fuzzy logic method. The aim of the study is to make sustainability performance measurable with a model that is applicable, repeatable, and based on numerical data. The measurement set developed for this study to measure the sustainability performance of cities is approached with the fuzzy logic method. The results obtained have the potential to serve as a guide for city planners, policymakers, and decision-makers to create more sustainable cities. The study starts by providing background information from the literature, followed by information about the sustainability of cities in Turkey and fuzzy logic. Then, the method section explains the model created for this study. Finally, the findings are presented and evaluations are made.

2 Background

2.1 The concept of the sustainable city and monitoring the sustainability of cities

In today's context of creating a sustainable world, it is of great importance to manage cities, which have local and global impacts on natural resources and ecological balance, as well as changes and transformations in these cities. Referred to as "urban sustainability" or the "sustainable city", the integrated development of cities with economic, social, and environmental sensitivities entails significant responsibilities for local governments, which are the closest public institutions to urban communities. The functions of local governments are manifested in areas such as producing urban sustainable policies and measuring urban sustainability performance (Akçakaya, 2016). Urban sustainability can be considered the part of sustainable development that emphasizes the balance between environmental, economic, and social sustainability, highlighting the improvement of human wellbeing and quality of life (Robati & Rezaei, 2022). On the other hand, the international organization ICLEI (Local Governments for Sustainability) states that "sustainable cities work towards providing environmentally,

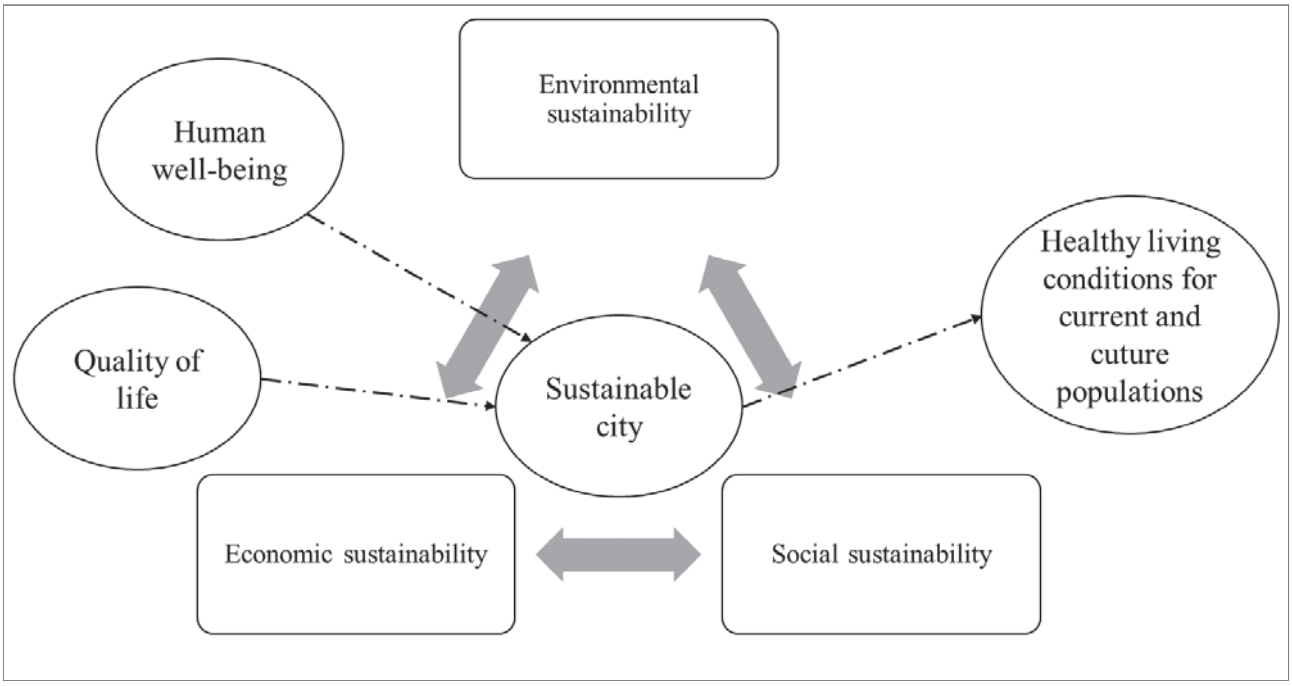


Figure 1: Definitions of urban sustainability (illustration: authors).

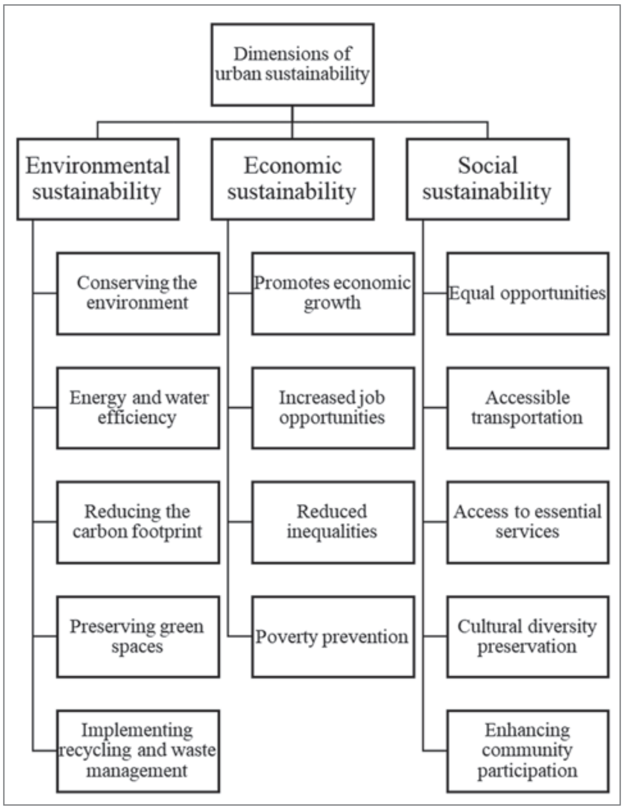


Figure 2: Dimensions of urban sustainability (illustration: authors).

socially, and economically healthy and flexible living conditions for current populations, without compromising the ability of future generations to have the same experience" (Figure 1). However, many issues in cities require responsible institutions to address and ideally resolve them (Michalina et al., 2021).

The concept of urban sustainability was addressed during the United Nations Habitat II Conference on Human Settlements, also known as the City Summit, held in Istanbul in 1996 (Alptekin & Saraç, 2017). This concept emerged from the idea that cities need to carefully and effectively utilize natural resources to meet the needs of current and future generations, as well as to inclusively support people. Sustainable cities are characterized by environmental sustainability measures such as conserving the environment, energy and water efficiency, reducing carbon footprints, preserving green spaces, and implementing recycling and waste management (Pınarcıoğlu & Kanbak, 2020). Economic sustainability implies that cities should promote economic growth while increasing job opportunities, reducing inequalities, and preventing poverty. Social sustainability, on the other hand, means that all communities living in cities have equal opportunities, accessible transportation, and easy access to education, health, housing, and other essential services (Figure 2). Furthermore, preserving cultural diversity, enhancing community participation, and strengthening democratic processes are also important for social sustainability (Michalina et al., 2021).

The Sustainable Development Goals (SDGs) consist of seventeen goals and 169 targets adopted by the United Nations in 2015 with the aim of promoting sustainable development globally by 2030 (UN, 2015). These goals aspire to build a more sustainable and equitable world, addressing both urban and rural areas. The Sustainable Development Goals, which seek to complete what the Millennium Development Goals could not achieve, prioritize the balance between the three dimensions of sustainable development: economic, social, and environmental. Urban sustainability holds a significant place within the Sustainable Development Goals. For global development, it is imperative that the majority of the population living in cities also become sustainable. For example, the goal Clean Water and Sanitation (SDG 6) comprises targets related to sustainable water resource utilization, clean water provision, and wastewater disposal within urban areas. Sustainable Cities and Communities (SDG 11) is a goal directly related to urban sustainability. It expects factors such as sustainable infrastructure, transportation systems, energy usage, and urban planning to contribute to the liveability and sustainability of cities. Clean Energy (SDG 7) is a goal that encourages the promotion of renewable energy in urban areas. Good Jobs and Economic Growth (SDG 8) aim for sustainable and inclusive growth. It describes the economic role that cities need to assume, such as job creation and promoting economic growth. Health and Wellbeing (SDG 3) is greatly impacted by urban planning. A clean environment, green spaces, and well-planned cities can contribute to people living healthier lives. Reducing Inequalities (SDG 10) is significant for social sustainability in cities. Decreasing inequalities in areas such as income, education, and living standards within urban areas is a key target.

Sustainable urbanization is considered one of the key elements of sustainable growth. Therefore, measuring the sustainability of cities and evaluating their performance are thought to be responses to achieving growth goals. As a result, urban sustainability indicators, designed as a framework comprising environmental, economic, and social aspects, are used as tools to assess the sustainability performance of cities (Pınarcıoğlu & Kanbak, 2020). Monitoring sustainable urban development poses a challenge for policymakers in terms of selecting relevant thematic categories and indicators. The selection of categories and indicators is carried out based on meeting specific criteria and requirements. The entire process of selecting categories and indicators must be transparent, methodologically accurate, and clearly justified. In most cases, eliminating the subjective nature of this process is difficult because the selection of categories and indicators is not value-neutral; rather, it reflects the biases, failures, intentions, assumptions, and worldviews of the framers of the framework (Michalina et al., 2021).

The European Commission's 2018 report *Indicators for Sustainable Cities* discusses the function of performance indicators in measuring sustainability performance. In this context, urban sustainability indicators can provide urban planners, local administrators, and policymakers with the ability to measure the socioeconomic and environmental performance of the city. Urban sustainability indicators that assist in measuring the city's performance in areas such as urban design, infrastructure services, policies, waste disposal systems, pollution, and accessibility to services not only aid in identifying issues but also help identify areas of improvement through good governance and research (Akçakaya, 2016; European Commission, 2018). Due to the significant variations in terms of available resources, population size, and urban metabolic processes among cities, the richness of sustainability indicators is beneficial. However, selecting appropriate sustainability indicators can be challenging (European Commission, 2018). There are measurable and comprehensible economic, social, and environmental indicators that allow for comparisons between different geographical regions and times to determine whether sustainable development is taking place in cities and to what extent (Çolakoğlu, 2019). Sustainability indicators are a proven method to promote sustainable urban development, and there are hundreds of different sets and frameworks available. The United Nations Human Settlements Programme (UN-Habitat), the UN Sustainable Cities Program, the World Bank's City Strength Diagnostic, the Sustainability Index for Cities, and the European Sustainable Cities Award have all introduced various indicators to measure the sustainability of cities (European Commission, 2018). Urban sustainability indices allow city planners and policymakers to assess the economic, social, and environmental impacts of applied urban plans on infrastructure development, policies, pollution, and citizens' access to services (Robati & Rezaei, 2022). Generally, there is no clear consensus on the methodology or standards in indicator sets that define the fundamental elements a city needs to ensure its sustainability (Pires et al., 2014).

2.2 Sustainability of cities in Turkey

There are a considerable number of studies on the sustainability performance of cities in developed countries, but there are relatively few studies focusing on emerging economies such as Turkey, mainly due to the incipient stage of the indicator-based approach (Kusakci et al., 2022). Cities in Turkey, which have experienced significant urban growth in the past fifty years, are home to approximately 75% of the total population. Cities in Turkey face diverse environmental and social challenges that require a variety of sustainable measures. According to Turkey's Tenth Development Plan, the most critical urban issues are inadequate housing units, traffic congestion, security and infrastructure deficiencies, social cohesion, migration, and environmental degradation (Kusakci et al., 2022). Moreover, the World Bank Group has supported sustainable development in Turkey through the Sustainable Cities Project by expanding financing. The program aims to improve the economic, environmental, and social sustainability of cities by enabling municipalities to access funds for priority investments (World Bank, 2019). Unfortunately, a shared set of sustainability measurement indicators for all provinces in Turkey is not yet available.

As a member of the United Nations, Turkey also signed the Paris Agreement in 2021, indicating its increased efforts in addressing climate change. When examining the studies conducted on the sustainability of cities in Turkey up to this point, it is evident that various analysis methods have been used. Gülcan and Aldemir (2008) compared two provinces in the Aegean Region (Aydın and Denizli) in terms of economic and sociocultural factors. They stated that economic factors alone are not sufficient to evaluate sustainability. Therefore, other factors such as cities' cultural values and networks must also be included (Kusakci et al., 2022). The Sustainability Study of Turkey's Cities, conducted in 2011 in collaboration between Boğaziçi University and MasterCard, was examined. This study used both objective and subjective data. Objective data involved using indicators published at the province level to calculate sustainability and quality of life indices covering all eighty-one provinces in Turkey. In addition to objective assessment, a survey was conducted with business managers in twenty-nine provinces, including twenty-six regions at the NUTS 2 level and sixteen metropolitan municipalities for subjective evaluation (MasterCard Worldwide & Boğaziçi Üniversitesi, 2011).

Gazibey et al. (2014) analysed the sustainability performance of the eighty-one provinces in Turkey using social, economic, and environmental indicators and the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. The TOPSIS method is a technique for determining the preference ranking of alternatives in multi-criteria decision problems (Hwang & Yoon, 1981). The TOPSIS method aims to simultaneously identify alternatives that are closest to the "positive ideal solution" and farthest from the "negative ideal solution". The positive ideal point has the highest benefit and the lowest cost, and the negative ideal point is associated with the lowest benefit and the highest cost. Consequently, the ranking of alternatives is established in descending order based on their relative proximity values to the ideal solutions (Gazibey et al., 2014). The results indicated that Kocaeli, Istanbul, and Ankara were the top three sustainable cities. It was emphasized that the results from this study could assist in making decisions during the creation of new public policies and help achieve a balance between costs and benefits among stakeholders. The need for new indicators and the necessity of data collection related to these new indicators for evaluating the sustainability of provinces in the country were highlighted (Alptekin & Saraç, 2017).

Yıldırım et al. (2017) focused on examining the perception levels of local government personnel in Istanbul regarding environmental sustainability tools by evaluating indicators of Local Agenda 21, including social activities, renewable energy projects, energy efficiency projects, green transportation, and waste management. The results indicated that strategy-based practices such as sustainable planning and participatory policies were more successful than project-based applications (Kusakci et al., 2022). Alptekin and Saraç (2017) used the entropy weight determination method for determining the importance levels (or weights) of each variable in the indicator set that assists in measuring sustainable development. They also employed the grey relational analysis technique, a multi-criteria decision-making method, to establish rankings for sustainable development among provinces in Turkey (Alptekin & Saraç, 2017). Finally, in their study conducted in 2022, Kuşakçı et al. used the IT2D-AHP method to reveal that the level of urban sustainability in the thirty metropolitan cities in Turkey varied in economic, social, environmental, and institutional dimensions through the Sustainable Cities Index (Kusakci et al., 2022). The aim of all these studies is to raise awareness about urban sustainability, provide data-based contributions to policymakers' decision-making processes, and offer a roadmap for measuring and improving the performance of cities in terms of sustainability.

Defining urban sustainable development in purely quantitative terms is difficult, and over the past decades researchers have acknowledged the inherently uncertain and ambiguous nature of defining and addressing indicators related to the efficient and effective use of resources through various data collection methods (Hincu, 2011). The outcomes of sustainable development are uncertain in both qualitative and mathematical sustainability assessments. To obtain a sustainable model for a city system, the sustainability of subsystems can be integrated using fuzzy logic (Jaderi et al., 2014). Sustainable development is a concept that simultaneously meets the needs of economic, social, and environmental dimensions. Andriantiatsaholiniaina et al. (2004) developed the SAFE (Sustainability Assessment by Fuzzy Evaluation) model, which can be explained by fuzzy logic and uses basic, environmental integrity, economic efficiency, and social solidarity indicators to measure sustainable development. They proposed this model for the Greek and American economies and argued that there is no single way to make effective sustainable decisions, advocating the use of different indicators for each country (Alptekin & Saraç, 2017).

2.3 Fuzzy logic

Fuzzy logic is a method that was introduced by Lotfi A. Zadeh in 1965. Fuzzy logic is a mathematical approach used to model and control systems that involve uncertainty, lack of precise boundaries, or transitions between specific values (Robati & Rezaei, 2022). This method is designed to handle uncertainties commonly encountered in complex and real-world scenarios. Fuzzy logic aims to equip machines with the ability to think and make conclusions like humans, using imprecise terms expressed in natural language (Phillis et al., 2017). The

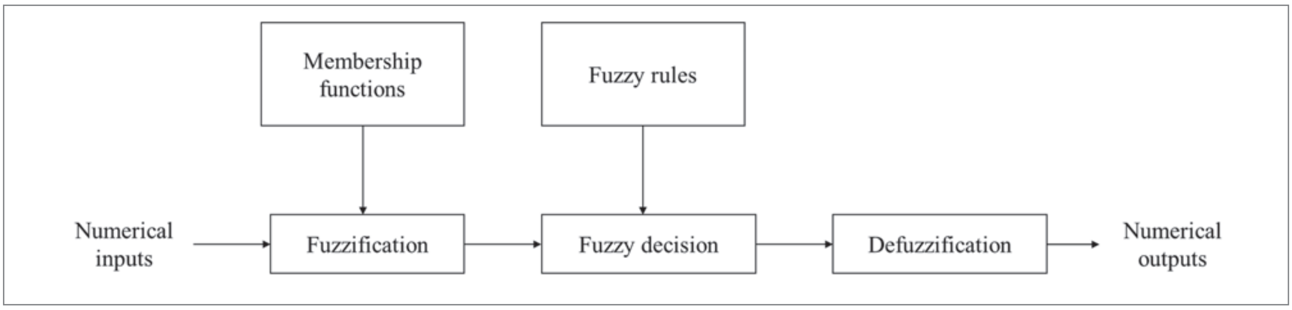


Figure 3: Fuzzy logic (illustration: authors).

applications of fuzzy logic are quite extensive, including control systems, artificial intelligence, robotics, image processing, machine learning, natural language processing, economics and finance, and environmental and energy management. In addition, fuzzy logic is used in various sectors such as healthcare, traffic management, industrial processes, and agriculture. Fuzzy methodologies can address assessment challenges in sustainability evaluations. As an appropriate method, in urban sustainability analysis, it is often used for purposes such as developing composite indices to rank and assess urban sustainability performances, evaluating urban renewal projects, and comparing local-scale units or cities from around the world (Buzási et al., 2022).

Unlike traditional binary logic, fuzzy logic evaluates the infinite possibility range within the interval (0–1) because it does not have strict binary thresholds. Fuzzy logic can be employed as a method to model and analyse uncertain and complex systems (Hincu, 2011). This method helps reduce uncertainty in the data, aiding in better understanding the system. The method also allows for the incorporation of expert opinions and experiences. The fuzzy logic method describes a process in which numerical data are first evaluated verbally and then expressed numerically again at the output. The fuzzy logic process is summarized in Figure 3. The method starts with the fuzzification process, in which numerical data are transformed into verbal expressions. For each input datum, membership functions are created in various shapes such as triangles, Gaussian curves, or trapezoids. These membership functions are defined using verbal expressions such as low, medium, and high. The second stage of the method is called the fuzzy decision-making process, in which the output expression is defined based on the relationship between membership functions. The rules in this stage are expressed as "if . . . and/or . . . then . . ." rules. In this way, a verbal output is obtained based on the relationship between different inputs. In the final stage of the method, the numerical counterpart of the verbal output expression obtained is calculated, and this stage is referred to as defuzzification (Figure 3).

3 Method

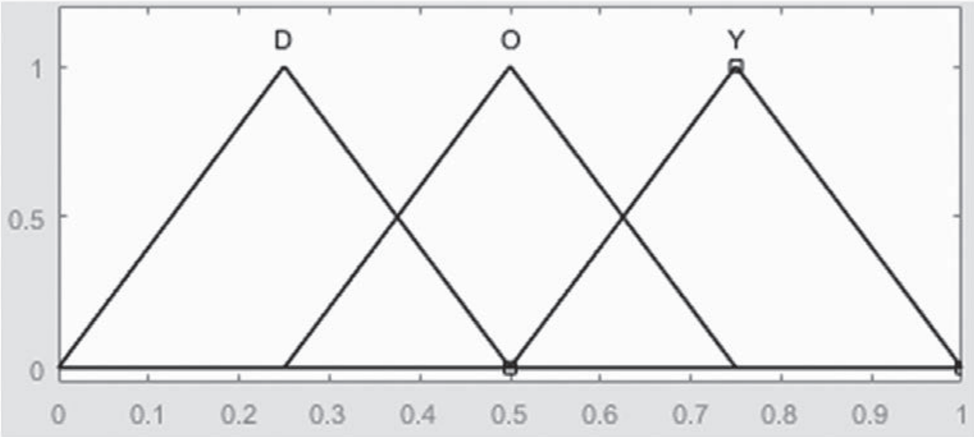
This study employs the fuzzy logic method within a model based on an indicator set to monitor the sustainability performance of all cities in Turkey. The sustainability performance of a city is addressed based on numerical data along with sub-components defined within the main ecological, economic, and social components. The ecological component includes subcomponents of air, water, soil, and energy. Two indicators are used for air, two for water, three for soil, and two for energy. The economic component includes subcomponents of work life and livelihood, with three indicators used for each. For the social component, the subcomponents are defined as population, education, health, and housing. Population is examined through two indicators, education through four, health through three, and housing through three. The results were obtained for the main components by applying fuzzy logic rules to the indicators. By applying these fuzzy logic rules again to the data obtained, the sustainability levels of all cities in Turkey were calculated individually.

In this study, careful attention has been given to whether each selected indicator for determining the sustainability performance of provinces has a counterpart at the provincial level. The indicators utilized in the study have also been employed in previous research related to this subject in Turkey. Detailed explanations regarding the data, the reference study for the data, and the impact of the fuzzy logic rules (positive/negative) are provided in Table 1. The limitations of this study include accessing data at the provincial level and selecting the same or the nearest available year as the reference year. Although data in Turkey are recorded by the Turkish Statistical Institute (TSI, 2020, 2021, 2022), some data were obtained from other sources. Data related to commercial establishments were obtained from the Union of Chambers and Commodity Exchanges of Turkey (UCCE, 2022), housing depreciation data from the Endeksa website (Endeksa, 2022), forest assets from the General Directorate of Forestry (2021), and electricity-related data from the Energy Market Regulatory Authority (EMRA, 2022).

Table 1: Sustainability performance model indicators.

	Indicator		References	Impact
Economic	Work life			
		Unemployment rate	Gazibey et al., 2014; UN, 2015 (SDG 8); Alptekin & Saraç , 2017	Negative
		Labour force	Gazibey et al., 2014; Alptekin & Saraç , 2017	Positive
		Companies	Alptekin & Saraç , 2017	Positive
	Livelihood			
		GINI coefficient	UN, 2015 (SDG 4)	Negative
		Regional poverty	UN, 2015 (SDG 10)	Negative
		GDP	UN, 2015 (SDG 8); Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
Ecological	Air quality			
		Annual PM10 levels	MasterCard, 2011; Gazibey et al., 2014; UN, 2015 (SDG11); Alptekin & Saraç , 2017	Negative
		Cars per capita	Kuşakçı et al., 2022	Positive
	Water			
		Access to potable water	MasterCard, 2011; Gazibey et al., 2014; UN, 2015 (SDG 6); Kuşakçı et al., 2022	Positive
		Access to sewerage network	MasterCard, 2011; Gazibey et al., 2014; SDG 6; Kuşakçı et al., 2022	Positive
	Soil			
		Built-up areas open for public use	UN, 2015 (SDG 11)	Positive
		Forest area	MasterCard, 2011; UN, 2015 (SDG 15)	Positive
		Municipal waste collection and treatment	MasterCard, 2011; UN, 2015 (SDG 11); Kuşakçı et al., 2022	Positive
	Energy			
		Electricity consumption	MasterCard, 2011	Negative
		Renewable energy	Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
Social	Population			
		Population density	MasterCard, 2011; Gazibey et al., 2014; Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Negative
		Net migration	Kuşakçı et al., 2022	Negative
	Education			
		Literacy	MasterCard, 2011; Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
		Primary school enrolment	UN, 2015 (SDG 4); Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
		Junior high school enrolment	UN, 2015 (SDG 4); Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
		High school enrolment	UN, 2015 (SDG 4); Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
	Health			
		Under-5 mortality rate	Gazibey et al., 2014; SDG 3; Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Negative
		Physicians per capita	MasterCard, 2011; Gazibey et al., 2014; UN, 2015 (SDG 3); Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
		Life expectancy	Kuşakçı et al., 2022	Positive
	Housing			
		Depreciation (rent)	UN, 2015 (SDG 11)	Negative
		House sales	Alptekin & Saraç , 2017; Kuşakçı et al., 2022	Positive
		Buildings with building permit	Kuşakçı et al., 2022	Positive

Source: Authors.



	Basic indicators			Sub-components, components, and sustainability		
	L	M	H	L	M	H
P1	0,00	0,25	0,50	0,00	0,20	0,50
P2	0,25	0,50	0,75	0,20	0,50	0,80
P3	0,50	0,75	1,00	0,50	0,80	1,00

Figure 4: Membership functions and limits (illustration: authors).

The data have been normalized within their value ranges and scaled to a range of 0 to 1. Normalization has been applied to the data in the study because the indicators are expressed in different measurement units. This ensures that cities can be compared. The normalization process has been performed based on the minimum and maximum values in the data sets related to the indicators, using the following formula:

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

where x_{norm} is the normalized value, x is the real value, x_{min} is the minimum value, and x_{max} is the maximum value in the data set.

This model starts from the indicators and ultimately reaches the sustainability performance degree. All membership functions have been chosen in the form of a triangle due to their convenience and frequent preference in the literature (Figure 4). Membership functions at all stages have been uniformly and evenly distributed. In the first stage of the model, membership functions for the indicators have been defined as Low (L), Medium (M), and High (H) in triplets. The boundary values used to create these triangles are provided in the table as P1, P2, and P3. The basic indicator, sub-component, component, and sustainability limits in the study are given in Figure 4.

Rules were written for the relationships between indicators and sub-components. In writing these rules, all components were treated with equal weight in line with expert opinions. The positive effects of some components and negative effects of others were considered in writing the rules. By running the MATLAB program, data in the range of 0 to 1 for sub-components were obtained. In the second stage, triplet membership functions were created for sub-components using Low (L), Medium (M), and High (H) expressions based on the data related to sub-components. Rules were written for the relationships between sub-components and components. By running the MATLAB program, results in the range of 0 to 1 for components were obtained. In the final stage, membership functions for components were created as Low (L), Medium (M), and High (H) expressions in triplets. Rules were written for the relationships between components and sustainability, and the sustainability performance values were obtained in the range of 0 to 1 as a result of the model (Figure 5).

In this study, the Mamdani fuzzy inference method was applied. The Mamdani method consists of four stages: fuzzification of input variables, evaluation of rules, aggregation of rule outputs, and defuzzification. In the fuzzification stage, numerical values of the inputs are associated with membership degrees in their corresponding membership functions. The evaluation of rules determines the output based on the membership degrees of the inputs, finding the corresponding output function values. The values of the inputs are applied to all written rules, and the output functions are aggregated.

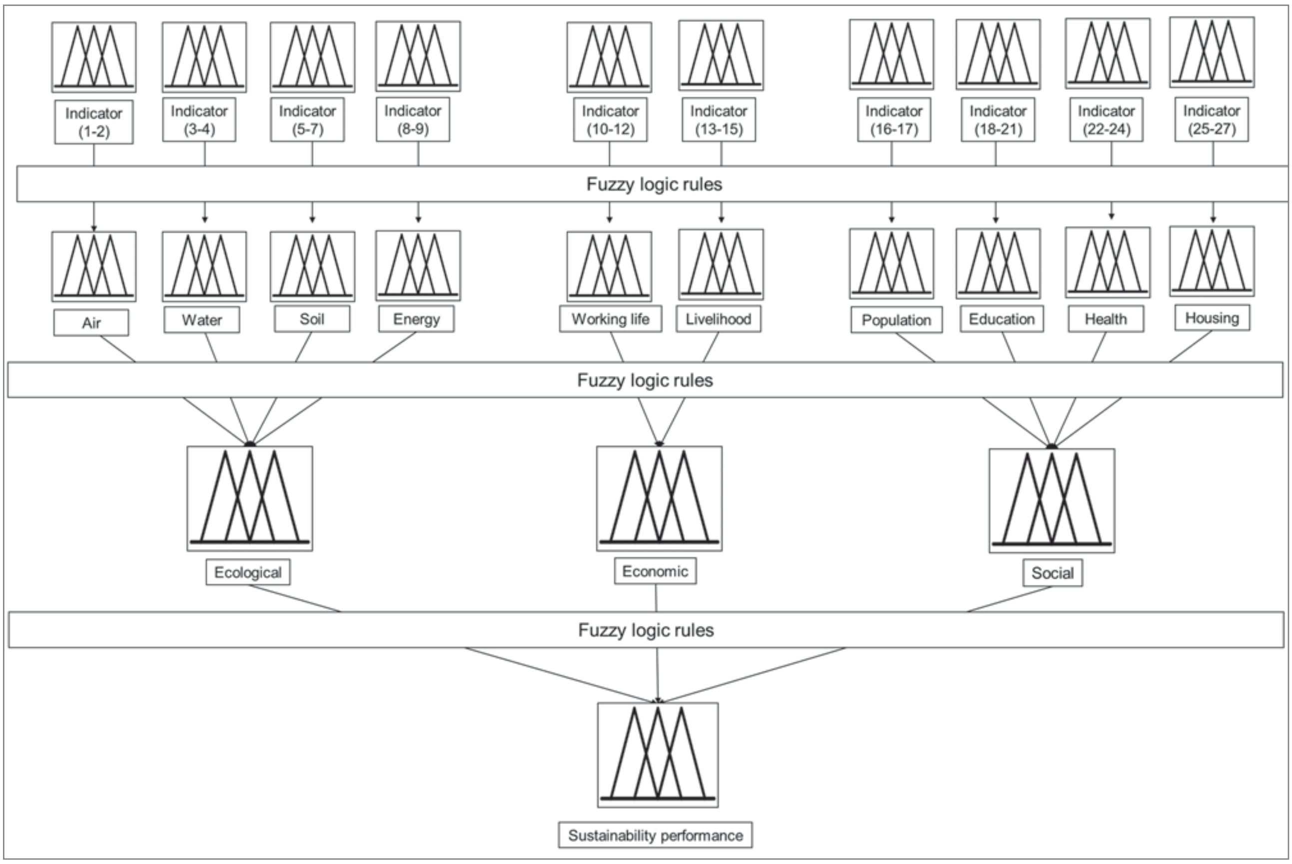


Figure 5: Sustainability performance model (illustration: authors).

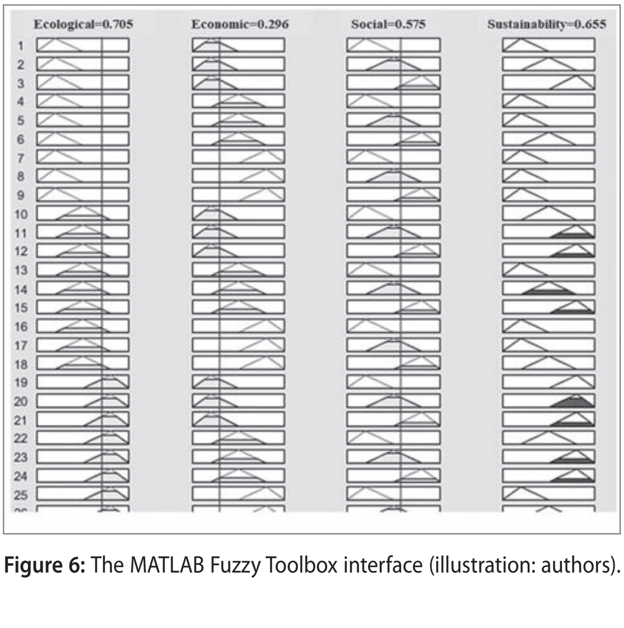


Figure 6: The MATLAB Fuzzy Toolbox interface (illustration: authors).

This stage involves the summation of all rule outputs. The final stage, defuzzification, expresses the obtained fuzzy set result as a single number. For this purpose, the centroid technique was used. In the centroid technique, the centre of gravity of the output fuzzy set is calculated. The formula used for this is:

$$x_{norm} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

The COG (centre of gravity) formula represents the centroid of the output fuzzy set. $\mu_{(x)}$ denotes the membership degree, and x represents the value of this membership degree in the output function. Using these values, the centroid is calculated within the boundaries of a and b, providing the numerical value of the output function. The MATLAB Fuzzy Toolbox interface for calculating sustainability values is provided in Figure 6. Numerical data related to the ecological, economic, and social components of the city for which the calculation will be performed intersect with the membership functions in the rules. These values correspond to fuzzy sets obtained in the sustainability output. This process is applied to all rules, and all sustainability output sets are aggregated. The centroid of the aggregated set is calculated, and the sustainability index for that city is computed.

4 Results

The results obtained for each of the eighty-one provinces in Turkey were divided into five quantile (twenty-percentile) groups. The cities were ranked as follows: sixteen cities in

Table 2: Ecological performance.

Ecological level	Provinces
Level 1: lowest	Malatya (0.293), Hakkari (0.295), Batman (0.297), Hatay (0.3), Burdur (0.308), Kırşehir (0.421), Amasya (0.423), Tokat (0.424), Muğla (0.44), Rize (0.442), Aydın (0.45), Ardahan (0.463), Zonguldak (0.475), Ordu (0.475), Bilecik (0.481), Adıyaman (0.483)
Level 2: low	Erzincan (0.486), Sinop (0.490), Bitlis (0.495), Tunceli (0.498), Uşak (0.499), Mardin (0.501), Kahramanmaraş (0.503), Osmaniye (0.508), Bayburt (0.509), Düzce (0.509), Kırıkkale (0.510), Istanbul (0.519), Kırklareli (0.519), Gümüşhane (0.528), Aksaray (0.529), Bartın (0.532)
Level 3: medium	Van (0.533), Kütahya (0.536), Samsun (0.536), Çorum (0.543), Bursa (0.545), Tekirdağ (0.55), Giresun (0.556), Edirne (0.57), Antalya (0.573), Nevşehir (0.577), Izmir (0.578), Niğde (0.580), Karabük (0.585), Elazığ (0.593), Trabzon (0.593), Konya (0.595), Kars (0.597)
Level 4: high	Denizli (0.652), Eskişehir (0.614), Yozgat (0.630), Şırnak (0.657), Manisa (0.616), Afyonkarahisar (0.547), Çanakkale (0.636), Siirt (0.651), Kocaeli (0.635), Diyarbakır (0.562), Çankırı (0.602), Kilis (0.609), Kastamonu (0.579), Şanlıurfa (0.507), Balıkesir (0.599), Artvin (0.640)
Level 5: very high	Muş (0.645), Isparta (0.631), Kayseri (0.644), Bolu (0.647), Mersin (0.653), Adana (0.655), Bingöl (0.647), Iğdır (0.656), Yalova (0.629), Ağrı (0.567), Sivas (0.662), Ankara (0.660), Gaziantep (0.561), Erzurum (0.660), Karaman (0.665), Sakarya (0.614)

Source: Authors.

Table 3: Economic performance.

Economic level	Provinces
Level 1: lowest	Mardin (0.284), Kahramanmaraş (0.286), Osmaniye (0.286), Şırnak (0.286), Siirt (0.290), Kırşehir (0.292), Nevşehir (0.292), Niğde (0.292), Batman (0.293), Sivas (0.293), Yozgat (0.294), Şanlıurfa (0.297), Hatay (0.300), Sinop (0.30), Ardahan (0.303), Kars (0.303), Iğdır (0.303)
Level 2: low	Diyarbakır (0.319), Hakkari (0.364), Aksaray (0.365), Kırıkkale (0.381), Edirne (0.385), Amasya (0.387), Çorum (0.387), Karaman (0.389), Kastamonu (0.391), Tokat (0.391), Konya (0.392), Kayseri (0.395), Muş (0.399), Bitlis (0.400), Çankırı (0.407) Samsun (0.414)
Level 3: medium	İzmir (0.419), Gaziantep (0.420), Adıyaman (0.424), Bartın (0.424), Karabük (0.424), Kilis (0.424), Van (0.424), Zonguldak (0.424), Ağrı (0.424), Kırklareli (0.429), Erzurum (0.432), Bayburt (0.437), Mersin (0.466), Adana (0.476), Çanakkale (0.482), Balıkesir (0.484)
Level 4: high	Erzincan (0.492), Gümüşhane (0.492), Ordu (0.492), Giresun (0.492), Trabzon (0.493), Rize (0.493), Ankara (0.499), İstanbul (0.500), Afyonkarahisar (0.531), Tekirdağ (0.557), Aydın (0.558), Düzce (0,562), Sakarya (0,564), Isparta (0.570), Bolu (0.576), Yalova (0.582)
Level 5: very high	Kocaeli (0.583), Kütahya (0.588), Artvin (0.592), Burdur (0.598), Manisa (0.604), Uşak (0.609), Malatya (0.609), Bingöl (0.610), Elazığ (0.610), Tunceli (0.610), Denizli (0.669), Muğla (0.672), Antalya (0.677), Bilecik (0.691), Eskişehir (0.696), Bursa (0.703)

Source: Authors.

the first group, sixteen in the second group, seventeen in the third group, sixteen in the fourth group, and sixteen in the last group. The cities, sorted from the lowest to the highest degree, were mapped. The outputs obtained from the ecological, economic, and societal main components of the cities grouped according to sustainability performance were also classified and mapped using the same system. The most populous cities in Turkey (Istanbul, Ankara, and Izmir) were evaluated under each main component.

4.1 Ecological main component

Within the ecological main component, nine different indicators were evaluated within four sub-components. According to the evaluation results, the province with the lowest ecological performance level, in the first group, is Malatya. After Malatya, the provinces with the lowest performance are Hakkari, Batman, Hatay, and Burdur. The province with the highest performance in the last group is Karaman. The Erzurum, Sakarya

Table 4: Social performance.

Social level	Provinces
Level 1: lowest	Sinop (0.297), Ağrı (0.301), Şanlıurfa (0.350), Afyonkarahisar (0.398), Gaziantep (0.402), Kırşehir (0.404), Bitlis (0.405), Van (0.413), Niğde (0.438), Tekirdağ (0.442), Diyarbakır (0.451), Sakarya (0.456), Kütahya (0.459), Kastamonu (0.460), Mardin (0.461), Balıkesir (0.465)
Level 2: low	Bartın (0.472), Uşak (0.473), Yalova (0.474), Kars (0.475), Manisa (0.476), Yozgat (0.477), Batman (0.485), Bursa (0.490), Hatay (0.492), Kocaeli (0.493), Çankırı (0.495), Nevşehir (0.496), Kırıkkale (0.498), Gümüşhane (0.500), Sivas (0.500), Siirt (0.501)
Level 3: medium	Muş (0.501), Bilecik (0.502), Aksaray (0.507), Tunceli (0.507), Kahramanmaraş (0.514), Düzce (0.515), Osmaniye (0.521), Adıyaman (0.527), Hakkari (0.535), Malatya (0.536), Zonguldak (0.537), Kayseri (0.538), Burdur (0.539), Konya (0.539), Çorum (0.540), Karaman (0.540), Kilis (0.540)
Level 4: high	Mersin (0.540), Amasya (0.540), Şırnak (0.542), Bolu (0.544), Karabük (0.546), Elazığ (0.552), Erzurum (0.556), Çanakkale (0.559), Denizli (0.560), Kırklareli (0.561), Adana (0.575), Iğdır (0.590), Rize (0.590), Bingöl (0.594), Samsun (0.601), Muğla (0.620)
Level 5: very high	Tokat (0.623), Giresun (0.626), Bayburt (0.629), Erzincan (0.638), Ardahan (0.641), Trabzon (0.642), Ordu (0.647), Isparta (0.649), Edirne (0.651), Eskişehir (0.654), Izmir (0.671), Artvin (0.686), Ankara (0.688), Aydın (0.702), Antalya (0.704), Istanbul (0.711)

Source: Authors.

Table 5: Sustainability performance.

Sustainability level groups	Provinces
Level 1: lowest	Bilecik (0.359), Malatya (0.386), Bursa (0.394), Burdur (0.396), Uşak (0.417), Tunceli (0.423), Denizli (0.460), Hakkari (0.460), Kütahya (0.463), Düzce (0.464), Muğla (0.472), Eskişehir (0.478), Elazığ (0.490), Van (0.493), Tekirdağ (0.494), Sinop (0.497)
Level 2: low	Hatay (0.500), Batman (0.503), Bitlis (0.503), Manisa (0.508), Ağrı (0.509), Afyonkarahisar (0.511), Antalya (0.516), Rize (0.522), Amasya (0.523), Gümüşhane (0.523), Tokat (0.529), Kocaeli (0.532), Şanlıurfa (0.532), Bartın (0.535), Zonguldak (0.538), Adıyaman (0.544)
Level 3: medium	Artvin (0.554), Kırklareli (0.556), Bingöl (0.558), Isparta (0.560), Karabük (0.566), Kırşehir (0.567), Gaziantep (0.571), Bolu (0.574), Diyarbakır (0.577), Samsun (0.577), Yalova (0.577), Kastamonu (0.580),Konya (0.581), Çorum (0.585), Ordu (0.586), Kırıkkale (0.588), Erzincan (0.590)
Level 4: high	Çanakkale (0.591), Aydın (0.593), Niğde (0.594), Balıkesir (0.594), Giresun (0.594), Ardahan (0.596), Bayburt (0.597), Sakarya (0.599), Aksaray (0.601), Çankırı (0.603), Trabzon (0.606), Kilis (0.610), Edirne (0.613), Kars (0.621), Mardin (0.622), Yozgat (0,627), İzmir (0.627),
Level 5: very high	Muş (0.645), Kayseri (0,646), Mersin (0.649), Siirt (0.651), Nevşehir (0.653), Adana (0.655), Iğdır (0.655), Ankara (0.658), Şırnak (0.658), Karaman (0.660), İstanbul (0.661), Sivas (0.662), Osmaniye (0.664), Kahramanmaraş (0.664), Erzurum (0.665)

Source: Authors.

Gaziantep, and Ankara provinces reached the highest values after Karaman. Table 2 shows the distribution of performance values for all cities and the groups they belong to. In terms of ecological performance, the Ankara province has a higher value compared to Istanbul and Izmir. Istanbul is in the second group and Izmir is in the third group, whereas Ankara is in the best group, which is the fifth group.

4.2 Economic main component

The economic main component consists of two sub-components and a total of six indicators. The values obtained in the economic component were lower than the values observed in all other main components. Mardin had the lowest economic performance, and Bursa showed the highest performance.

Izmir is in the third group, and Ankara and Istanbul are in the fourth group. Table 3 shows that the Aegean region and the Southeast Anatolia region stand out economically.

4.3 Social main component

The social main component has more indicators than the economic and ecological components. Within the social component, consisting of a total of twelve indicators, there are four sub-components. As a result of the evaluation, it can be seen that the Sinop province has the lowest performance. The Ağrı, Şanlıurfa, Afyonkarahisar, and Gaziantep provinces have the lowest performance after Sinop. The province with the highest performance is Istanbul. Antalya, Aydın, Ankara, and Artvin are other provinces in this group. The Izmir, Ankara, and Istanbul provinces are all in the highest level, which is the fifth group. Table 4 shows the results of the social main component.

4.4 Sustainability performance

When the results of the sustainability performance ratings are evaluated based on the 2022 data, it is observed that Bilecik, Malatya, Bursa, Burdur, and Uşak are the lowest-ranking provinces. The provinces showing the highest sustainability performance are Erzurum, Karaman, Kahramanmaraş, Osmaniye, Sivas, and Istanbul (Table 5). With differentiation in each region, higher sustainability performance in cities located in the middle of Turkey is evident. According to the analysis results, there are significant differences in sustainability levels among provinces.

5 Discussion

This study was conducted using a fuzzy model with the aim of assessing the sustainability performance of cities in Turkey. This model takes into account three main components – namely, the economy, ecology, and society – and encompasses a total of twenty-seven indicators. Based on the research findings, it is observed that different cities in Turkey exhibit varying levels of sustainability performance. When comparing the results of this study to those of previous research, various differences and similarities are observed.

The study conducted by MasterCard (2011) utilized sixty-nine indicators under the categories of economic, social, and environmental components, and it demonstrated that the western regions of Turkey are more sustainable, whereas the eastern and southeastern regions are less sustainable. Another study by Gazibey et al. (2014) employed a total of fifty-two indicators and identified Kocaeli, Istanbul, Ankara, Izmir, and Canakkale as the most sustainable cities, while ranking Adiyaman, Mardin, Sanliurfa, Kilis, and Hakkari as less sustainable. These results support the thesis that western Turkey is more sustainable and the southeastern regions less so. A study by Alptekin and Saraç (2017) examined fifty-one indicators under the categories of economic, social, and environmental components. According to data from 2013, they ranked Istanbul, Ankara, Antalya, Kocaeli, and Izmir as the most sustainable cities and identified Kilis, Duzce, Sinop, Bartin, and Kastamonu as less sustainable. These results also indicate that western Turkey is more sustainable, with cities in the Black Sea and Southeast Anatolia regions being less sustainable.

Finally, a study by Kusakci et al. (2022) considered fifty-three indicators under the categories of economic, environmental, social, and institutional components, but only examined three major cities. In this study, they designated Antalya, Mugla, Eskisehir, Ankara, and Kocaeli as the most sustainable cities while ranking Van, Mardin, Ordu, Diyarbakir, and Sanliurfa as less sustainable. Similar to other studies, this study found that the sustainability performance in the southeastern provinces of Turkey is lower, but, uniquely, it observed that the central Anatolian and Mediterranean regions of Turkey exhibited higher sustainability performance, possibly due to differences in the model framework, the methodology, and the pandemic effects specific to the year when the data were collected (Figure 7).

In all the studies conducted on the sustainability of cities in Turkey, it is observed that the cities with the highest population – namely, Istanbul, the capital Ankara, and Izmir – are evaluated among themselves. When the sustainability performance of these cities is assessed using the model employed in this study, the ranking is as follows: Istanbul, Ankara, and Izmir. This result is consistent with similar studies in the literature, in which cities with higher populations, typically large metropolitan areas, tend to exhibit higher sustainability performance compared to smaller cities. The results obtained in this study indicate that smaller cities can compete with larger cities in terms of sustainability performance, emphasizing the need to harness the potential of smaller settlements in terms of sustainability. For instance, in this study, the Erzurum province emerged as having the highest sustainability performance, which can be attributed to the rule-based and flexible nature of the fuzzy logic method. However, it is important to note that this study, like others, has certain limitations. One limitation is that the data used are specific to a particular period. In addition, the use of equal weights for indicators and their selection represents other limitations. Future studies could examine the effects of using different indicators and adjusting the weights of indicators.

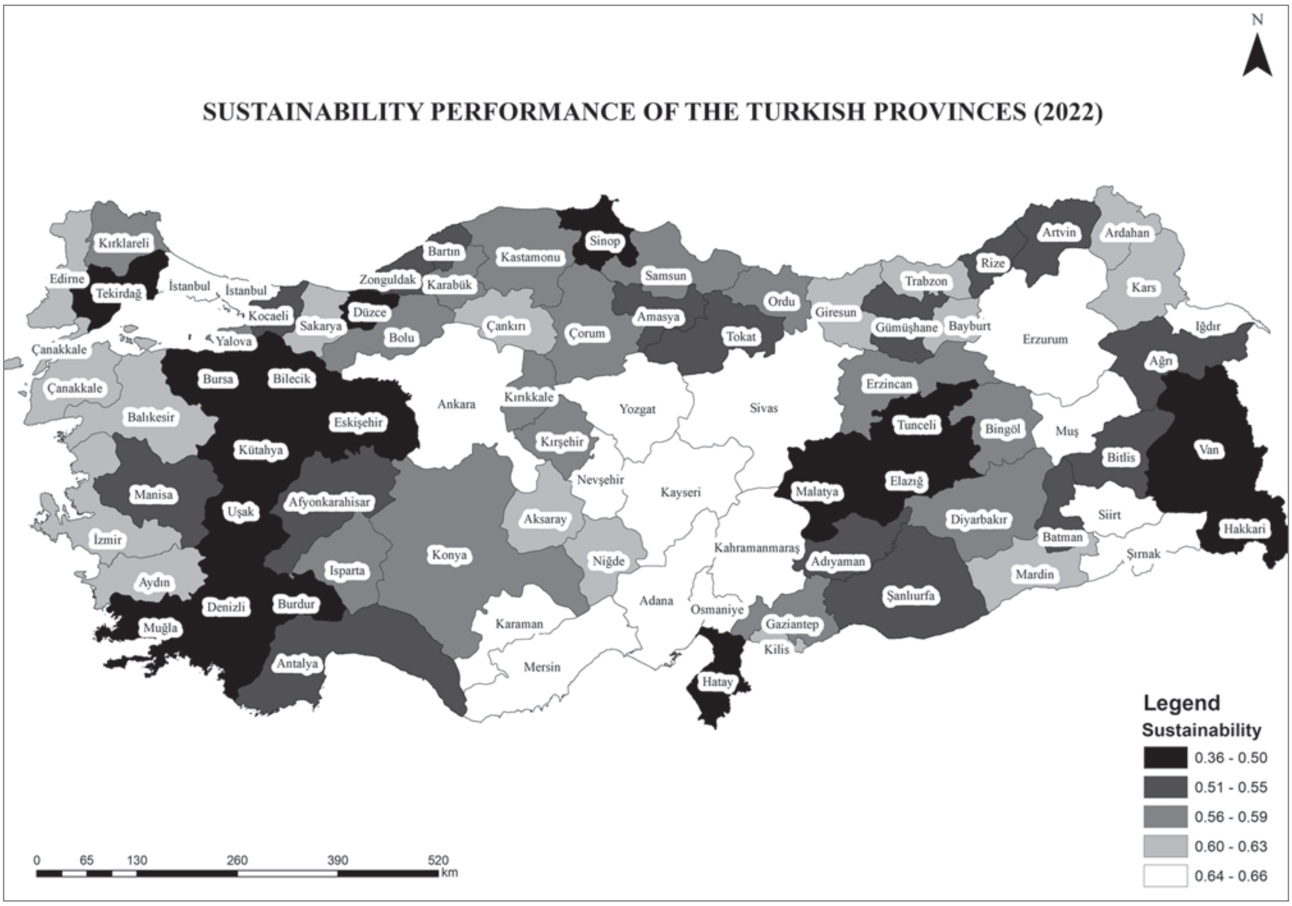


Figure 7: Sustainability performance of Turkish provinces (illustration: authors).

6 Conclusion

Cities have been important centres for the social, economic, and cultural development of humanity throughout history. However, with the increasing pace of urbanization, population growth, and environmental impacts, the concept of sustainability has become a significant issue for cities. Sustainable cities combine planning, management, and technological perspectives to ensure long-term liveability and wellbeing from environmental, economic, and social perspectives. These cities work toward achieving sustainability goals to create a healthy and liveable environment for future generations. Policymakers, local governments, urban planners, and academics today face a wide variety of existing sustainability indicator frameworks.

This study measured the sustainability performances of cities in Turkey through the application of the fuzzy logic method, considering economic, ecological, and social components. The cities were divided into quantiles (twenty-percentile) groups based on their achieved sustainability levels. The performance results will serve as a guide for identifying areas where more work needs to be done in terms of specific sustainability components in cities. The fuzzy logic method has been shown to be an important analytical tool in the field of sustainability due to its ability to address uncertainties and complexities. It is believed that this model will provide urban planners, policymakers, and decision-makers with better opportunities to develop strategies and policies for creating more sustainable and liveable cities. This model, which is repeatable, adaptable, and allows for comparisons based on numerical results, is expected to contribute to the literature. Future studies will repeat this model for data from different years, compare the results, and observe changes in cities' sustainability levels over time.

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Notes

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