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ORIGINAL ARTICLE

Analysis of Sustainable Development Priorities in Geopark Areas: The Case of Türkiye

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Abstract

This study is part of the process of developing a model aligned with the sustainability dimensions of geoparks, which are considered sensitive and fragile areas within the balance between protection and use, with examples from Türkiye. To achieve this, a hybrid multi criteria decision making framework was developed by integrating the Analytical Hierarchy Process (AHP) and the Technique for Ranking Preference by Similarity to Ideal Solution (TOPSIS). The evaluation of numerous decision parameters within this approach was analysis across three dimensions: socio-economic, cultural-educational, and environmental, related to sustainable development goals. Experts identified the priority sustainability criteria for geoparks, and an expert panel was formed for the case studies; these opinions were found to be reliable. The approach's sensitivity has been tested to confirm the model's stability. The developed model determined that environmental criteria, geological/hydrological risks, and conservation status are the most decisive dimensions for protection and use within the context of geopark sustainability. In socio-economic dimensions, transportation infrastructure, tourism pressure, and local development play a critical role in geopark priority rankings. Cultural and educational dimensions, on the other hand, are distinguishing criteria for geoparks with a strong perspective and ranking of scientific visibility, geo-education, and cultural heritage. This study demonstrates that selected geoparks in Türkiye are designated as areas of local, national, and international importance based on sustainability indicators. The research emphasizes the importance of geoparks in sustainable development and presents a scientifically grounded, extensible geopark assessment model to analyze their performance.

Keywords Sustainability · Geoheritage · Geoparks · Geotourism · Türkiye

Introduction

The tourism sector, along with its economic and social growth dynamics, is witnessing the rise of practices that promote natural, cultural, and educational sustainability. While this expansion fosters economic growth and enhances nature–culture interaction, it has also raised significant concerns about environmental sustainability (Holden 2016; Danish and Wang 2018; Khan et al. 2020; Mu et al. 2025). In recent years, global climate change (Schröter et al. 2005; Hein et al. 2009; Prideaux et al. 2020; Gössling and Scott 2025; Sharma et al. 2025; Lopes and Nascimento 2025; Liu et al. 2025; Becken and Loehr 2025) and environmental degradation (Hall 2010; Liu et al. 2022) have intensified the examination of mass tourism. These studies became particularly pronounced during and after the pandemic, deepening the debate on tourism's impact. Moreover, the shift towards nature-based and alternative tourism models has gained significant momentum. Driven by environmental concerns and

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the trend toward individualized tourism, it has moved to the forefront of global issues. In this process, geotourism has evolved beyond merely preserving geosites diversity; it has become a holistic approach that actively promotes sustainable development.

Geotourism is a form of nature-based tourism that focuses specifically on geology and the natural landscape (Newsome and Dowling 2010; Ólafsdóttir and Tverijonaite 2018). In another definition, Dowling (2011) describes geotourism as a tourism approach that prioritizes the conservation of geological heritage and makes sustainable contributions to the environment, economy, and society. Sustainable geotourism objectives include providing geological and geomorphological experiences for visitors interested in this diverse alternative tourism offering, improving the quality of life by fostering development initiatives and local employment in the areas where geoparks and geosites are located. In particular, these approaches foster awareness through educational processes while balancing conservation and utilization. It also offers a comprehensive tourism practice that generates economic and social benefits at the local level (Dowling 2011; Fassoulas et al. 2013; Rathore et al. 2024). Within these practices, the harmony between sustainability, comprehensive use, and conservation requires specific planning. These historical formations, analysed from cultural, educational, and scientific perspectives, are defined as geoheritage based on their structure, development, formation, and chemical characteristics (Brocx and Semeniuk 2007; García-Ortiz et al. 2014; Reynard et al. 2016; Brilha 2016; Newsome and Dowling 2018; Carrión-Mero et al. 2024). Geoparks, which serve as a critical platform for conserving geological diversity and promoting geotourism, have experienced remarkable growth worldwide in recent years (Wang et al. 2025). Geotourism, in particular, has experienced significant growth since the early 2000 s, primarily due to the establishment of geoparks and the increasing global interest in sustainable tourism (Irfan et al. 2024).

Although there are many definitions (Turoğlu 2025), geoparks are areas where sustainable forms of social, economic, local, and regional development (Farsani et al. 2011; Frey 2021; Zgłobicki et al. 2024) are protected and supported (McKeever 2009) which are seen as a representative of valuing geotourism and geoheritage (Sotiriou and Nunes 2024). Regardless of the definitions, criteria, and protection measures for geoparks or geosites, when these areas are designated as geoheritage, they come into existence with the concepts of valuing and sustaining for the future (Pimentel et al. 2024). In this context, the promotion of the geopark movement, the growing interest in geodiversity, geoconservation, and geotourism, particularly sustainability, is seen as a legacy. These practices have emerged strongly in many countries that prioritize the balance between conservation and use (Dowling 2008; Newsome et al. 2012). Geoparks are managed through a holistic approach that integrates principles of conservation, education, and sustainable development (Ito et al. 2023). Geopark practices are directly related to UNESCO's 2030 Agenda, as they support sustainable economic growth in geoheritage areas of international importance. The 2030 Agenda for Sustainable Development has reemphasized the importance of planetary sustainability in enabling social and economic development. Within this framework, it has been explicitly stated that sustainable tourism should be promoted as one way to manage natural resources sustainably.

Within the scope of the UNESCO Global Geopark (UGGp) concept, a geosite should serve, first and foremost, the main objectives of the geopark: geoconservation, geoeducation and geotourism (UNESCO 2015; Brilha 2018). Indeed, the concept of geoparks has become increasingly important in recent years to attract large numbers of tourists and promote sustainable economic development through geotourism based on the park's geological resources (Gray 2013; Cai et al. 2019; Duarte et al. 2020; Frey 2021; Wu et al. 2021; Deng and Zou 2022; Xu and Wu 2022; Jia et al. 2023). Geoparks, which essentially adopt a balance between conservation and use as a sustainable tourism strategy, aim to develop geoscientific heritage both domestically and internationally; in this process, they require not only conservation but also proper management and operational coordination (Huang 2010). The growing interest is reflected in the rise in the number of UNESCO Global Geoparks, enabling the enrichment of existing geopark lists through the identification of new geosites. Essentially, UNESCO Global Geoparks (UGGp) are areas that support education, culture, conservation, and utilization in line with the Sustainable Development Goals. The "UNESCO Global Geoparks" designation, announced in 2015 and which strengthens the promotion of geoparks at the international level, has been an important step towards the sustainability of these areas (Fassoulas et al. 2018). There are 229 officially designated UNESCO Global Geoparks worldwide as of 2025 (UNESCO 2025). In addition to this number, local governments have also designated many areas to balance conservation and use, ensuring economic, social, and environmental sustainability. This demonstrates the strategic importance of these areas, both nationally and globally (Jing et al. 2022).

Numerous national and international studies have been conducted on the protection of geoparks, the determination of their current status, and their management (dos Santos Costa et al. 2024; Mir 2024; Moradipour et al. 2024; Sen et al. 2024; Wolniewicz 2024; Rathore et al. 2024; Zhu et al. 2024; DeFelipe et al. 2025). In addition, the research scope is seen as a valuable starting point, and geosites are grounded in qualitative and individual assessments at the

local and regional levels. This has highlighted the need to integrate holistic and mixed approaches into research, particularly for the conservation of geoparks and the development of sustainable priority strategies (Schröter et al. 2005; Zorlu et al. 2024a; El Hamidy et al. 2024; Nemeth et al. 2024; Guerini et al. 2024; Smelror and Solbakk 2024; Kubalíková et al. 2025; Wang et al. 2025; Petrović et al. 2025; Irfan et al. 2025). Therefore, to fill this gap in the literature, new methods are needed that will reduce the subjectivity issue (Zorlu et al. 2024b) and incorporate the views of decision makers into the process, particularly multi criteria decision making (MCDM) approaches.

Geological landscapes are natural archives that record the world's history spanning millions of years. They directly impact the connection people form with their environment and their culture. These places form the foundation for a healthy balance, both environmentally, economically, and socially. In this context, areas with geoscientific values align with the sustainable development goals in terms of protection and use balance. In terms of protecting natural resources, empowering local communities, and ensuring economic diversity, geoparks are important tools for putting the sustainability principles of the 2030 Agenda into practice in the field (Fassoulas et al. 2018; UNESCO 2021; Martínez-Martín et al. 2023).

In this context, when looking at the SDG principles, SDG 4 (Quality Education), SDG 8 (Decent Work and Economic Growth), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), SDG 15 (Life on Land), and SDG 17 (Partnerships for the Goals) have powerful relationships. In contrast, SDG 1 (Poverty Reduction), SDG 5 (Gender Equality), SDG 7 (Clean Water and Sanitation), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action) goals stand out with their strong relationship structure that directly contributes to geoparks (Catana and Brilha 2020; UNESCO 2021; Ferreira and Valdati 2023; Table 1; Fig. 1). Therefore, geoparks are not only areas dedicated to the preservation of geomorphological heritage, but also serve as spatial laboratories that contribute to the comprehensive integration of the economic, environmental, and social dimensions of the 2030 Agenda.

Although numerous studies exist on the protection of geoscientific heritage sites and determining their sustainability, approaches that evaluate geoparks in line with SDG targets and from a multidimensional perspective (environmental, socioeconomic, and cultural) are limited (Zhu et al. 2024; Ferdowsi 2025; Motalegh and Ferdowsi 2025). In this context, the most critical element in geopark management is ensuring a balance between protection and use. However, the ecological, socioeconomic, and cultural priorities of

Table 1 The level and scope of the relationship between the Sustainable Development Goals (SDGs) and the UNESCO International Geoscience and Geoparks Programme

Sustainable development goals (SDG)	Relation strength(scale)		Justification (UNESCO-based)
SDG 1- No Poverty	4	Strong	Geotourism and local entrepreneurship generate rural employment and income
SDG 2- Zero Hunger	3	Moderate	Agro-tourism and local food production contribute to sustainable agriculture
SDG 3- Good Health and Well-being	3	Moderate	Nature-based tourism and outdoor activities promote health and well-being
SDG 4- Quality Education	5	Very Strong	Geoparks act as open-air classrooms; education is a core mission
SDG 5- Gender Equality	4	Strong	Women's cooperatives and local production strengthen gender equality
SDG 6- Clean Water and Sanitation	4	Strong	Supports water conservation and management of hydrological heritage
SDG 7- Affordable and Clean Energy	3	Moderate	Raises awareness on geothermal and renewable energy (in some geoparks strongly)
SDG 8- Decent Work and Economic Growth	5	Very Strong	Geotourism and local economy foster job creation and economic growth
SDG 9- Industry, Innovation and Infrastructure	3	Moderate	Encourages innovative tourism infrastructure and local development projects
SDG 10- Reduced Inequalities	4	Strong	Promotes inclusive development and equality in disadvantaged regions
SDG 11 - Sustainable Cities and Communities	5	Very Strong	Directly linked to sustainable urban and community strategies
SDG 12 - Responsible Consumption and Production	5	Very Strong	Promotes local products, branding and responsible consumption habits
SDG 13 - Climate Action	4	Strong	Raises awareness of climate change and offers nature-based solutions
SDG 14 - Life Below Water	2	Weak	Limited direct contribution except for lakes and coastal geoparks
SDG 15 - Life on Land	5	Very Strong	Biodiversity and land conservation are core missions of geoparks
SDG 16 - Peace, Justice and Strong Institutions	3	Moderate	Linked with participatory governance and transparent decision making
SDG 17 - Partnerships for the Goals	5	Very Strong	Strong global–local partnerships through UNESCO Geopark Network (GGN)

Source: adapted from (UNESCO 2021)



Fig. 1 The strength of the relationship between the UNESCO international geoscience and geoparks programme and the sustainable development goals (SDGs) (UNESCO 2021; prepared by the authors)

geoparks in different regions vary. Numerous national and international studies have contributed to the assessment and documentation of geoparks and geosites. However, in addition to these valuable assessments, there are aspects that must contribute to sustainability, prioritization, and decision making processes (Yordkayhun et al. 2022; Long et al. 2022; Herrera-Franco et al. 2022; Ruban et al. 2022; Ahmadi et al. 2022; Alberico et al. 2023; Elkaichi et al. 2023; Jia et al. 2023; Xia et al. 2024; Zheng et al. 2025; Wang et al. 2025; Louz et al. 2025; Li et al. 2025; Do 2025). Studies on the numerical evaluation of areas have become widespread in the last twenty years (Brilha 2018). Qualitative approaches have long been used to classify areas of outstanding universal value, including geoscientific heritage, geomorphological sites, natural heritage areas, and protected landscapes. Methods that highlight the unique characteristics of these areas have come to the fore in the evaluation processes. However, Brilha (2016) provided a pioneering framework for the quantitative assessment of geoheritage areas, providing a new perspective in this field. In this context, interest in quantitative methods for evaluating sensitive and protected areas has increased; along with SWOT analysis, the use of multi criteria decision making models, such as SWOT-AHP (Analytical Hierarchy Process) and Fuzzy AHP, has expanded. In response to this gap, this study proposes a new approach that links geopark assessments to the Sustainable Development Goals (SDGs) and addresses concerns about sustainability priorities and policy choices. The methods used in this study complement the existing literature and provide a systematic framework to guide future research. In this context, the developed model can produce results applicable to sustainable planning and management at local, national, and global levels, prioritizing the balance between protecting and using geoparks and geosites (Brilha 2016; Sahani 2021; Vandelli et al. 2024).

This article aims to address the lack of multi criteria decision making, prioritization planning, and sustainable spatial approaches for geoparks at the local, national, and global levels. The primary focus of the research, along with a case study based on quantitative data, provides a potential, holistic framework for geopark planning and prioritization in support of sustainable development goals. In line with this purpose, the first stage is to establish the relationship between sustainable development goals and to determine the importance of criteria by targeting the United Nations, UNESCO approaches and literature studies methodologically. The second phase involves developing a model for the criteria priorities determined for the potential cases within the SDG-geopark relationship (Table 2). This model was analyzed using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method, which incorporates the conservation-use balance and provides

Table 2 Main and sub-criteria in the Geoparks sustainability assessment model approach and the relationship with SDGs

Sustainability dimension	Main-criterion definition	Sub-criteria	Related SDGs	SDG Sub-Target	Sub-criterion definition
Environmental Sustainability	Within the context of environmental sustainability approaches, the ecological integrity of a geosite or geopark reflects the natural resource values within the area, its geoheritage is affected by the balance between conservation and use, and its vulnerability to degradation stemming from natural and human activities	C1- Endemic species presence, habitat sensitivity	SDG 15	15.5: taking urgent measures to halt biodiversity loss	It describes the presence of species unique to a geopark within the research areas at local, national, and global levels, and the extent to which these ecosystems are vulnerable to impact and damage, taking into account human factors
		C2-Geological/hydrological risks (fault line, erosion, landslide)	SDG 13/11/6	13.1: increasing resilience to disaster risk 11.5: reducing damage caused by natural disasters 6.6: protection of water-related ecosystems-Spring waters, lakes, karst structures	It represents the geological stability of the site, its proximity to faults or exposure to earthquakes, the presence of geomorphological and geological natural disaster risks such as floods, inundations, landslides, and erosion, and the threats to tourist and visitor safety associated with these risk scenarios
		C3-Protection status (protected area, geopark, UNESCO, etc.)	SDG 16	16.6: strengthening effective, accountable, and inclusive institutional structures	Alternatively, it includes whether the site is included in UNESCO's Geopark Protection System, whether it has a similar protection status held by local or national authorities, and the human limitations within these statuses
		C4-Land use pressure (construction, mining)	SDG 15	15.1: protection and sustainable use of terrestrial ecosystems	Within the scope of human activities, it refers to the degradation of underground natural resources in the geosite and geopark surroundings, the unplanned and uncontrolled development of buildings, and the pressures on the land that will affect the agricultural and environmental landscape
Socio-Economic Sustainability	Geoheritage contributes to local community economic well-being and social development processes in areas with geosite or geopark value, enhances tourist satisfaction, and supports infrastructure development that supports sustainable management	C5-Local development and tourism potential	SDG 8/ SDG 2	8.3: Promoting local entrepreneurship and sustainable economic growth 2.3: Increasing the income and productivity of small producers (local communities, cooperatives)	It refers to the capacity of geotourism areas to be used for alternative tourism processes that transform into local employment and income-generating activities, create opportunities to improve infrastructure services such as food, beverages, and accommodation, and contribute to the local, national, and global economy
		C6-Local community participation, women's cooperatives	SDG 5/11/1/10	5.5: Full participation of women in decision making processes 11.3: Participatory, sustainable settlement planning 1.4: Access to basic services and equal access to economic resources 10.2: Increasing social, economic, and political inclusion—Participation of local people in decision making processes	It particularly addresses the elimination of inequalities, the inclusion of local people in decision making and development processes within geopark governance models (especially women's entrepreneurship, associations, and cooperatives), and the existence of models for utilizing the area's tourism potential
		C7-Access and transportation infrastructure (roads, signage, disabled access)	SDG 9/11	9.1: Resilient infrastructure 11.2: Accessible transportation systems for all	Innovation in transportation routes and ease of access within the physical infrastructure, safe routes for site guidance and hiking areas, and the availability of accommodations for individuals with disabilities
		C8-Tourism pressure and carrying capacity	SDG 12	12.b: Implementation of sustainable tourism monitoring and planning policies	It refers to the physical, ecological, and social carrying capacity of tourist experiences and visits within a sensitive and protected area ecosystem, despite their destructive and disruptive characteristics and the challenges posed by this density

Table 2 (continued)

Sustainability dimension	Main-criterion definition	Sub-criteria	Related SDGs	SDG Sub-Target	Sub-criterion definition
Cultural-Educational Sustainability	Geoheritage encompasses integrating geosite and geopark values through a holistic approach that involves all segments of society in the conservation and utilization process, contributing to scientific research and educational development, and enhancing the development of local identity within the context of local preservation	C9-Geo-educational potential and literacy (guidance, boards)	SDG 4	4.7: Providing education, awareness, and skills for sustainable development	Lifelong learning refers to the acquisition of knowledge at various educational levels and the provision of geological adventures through informative information boards, educational paths, guidance, and interactive applications, in addition to the provision of these capabilities
		C10-Digital promotion and social media visibility	SDG 17	17.8: Increasing the use of digital technologies and access to information	It refers to the availability of social media, web addresses, virtual tours, and mobile applications designed and guided by geopark sites, enabling tourists to access these services
		C11-Local narratives, cultural memory and geo-identity	SDG 11	11.4: Protecting cultural and natural heritage	It reflects the potential for local communities to embrace and engage with the tangible and intangible cultural richness of heritage sites within the context of geological values
		C12-Academic research and scientific guidance	SDG 4/13	4.3: Increasing technical and vocational training opportunities 13.3: Strengthening climate literacy and academic capacity	It refers to the site's educational and research use, its inclusion in scientific publications, the availability of books that facilitate scientific guidance and tourist activities, and its popularity in both student- and professional-focused fieldwork

Source: adapted from (Pereira et al. 2007; Pereira and Pereira 2010; García-Ortiz et al. 2014; Brilha 2016; UNESCO 2017, 2024; Różycka and Migoń 2018; Jing et al. 2022; Golfinopoulos et al. 2022; Migoń and Pijet-Migoń 2023; Kubalíková et al. 2023a, 2025; Sen et al. 2024; Kchikach et al. 2024; Mikhailenko et al. 2024; Lopes et al. 2024; Zhu et al. 2024; Zafeiropoulos et al. 2025)

direct, objective input to support sustainability and decision making. The development of the model contributes to the planning and prioritization of geoparks across the Environmental Sustainability, Socio-Economic Sustainability, and Cultural-Educational Sustainability development dimensions. In addition, the model has been developed to apply across all areas at the global level, with a criteria structure suitable for long-term management strategies and improvement, as well as for SDG related prioritization or assessment of geoparks.

Study Area

Türkiye is one of the world's most remarkable regions due to its geological and geomorphological diversity. Located in the Alpine-Himalayan orogenic belt, Anatolia was shaped by the evolution of the Tethys Ocean as a result of the interaction between the African, Eurasian, and Arabian plates, and its complex tectonic structure spans different periods (McKenzie 1978; Sengör and Yilmaz 1981; Bozkurt 2001; Robertson et al. 2013; Şengör and Yazıcı 2020). The main geoparks analysis within the scope of sustainability and multi criteria decision making (MCDM) are; Kula-Salihli UNESCO Global Geopark, Ida-Madra Geopark, Denizli Travertine Geopark, Zonguldak Coal Geopark, Cappadocia Geopark, Narman Geopark, Nemrut (Caldera) Geopark, and Cilo-Sat Geopark (Fig. 2).

Located in Western Anatolia, within the borders of Manisa Province, the Kula-Salihli UNESCO Global Geopark is Türkiye's first and currently only officially recognized geopark (Binal and Ercanoğlu 2010; Aytaç et al. 2023). Covering an area of approximately 2.320 km^2, the geopark is located in the Eastern Aegean, one of the most seismically active regions in the world, and encompasses the young Kula volcanic area and the tectonically highly active Bozdağ Mountains. The Kula-Salihli Geopark, notable for its volcanic cones, lava flows, basalt columns, lava caves, fossil footprints, and alluvial fairy chimneys; stands out as one of Türkiye's most unique geological areas thanks to its extensive lava plateau, morphological structure shaped by a graben system, distinct erosional forms, and rich geological history dating back to the Paleozoic era. This geological wealth encourages the high-level use of the Geopark for geological research and education at national and international levels, in addition to its protection in the tourism and sustainability dimensions (Akbulut et al. 2023; Štrba and Palgutová 2024).

Located in the northwest of Türkiye, the Ida-Madra Geopark is within the borders of both the Aegean and Marmara regions. Covering an area of approximately 17.000 km^2, the geopark encompasses the entire province of Balıkesir, as well as the districts of Ayvacık and Ezine in the province of Çanakkale, and the district of Bergama in İzmir. The area contains lithological and geomorphological units

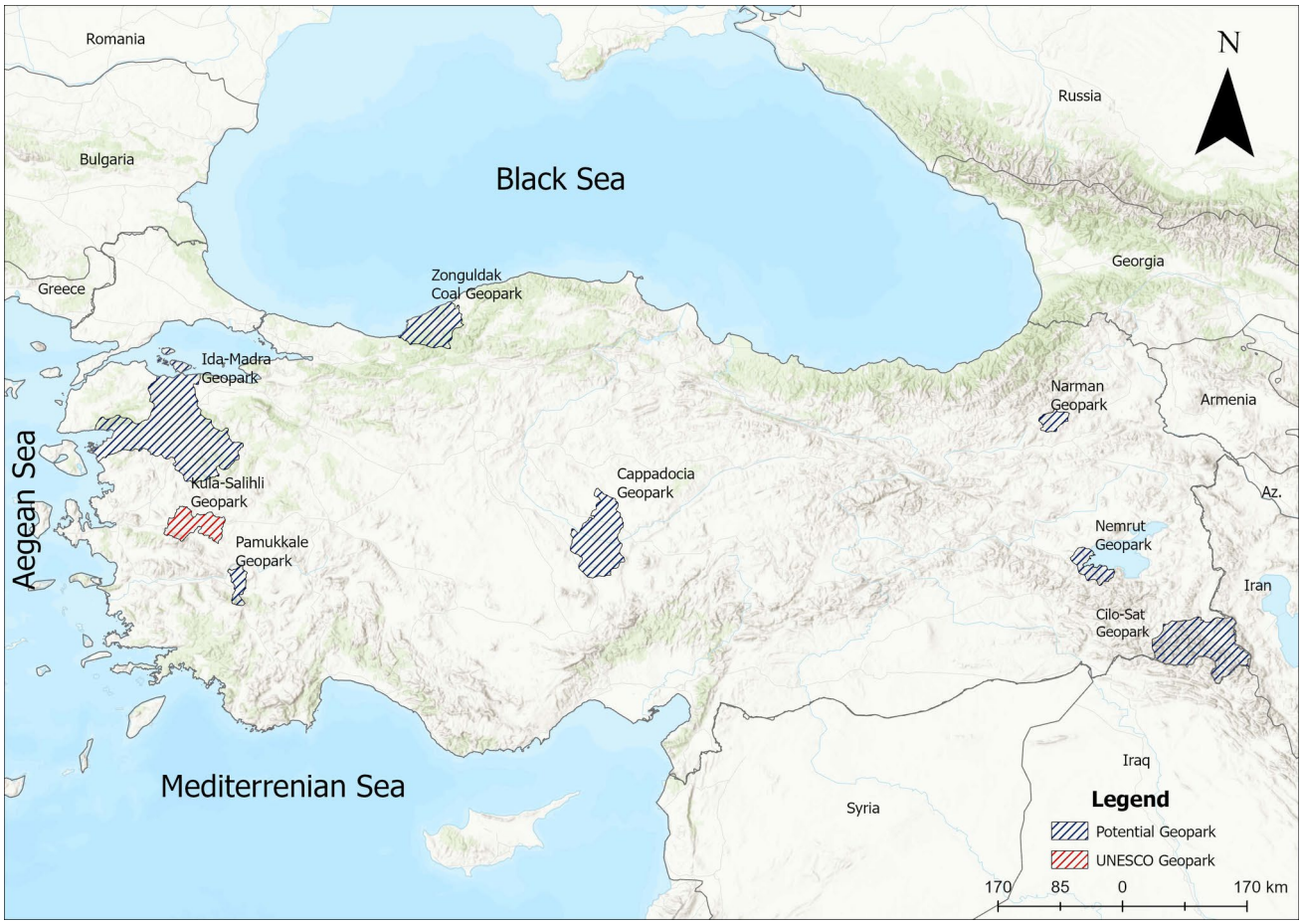


Fig. 2 Study areas of selected potential and UNESCO geoparks in Türkiye (Source: Prepared by the authors)

dating from the Precambrian to the Holocene. There are 11 thematic focal points of scientific, aesthetic, and educational value in the geopark area, including tor topography, coastal features, caves, hot springs, travertine chimneys, canyons, ancient quarries, and viewing areas, developed mainly due to exfoliation and weathering on granites. These are the Hisaralan Geothermal Field and Travertine Chimneys, Hisaralan Hot Springs and Travertines, Ayvalık Islands Coastal Geomorphosites, Şahinderesi Canyon Karst and Geoarchaeology, Kazdağı (Ida), Kapıdağ Peninsula Granite Tor Topography, Çataldağ (Susurluk) Granite Wall, Kozak (Madra) Granite Tor Topography and Yörük Culture, Kestanbol (Alexandra Troas) Ancient Granite Quarries, Balya Mining Industrial Heritage, and Marmara Island Marble Industrial Heritage areas (Efe et al. 2022a, b, c, d; Çiftçi and Güngör 2023).

The Denizli Travertine Geopark, which took another step toward becoming an official geopark with the protocol signed in October 2023 between the Denizli Governor's Office, Denizli Metropolitan Municipality, and Pamukkale University, hosts widespread travertine formations within the borders of Denizli, primarily in Pamukkale, some of which are of international importance, as well as Kaklık Cave, South Waterfall, Kamara Bath, Gökpınar Valley. Pamukkale Travertines, which attract attention with their karst formations, and the ancient city of Hierapolis (Denizli), which has high cultural heritage value, are on the UNESCO World Heritage List and, when evaluated within the framework of sustainability principles, occupy an important position as potential geopark components (Kaygılı et al. 2018; Özkul et al. 2024).

The Zonguldak Coal Geopark, designated as a National Geopark on December 23, 2022, is located in Zonguldak, in the Western Black Sea Region of the Black Sea Region in northwestern Türkiye. The geopark is a unique geoheritage area that represents the geological diversity, industrial heritage, and cultural identity of the Zonguldak Basin, Türkiye's only exploitable coal basin. The Zonguldak Coal Geopark is important for tracing diagenetic processes and geological basin evolution between Upper Carboniferous window sections, coal seams in the Namurian-aged Alacaağzı Formation, and the rock sequences that overlie them, as well as Carboniferous sedimentary packages (Yalçın et al. 1994; Görür et al. 1997; Hoşgörmez 2007; Yalçın and Yılmaz 2010). Within the geopark boundaries,

the area features landforms such as coastal cliffs, tafoni developed in limestone (e.g., Kireçlik Burnu tafoni), cave systems (Cumayanı, Gökgöl, Sofular, etc.) and karst drainage structures. These morphological elements are important observation areas for tracking both surface evolution and subsurface-surface interactions. Within the geopark boundaries, there are 50 main geosites, 59 potential geosites, five natural monuments/parks, 169 industrial heritage elements, as well as mines, loading docks, historic mining settlements, and building remains associated with the life of coal miners (Zonguldak Coal Geopark 2025).

The Cappadocia Geopark is located within the Nevşehir province, in the central part of the Cappadocia Volcanic Province, which lies within the boundaries of the Central Anatolia Region. The geopark spans an area of 5.485 km^2. The geopark is characterized by Miocene-aged ignimbrites, tuff deposits, and lake sediments (Ciner and Aydar 2019). The interaction of wind, precipitation, and underground water with weathering and mass movements in these lacustrine and volcanic stratigraphic sequences has resulted in the development of characteristic geomorphological features such as fairy chimneys, canyons, mesas, buttes, and badlands topography. The Cappadocia geopark also has great value in terms of cultural geomorphology with its rock-carved architecture and underground cities. In the past, people carved ignimbrites in these areas to create extensive underground cities, houses, and churches, such as Derinkuyu and Kaymaklı. Göreme and Cappadocia, both declared national parks, are internationally protected as UNESCO World Heritage Sites. With its geological and cultural integrity, geoheritage structure, unique historical fabric, human-rock interaction, and historical, scientific, and educational processes, it is a significant geopark area.

Narman Canyon is located within the Narman district of Erzurum province. It is notable for its lithological features, consisting of volcanic sediments with red hues developed during the Eocene-Holocene period, and its current geomorphological appearance (Bozkuş 1998). The protected area is composed of Pliocene–Quaternary period covered sediments and structures shaped by the erosion of these sediments by deep valleys and river branches (Güngör et al. 2012). In this tectonically controlled area, erosion features and red fairy chimneys, which develop on iron oxide-rich red lithology, are notable geosites. In the geopark area, where evidence of settlement dates back 3000 years (Cengiz and Akkuş 2012; Akpinar Külekçi and Koç 2020), there are 14 geopark routes and 58 inventoried geosites. Furthermore, the region is enriched by its ethnographic, biological, and tourist elements; it hosts important natural and cultural resources that can be evaluated in terms of ecotourism and geotourism activities (Akpinar Külekçi and Koç 2020).

Nemrut Caldera is located on the Eastern Anatolian Orogenic Complex (Sengör and Yilmaz 1981) and is considered one of the world's largest caldera lakes (Ertekin et al. 2021; Çiftçi and Güngör 2023). The Nemrut Volcano is a stratovolcano that has erupted multiple times with Plinian-type eruptions (Pearce et al. 1990; Notsu et al. 1995; Karaoğlu et al. 2005; Özdemir et al. 2006; Çubukçu et al. 2012; Ulusoy et al. 2012; Sumita and Schmincke 2013a, b; Kearney et al. 2025). According to the dating results obtained on the pumice stones, the oldest eruption is estimated to have occurred 124.000 years (±4.000 years) ago (Sumita and Schmincke 2013a). The caldera of the Nemrut volcano was formed as a result of an eruption that occurred 33.000 years ago (Karaoğlu et al. 2005; Sumita and Schmincke 2013a, b; Kearney et al. 2025). The caldera, caldera lake, volcanic islands within the caldera lake, lava flows, obsidian and pumice deposits, basalt columns, maars, geothermal steam vents, rhyolitic domes, and fairy chimneys constitute the natural geosites of Nemrut Geopark.

Located east of the Southeastern Taurus Mountains, within the borders of Hakkâri province, the Cilo-Sat Geopark/Geomiras area is a unique site that combines elements of mountaineering and glacial geomorphology. The Cilo Mountains, which feature the Uludoruk (Reşko) peak at approximately 4.135 m, possess a highly complex geological structure due to their location in the collision zone between the Anatolian and Arabian plates. The layered structure, ophiolite assemblages and nappe transition zones in the region are the most important formations that add geological and lithological value to the area (Yılmaz 1994). The area, with its glaciation, features a rich topography, including an alpine-type glacier area, cirques, moraines, glacial valleys, lakes, and waterfalls. In addition, thousands of years of rural activities and local life elements have added cultural depth to the area's natural identity (Azzoni et al. 2022).

These areas represent Türkiye's geomorphological and geological diversity, from volcanic and tectonic landscapes to karst and glacial features. They not only highlight the country's rich geoheritage but also provide a comparative basis for assessing geopark potential, conservation strategies, and geotourism development in line with the UNESCO Global Geoparks principles. Indeed, the studies conducted in the research area are important representatives that reveal this rich potential. When studies conducted in Türkiye are examined, it is evident that they address various areas at both regional and local scales (Göktaş and Boyraz 2025). These studies generally aim to reveal the existing potential and support geotourism (Kazancı 2012; Gürer et al. 2019; Özgeriş and Karahan 2021; Kırlar Can and Usta 2021; Güngör 2024; Mülayim et al. 2025). However, in recent years, the tendency to present not only a local and regional

perspective, but also an international perspective through various methods and methodologies has gradually strengthened. Erginal et al. (2021) used Mersin Province as a case study to examine the geoarchaeological heritage of eolinites through XRD, sonar, and petrographic analysis. Dede and Zorlu (2023) carried out a quantitative assessment of the geoheritage in the Karçal Mountains using the entropy based WASPAS approach. Zorlu et al. (2023) presented an evaluation that weighted different criteria using the GAM and MEREC-based PROMETHEE-GAIA method in a comparative analysis of geoheritage areas. Zorlu, Polat, Yılmaz, and Dede (Zorlu et al. 2024a) developed an integrated fuzzy coarse multi criteria group decision making model to determine the quantitative value of geoheritage resources, making a significant contribution to methodological diversity in this field. Therefore, the research area, with its geological, geomorphological, and cultural diversity, has considerable potential to meet the geopark designation criteria not only at the national but also at the international level.

Overall, these areas represent Türkiye's geodiversity, ranging from geological and lithological formations to karst, glacial, and fluvial features. These studies highlight the country's rich geoheritage and provide a comparative basis for assessing the potential, strategies, and developments of UNESCO's global Geoparks. Indeed, the work carried out in these areas is a valuable resource that unlocks these potentials.

Methodology

The evaluation of geoparks necessitates a multidimensional decision making process that balances the protection of natural and cultural heritage with the development of sustainable tourism. Therefore, multi criteria decision making (MCDM) methods, particularly the AHP and TOPSIS approaches, are widely used to systematically compare the geological, environmental, and socio-economic characteristics of geoparks and to prioritize areas.

The methods and methodological approaches used in geosite and holistic geopark research have diversified in recent years. In particular, techniques such as the Analytical Hierarchy Process (AHP), SWOT, or Delphi have been incorporated into research in a hybrid manner within the context of multi criteria decision making methods (Salamzadeh et al. 2021; Wang et al. 2025). In some studies, these approaches helped to classify the importance levels of geosites more objectively with principal component analysis (PCA) (Jia et al. 2022). Various multi criteria decision making approaches have been developed to solve these classification and prioritization problems. Among these, Fuzzy AHP (FAHP) has been combined with TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) to determine the educational, touristic, and scientific values of geosites (Li et al. 2025). In the area where case studies were selected to strengthen the scope of quantitative approaches in the evaluation and prioritization of geosites, studies related to decision making processes such as Combinative Distance Based Assessment (COBRA), Measurement and Ranking of Alternatives by Compromise Solution (MARCOS) and Stepwise Weight Assessment Ratio Analysis (SWARA) were developed (Zorlu et al. 2024a, b). In addition to these approaches, other approaches have been developed to assess the efficiency dimensions of management activities in areas with geological value, such as Data Envelopment Analysis (DEA) (Jeon et al. 2025) and the multifaceted SWOT approach (Fassoulas et al. 2013; Cai et al. 2019).

In this context, prioritization and planning approaches developed based on expert opinions are increasingly gaining value. Interdisciplinary studies, particularly those addressing decision making challenges and investigating geologically valuable areas, offer methodological insights into the balance between conservation and use. In this context, our research comprehensively reviewed the literature on geopark management, geoscience, geotourism, environmental risk assessment, and geopark planning, encompassing approaches developed across numerous studies. In addition to this review, the Global Geopark Framework and SDGs targets, as declared by UNESCO, were taken into consideration. The model, which was determined and submitted for expert approval, was presented to a group of 13 experts. This group includes experts and academics specializing in 3 geography, 2 nature conservation and management, 2 ecology, 3 geology and geomorphology, 1 education and local development, 2 protected areas and tourism. Within the scope of the geopark SDG relationship, the expert group reached an agreement on three general dimensions and 12 criteria: Environmental Sustainability, Socio-Economic Sustainability, and Cultural-Educational Sustainability (Table 2; Fig. 3).

The Analytic Hierarchy Process (AHP) is based on evaluating the importance levels of complex problems by breaking them down into a hierarchical structure and making pairwise comparisons. In this method, a judgment matrix is created to determine the relative importance levels between criteria, and then the weights of alternative options are revealed by calculating the maximum eigenvalues and eigenvectors (Jia et al. 2022). The basic process of this analysis is the selection of criteria (Petruni et al. 2019). AHP incorporates expert judgment into the decision making process for a given case. It measures consistency by comparing criteria with each other and enables multidimensional criteria to be evaluated within a holistic framework (Saaty

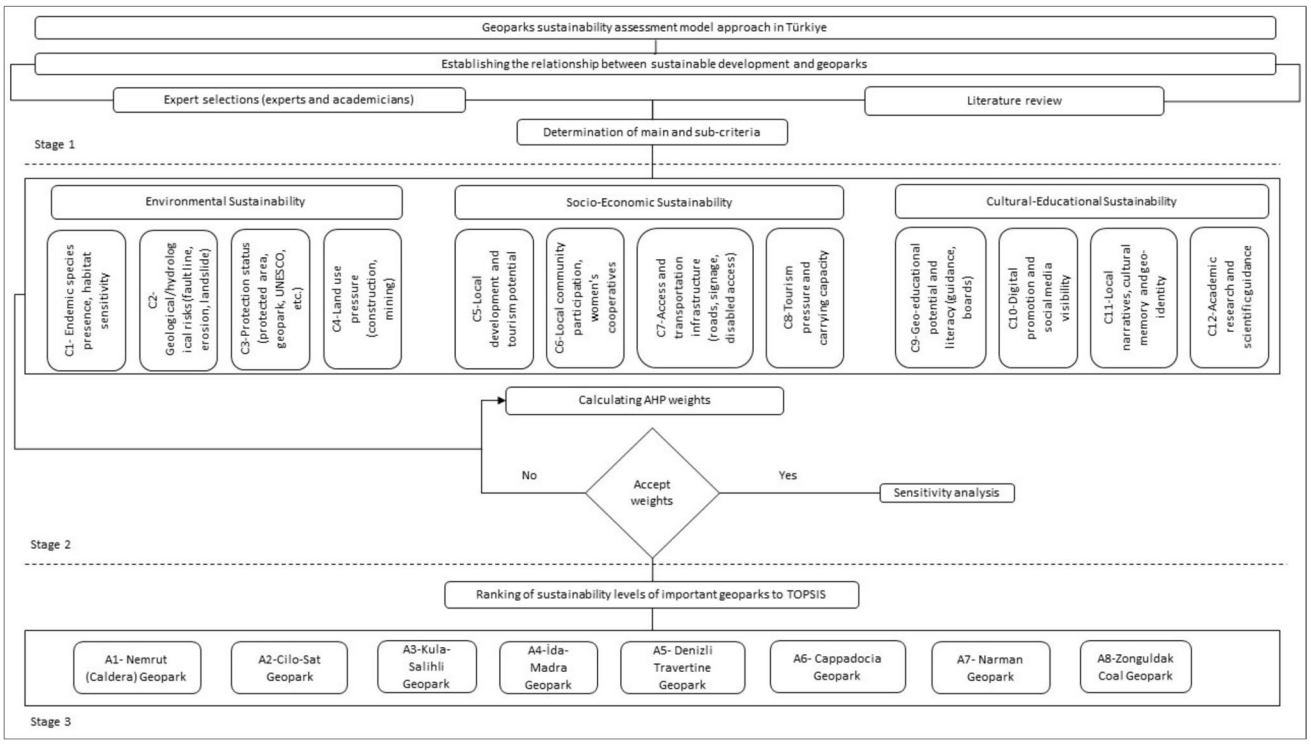


Fig. 3 Hierarchical model of geoparks in Türkiye (Source: prepared by the authors)

1980; Saaty and Vargas 2013; Baffoe 2019). In this context, the AHP contributes to a robust planning and decision making framework for comparative benchmarking within the scope of the determination and multidimensional evaluation of social, economic, and ecological contributions in geosite and geopark research (Long et al. 2022; Ansori et al. 2024; Insani and Haryono 2025). In the model used in this study, experts conducted the evaluation processes within the criteria groups, considering the criteria definitions listed in Table 2. Experts determined the basic evaluation criteria for each criterion using the Analytic Hierarchy Process (AHP), a pairwise comparison approach developed by Saaty, with values ranging from 1 to 9. Table 3 shows the steps followed in the process (Saaty 1977, 1980; Wind and Saaty 1980).

The importance rankings, finalized by 13 experts using the AHP process, were prepared for the next stage using geometric averaging and direct weighting. This developed model was further subjected to a sensitivity analysis and tested at −10% and + 10%. Then, within the scope of their expertise on Türkiye's Geoparks, an expert group of five in geography, nature conservation and management, planning, and geology rated each geopark on 12 indicators identified in relation to the SDG targets. The TOPSIS Technique for Order Preference by Similarity to Ideal Solution (SDS) was used to calculate overall scores in this ranking. For the SDG-related model application, the case study geoparks were selected based on their geological diversity, relevance for exemplifying national contexts, and sustainable tourism potential. In this context, eight potential geoparks in Türkiye, one of which is registered with UNESCO, were selected as the sample group. The combined score classification of geoparks is as follows: 0–0.2 is local, 0.2–0.4 is regional, 0.4–0.6 is national, and geoparks exceeding 0.6 are classified as global. Scores were classified at equal intervals based on the relative proximity values of the TOPSIS method in the range of 0–1, in order to facilitate the interpretation of the results. Within this classification, the planning dimensions for prioritizing geopark values and balancing sustainable comprehensive protection and use were determined based on the UNESCO Global Geoparks Network framework, expert opinions, and relevant national/international literature (Brocx and Semeniuk 2007, 2016). The model, generally based on literature reviews and research frameworks aligned with the Sustainable Development Goals, consists of an expert panel using a likert-type scale (1 is the lowest value and 5 is the highest value) for combined scoring in geopark assessments. TOPSIS was used in this expert panel's evaluation approach.

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method is one of the most widely used methods developed to determine the most suitable alternative in multi criteria decision making problems (Hwang and Yoon 1981). In this method, alternatives are ranked such that they are simultaneously closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS). This process should include the weights assigned to

Table 3 Analytical hierarchy process (AHP) steps used in the evaluation of Geopark criteria

1.Identification of the problem and establishment of the hierarchical structure	Define goal → criteria (and sub-criteria) → alternatives as a hierarchy	
2.Construction of pairwise comparison matrices	$A = [a_{ij}]_{n\times n}, a_{ij} = \frac{1}{a_{ji}},\ a_{ii} = 1$	Experts use a score from 1 to 9 to determine and compare the importance of each criterion compared to other criteria. In this process: A: pairwise comparison matrix for geopark criteria $(n \times n)$ a_{ij}: the value in row , column j - for example, the relative importance of the criterion "geological diversity" to the criterion "accessibility" $a_{ij} = \frac{1}{a_{ji}}$: The property of reciprocity: if "geological diversity" is 3 times more important than accessibility, then accessibility is 1/3 more important than geological diversity.
3.Normalization of pairwise comparison matrices	$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$	The matrix values resulting from each expert's comparison include the step of normalizing the column to 1. This ensures comparability between the criteria (geopark criteria become scale-independent) r_{ij}: normalized value; the comparison value of each criterion expressed in the range [0–1] $\sum_{i=1}^{n} a_{ij}$: the sum of all values in column j; for example, the sum of the accessibility column

Scale of Pairwise Compasion (Saaty 1990)

1	Equal importance
5	Hdigh importance
7	Very high importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocity	If the comparison of factor with factor j is expressed as a_{ij} then: $a_{ij} = \frac{1}{a_{ji}}$ (Li et al. 2025)

4.Calculation of priority vector (criteria weights)	$Aw = \lambda_{\max} w, \sum_{j=1}^{n} w_j = 1$	After the normalization step, the average of each row is calculated, resulting from each expert's comparison. This determines the weights, or importance, of the criteria. This weight is expressed by w_j $w = (w_1, w_2, \ldots, w_n)^T$: weight vector w_j: weight of the j th criterion (e.g., "geological diversity", "accessibility"). For example, "geological diversity" 0.4, "tourism potential" 0.2.
5.Calculation of consistency ratio (CR)	$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} \frac{(Aw)_i}{w_i}$, $CI = \frac{\lambda_{max} - n}{n-1}$, $CR = \frac{CI}{RI(n)}$	It is performed to measure the consistency of the decisions made by experts. In these steps: $(Aw)_i$: the value obtained for the th criterion by multiplying the pairwise comparison matrix and the weight vector W_i: the weight of criterion i. (e.g. the weight of "accessibility") λ_{max}: the largest eigenvalue measures how consistent the expert judgments are CI: consistency index CR: if the consistency rate is CR<0.10, the evaluations of the experts comparing the geopark criteria are of acceptable consistency $RI\ (n)$: taken from Saaty's random consistency index table (based on the number of criteria)

Average random index (RI) based on Matrix Size (Saaty 2000)

n	1	2	3	4	5	…	15
RI	0	0	0.58	0.90	1.12	…	1.58

the identified criteria and the values associated with their potential among the alternatives. The primary goal of this approach is to create more understandable outcome indicators for decision makers and is applicable to all qualitative and quantitative studies (Chen and Tzeng 2004; Behzadian et al. 2012). The steps regarding the analysis carried out within the scope of the research are listed in Table 4 (Hwang and Yoon 1981; Tzeng and Huang 2011).

Results

Determination of AHP Criteria Weights and Sensitivity Analysis

The criterion weights obtained from the AHP method reveal the elements that shape the sustainability dimensions for geoparks within the model structure. Prioritization reveals not only the relative importance of the criteria but also the roles of environmental, socio-economic, and cultural dimensions within the scope of geopark sustainability.

In evaluating Geopark areas for sustainability, after pairwise comparison of criteria using the AHP approach, C2 (geological/hydrological risks: fault lines, erosion, landslides) was identified as the most important criterion, with a weight of 0.130. The conservation status criterion (C3) ranked second, with a weight of 0.127, while the presence of endemic species and habitat sensitivity (C1) ranked third, with a weight of 0.126. In contrast, the C4 criterion had the lowest weight within the environmental dimension, at 0.103 (Table 5; Fig. 4). In the socio-economic dimension of the model developed for the sustainability of geoparks, the local development and tourism potential (C5) criterion weights 0.092, while the local community participation and women's cooperatives criterion (C6) has a weight of 0.091. Furthermore, the tourism pressure and carrying capacity criterion (C8) is represented in this dimension with a weight of 0.072 and the access and transportation infrastructure criterion (C7) is represented with a weight of 0.060 (Table 5; Fig. 4).

In contrast, it has been determined that the criteria related to the cultural-educational sustainability dimension have relatively lower weights. Indeed, geo-education potential and literacy (C9) 0.062, access and transport infrastructure (C7) 0.060, academic research and scientific guidance (C12) 0.053, digital promotion and social media visibility (C10) 0.044, and local narratives, cultural memory, and geo-identity (C11) 0.041 (Table 5; Fig. 4). The model's consistency level is crucial for determining the weight values for the criteria using the AHP method. In this respect, the consistency ratio (CR) for the overall model structure was 0.077. Therefore, this value is below the threshold value of 0.10, indicating that the expert opinions in the analysis have a statistically reliable consistency structure.

A sensitivity analysis was conducted to determine the impact of changes in the weighting of AHP criteria in sustainable development prioritization on the outputs. Each criterion within the sustainability dimensions was divided into high, medium, and low sensitivity groups based on these results. The analysis revealed that environmental dimension criteria with high weights could significantly alter model sensitivity. The sensitivity values of criteria C1, C2, C3, and C4 were calculated to be between 0.238 and 0.300, and the stability values between 0.285 and 0.360. In the applied ± 10% weighting scenario, the C2 geological/hydrological risks criterion had the highest weight and sensitivity values within the model (Table 6; Fig. 5).

The sensitivity values of the criteria with moderate sensitivity were calculated to be in the range of 0.138–0.212. In particular, the socio-economic dimension (C5-C6-C7-C8) and the geo-education potential and literacy (C9) criterion, which is included in a different sustainability dimension, have a ± 10% sensitivity, which is limited but measurable in ranking and prioritizing scenarios. The low sensitivity of criteria C10–C11 and C12 indicates a limited potential to influence the model results under alternative scenario changes (Table 6; Fig. 5). In this context, sensitivity analysis revealed that the prominent variables in the model structure developed to analyze the sustainability of geoparks are important for model performance and that the model exhibits a stable sensitivity structure.

Determining the Sustainability Levels of Geoparks with the TOPSIS Method

TOPSIS is a widely recognised technique for ranking in multi criteria decision making problems. In this study, the sustainability levels of the 8 potential geoparks in Türkiye was analysed using the TOPSIS method, directly incorporating the criterion weights calculated via the AHP method in the previous stage. In this context, a decision matrix was established based on the evaluation of the eight geoparks by a group of five experts across the 12 determined criteria. The geometric mean of the experts ratings, ranging from 1 to 5 for each criterion (1 is the lowest value and 5 is the highest value), was calculated to populate the initial matrix values for each geopark (Appendix 1). Using the square roots of the data in the columns of the decision matrix, a normalised standard decision matrix was obtained. These normalized values were then multiplied by the criteria weights obtained from the AHP to create a weighted decision matrix (Table 7). This matrix formed the basis for determining the ideal (positive) and anti ideal (negative) solutions for each criterion. The ideal solution was defined by selecting the highest

Table 4 Stages of applying the TOPSIS method to the geopark evaluation process

1.Construction of the decision matrix	$X = [\chi_{ij}]_{m\times n}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n$	X : topsis matrix χ_{ij}: performance value of the -th geopark alternative (e.g., Kula–Salihli, Ida–Madra) with respect to the j-th criterion (e.g., geological diversity, accessibility) m : number of alternatives (e.g. geoparks examined) n: number of criteria (e.g. environmental, socio-economic, etc.)
2.Normalization of the decision matrix	$r_{ij} = \frac{xij}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}$	r_{ij}: normalized value; since the criteria are on different scales (e.g. number of visitors in thousands, geological score from 1–9), they are all set to the same scale [0–1]
3.Weighted normalized decision matrix	$v_{ij} = w_j \cdot r_{ij}$, $\sum_{j=1}^{n} w_j = 1$	w_j: criteria weights obtained from AHP (e.g. geological diversity 40%, tourism potential 25%) v_{ij} : weighted normalized value
4.Determination of positive and negative ideal solutions	$PIS = \left(\max_i v_{ij} \middle\| j \in \widehat{j}\right), \left(\min_i v_{ij} \middle\| j \in \check{j}\right),$ $NIS = \left(\min_i v_{ij} \middle\| j \in \widehat{j}\right), \left(\max_i v_{ij} \middle\| j \in \check{j}\right)$	where, $\check{j}$ and $\check{j}$ represent indicators to be maximized and minimized, respectively $\widehat{j}$: desirable criteria to be high (e.g. Endemic species presence, habitat sensitivity) $\check{j}$: criteria that are desirable to be low (e.g., Local narratives, cultural memory and geo-identity) PIS (Positive Ideal Solution): the set of best values for each criterion in the geopark evaluation NIS (Negative Ideal Solution): the set of worst values for each criterion in the geopark evaluation
5.Distances to PIS and NIS	$S_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, S_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}$	S_i^+: distance of the $i-$ th geopark to the positive ideal solution S_i^-: distance from the negative ideal solution v_j^+, v_j^- : positive and negative ideal values (ideality reference points)
6.Closeness coefficient	$C_i = \frac{S_i^-}{S_i^+ + S_i^-} 0 \le C_i \le 1$	C_i: proximity coefficient. If it is close to 1, the alternative (geopark) is the most suitable option. For example, a geopark with $C = 0.85$ is much more advantageous than others

Table 5 Weights of criteria used in evaluating geoparks determined using the AHP method

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	w	Rank
C1	0.13	0.09	0.11	0.10	0.22	0.33	0.23	0.22	0.16	0.17	0.19	0.10	0.126	3
C2	0.13	0.09	0.11	0.10	0.22	0.20	0.14	0.13	0.16	0.06	0.02	0.10	0.130	1
C3	0.13	0.09	0.11	0.10	0.22	0.20	0.14	0.13	0.16	0.06	0.19	0.10	0.127	2
C4	0.13	0.09	0.11	0.10	0.22	0.20	0.14	0.13	0.10	0.06	0.19	0.06	0.103	4
C5	0.04	0.03	0.04	0.03	0.07	0.20	0.05	0.04	0.16	0.03	0.19	0.10	0.092	5
C6	0.03	0.03	0.04	0.03	0.02	0.07	0.05	0.04	0.16	0.06	0.32	0.06	0.091	6
C7	0.03	0.03	0.04	0.03	0.07	0.07	0.05	0.04	0.10	0.03	0.06	0.06	0.060	9
C8	0.03	0.03	0.04	0.03	0.07	0.07	0.05	0.04	0.10	0.03	0.02	0.06	0.072	7
C9	0.03	0.02	0.02	0.03	0.01	0.01	0.02	0.01	0.03	0.06	0.02	0.06	0.062	8
C10	0.13	0.28	0.33	0.30	0.36	0.20	0.23	0.22	0.10	0.17	0.19	0.10	0.044	11
C11	0.04	0.28	0.04	0.03	0.02	0.01	0.05	0.13	0.10	0.06	0.06	0.06	0.041	12
C12	0.03	0.02	0.02	0.03	0.01	0.02	0.02	0.01	0.01	0.03	0.02	0.02	0.053	10

Consistency ratio (CR) values calculated among experts range from 0.036 to 0.100. The average CR consistency ratio within the scope of the AHP is 0.077. The matrix results calculated within the scope of each expert opinion are presented in the Appendix 1

values in each column, while the negative ideal solution was defined by selecting the lowest values. The euclidean distance of each alternative from these two extreme solutions was then calculated, thus determining the positive and negative ideal distance values (Appendix 1).

In the final stage, proximity to the ideal solution was determined using positive and negative ideal distance values. For this purpose, for each alternative value, the negative ideal solution value was divided by the sum of its own value and the positive ideal solution value of the same alternative. Thus, the ranking of prominent geoparks in Türkiye, based on the specified criteria and using the TOPSIS method, was revealed. The calculated Ci+value in this ranking indicates the geoparks' position in the ranking. Accordingly, the analysis concluded that the Kula-Salihli (0.74) geopark area ranked first. Indeed, Kula-Salihli is Türkiye's only geopark area with UNESCO Global Geopark status. In terms of sustainability level, the Cappadocia Geopark ranks second with a value of 0.66 Ci+, followed closely by the Denizli Travertine Geopark (0.65) area (Table 8; Fig. 6).

The areas ranked highest in the weighted matrix results are C3 (Protection status), C5 (Local development and tourism potential), C6 (Local community participation, women's cooperatives), C7 (Access and transport infrastructure (roads, signage, disabled access), C8 (Tourism pressure and carrying capacity) and C9 (Geo-education potential and literacy (guidance, information boards) among many other criteria. This situation can essentially be considered a reflection of the high level of tourism investment in these areas and their advanced tourism planning and marketing (Akgöz et al. 2022; Türk 2022). In contrast, Nemrut Caldera (0.56) and Ida-Madra (0.54) are ranked 4th and 5th, respectively, in the TOPSIS ranking. Nemrut Caldera, in particular, performed highly in the C1 (presence of endemic species, habitat sensitivity), C2 (geological/hydrological risks), and C3 (conservation status) criteria. These two areas are followed by the Narman Geopark (0.42) and the Cilo-Sat Geopark (0.41), which have lower Ci+values. The Zonguldak Coal Geopark (0.18) emerged as the area with the lowest sustainability level among the analysed areas (Table 8; Fig. 6).

Discussion

According to the analyses conducted in the study, the results obtained can be interpreted in three dimensions within the scope of sustainability and geopark relations, encompassing the research model. According to expert opinions on the research model, the first is prioritizing sustainability in the "environmental" dimension. The findings from pairwise comparisons indicate that environmental sustainability processes are more important for geoparks than

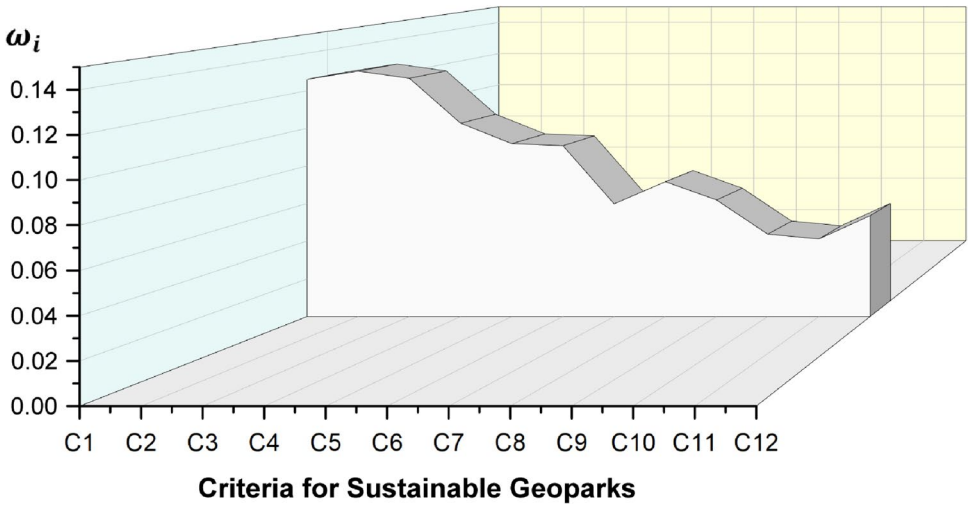


Fig. 4 Distribution of criteria weights

Table 6 Criteria weights for different scenarios and results of the model sensitivity analysis

Criteria	Weight (w)	Sensitivity (S)	Stability (ST)	Sensitivity (+10%)	Sensitivity (−10%)	Sensitivity group
C1	0.126	0.291	0.349	0.320	0.262	High
C2	0.130	0.300	0.360	0.330	0.270	High
C3	0.127	0.293	0.352	0.322	0.264	High
C4	0.103	0.238	0.285	0.261	0.214	High
C5	0.092	0.212	0.255	0.234	0.191	Medium
C6	0.091	0.210	0.252	0.231	0.189	Medium
C7	0.060	0.138	0.166	0.152	0.124	Medium
C8	0.072	0.166	0.199	0.183	0.150	Medium
C9	0.062	0.143	0.172	0.157	0.129	Medium
C10	0.044	0.102	0.122	0.112	0.091	Low
C11	0.041	0.095	0.114	0.104	0.085	Low
C12	0.053	0.122	0.147	0.135	0.110	Low

their socio-economic and cultural-educational dimensions. According to the developed model, environmental dimensions such as risks, ecological sensitivity, and protectability are among the key determinants of sustainability prioritization for geoparks. This situation reflects experts' sensitivity to risks to the natural environment and to the sustainability of geoparks, which are essentially heritage sites.

Geological/hydrological risks (C2) have a direct impact on the sustainability prioritization of geoparks, affecting the continuity of the areas through erosion, landslides, and faulting elements related to geological structure, within the scope of climate change sensitivity. This impact stands out as the strongest aspect of the model and is consistent with previous research findings (DeFelipe et al. 2025). Conservation status (C3), the presence of endemic species and habitat sensitivity (C1), and land use pressure (C4) emphasize the prioritization of protecting geomorphological features in these areas, while accounting for the fragility and pressure sensitivity of physical and human geography elements across different studies (de Lima et al. 2010; Fassoulas et al. 2012; García-Ortiz et al. 2014; Prosser et al. 2018; Zafeiropoulos et al. 2025). Conversely, the relatively low sustainability levels in areas where conservation measures are inadequate and environmental threats are more severe are noteworthy, demonstrating the importance of environmental factors (Gordon et al. 2018). The findings from this model are consistent with research highlighting the importance of geological diversity, geoheritage, and conservation elements within the context of sustainable use of geoparks (Xu and Wu 2022).

In the model developed for the scope of conservation and sustainability, the secondary dimension is the "socio-economic" dimension. In the study, socioeconomic factors such as local development, local community participation, tourism pressure, and infrastructure were found to be the most prominent factors in determining the sustainability levels of geoparks, following environmental criteria in the model developed for geopark sustainability assessment. Academic studies show that the development and diversification of tourism investments in areas designated as geoparks contribute to the economic development of those regions by diversifying the service sector. In this respect,

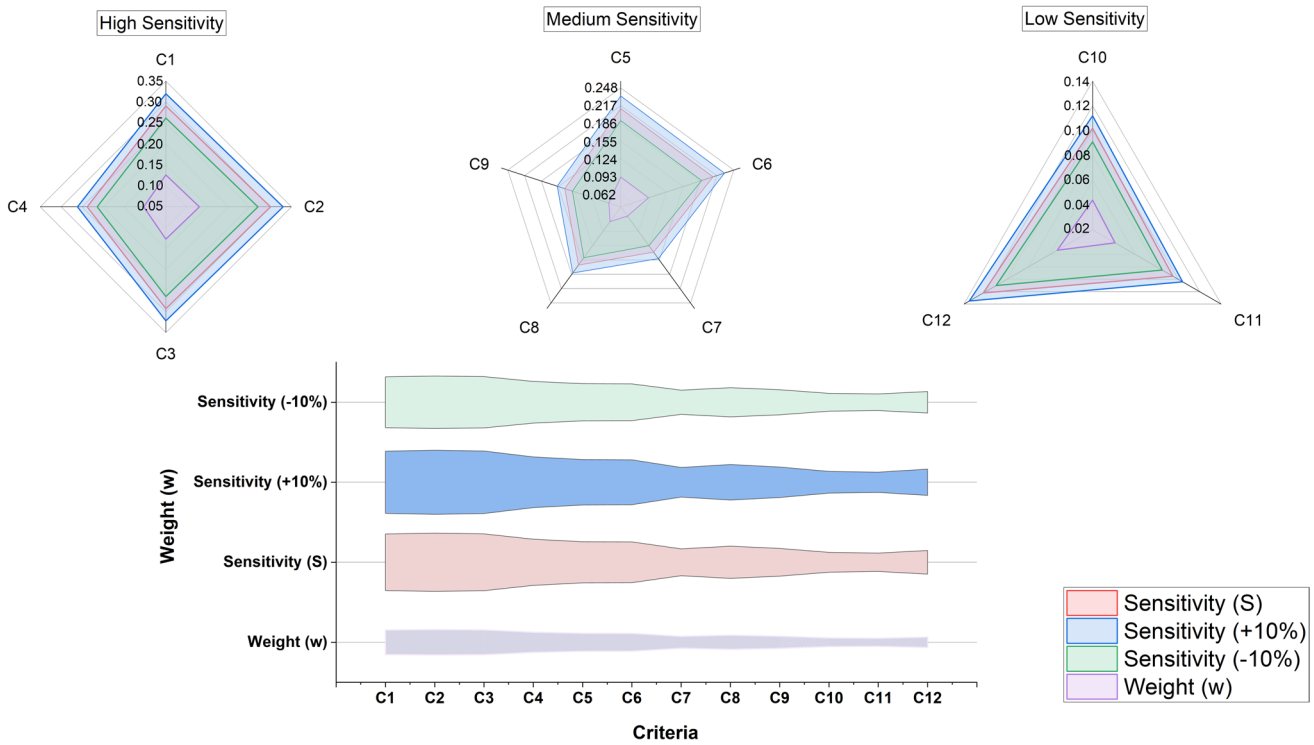


Fig. 5 Criteria weights across different scenarios and sensitivity analysis results (Note: Sensitivity analysis radar indicators are classified into high-medium–low levels)

geoparks provide benefits for rural or regional development by supporting the economic development of the local population in their regions through tourism (Lee and Jayakumar 2021). In this context, rather than viewing geoparks solely as geoheritage areas requiring protection, these areas can be considered potential development tools. This approach should consider the balance between protection and use, and embrace the participation of all stakeholders in the management processes of geoparks with a sustainable tourism approach (Tavares et al. 2015). Accessibility, tourism and transport capacity, and infrastructure, considered within the socio-economic dimension, provide a framework that is consistent with the principles of tourist satisfaction, local participation, and economic benefit emphasized in the geotourism literature (Kubalíková 2013).

The model fundamentally reflects local and regional development and the integrated utilization of potential, addressing these antecedents. Access and transportation infrastructure (C7) (roads, signage, disabled access) challenges fundamentally reduce visits and tourist interest in the area, and, conversely, affect the willingness of tourists to explore it. This, particularly in accessible areas, contributes to sustainable development by strengthening the identity of local people as tourist destinations, through both the Local development and tourism potential trend (C5) and the Local community participation, women's cooperatives (C6) processes (Pál and Albert 2021). According to experts, this criterion, which is prioritized at a medium level, is also the subject of various studies and holds importance at matching levels. However, the Tourism pressure and carrying capacity (C8) processes are significant for the protection and sustainability of geological areas. The proximity of geoparks to main roads, their easy accessibility, and the resulting increase in capacity overruns and tourist pressure have been highly highlighted in research (Carrión-Mero et al. 2021). However, the developed model assesses that these factors represent a balance between high priority areas requiring high protection and areas subjected to low pressure.

The third dimension in prioritizing geopark sustainability is "Cultural-Educational Sustainability". Although the criteria under the cultural-educational dimension of the model have lower weights than those in other dimensions, they still have a small impact on determining the top ranking positions of geoparks in the general evaluation under the TOPSIS method. In this sense, geoeducation, academic research activities, cultural memory, and digital promotional activities are crucial to improving the sustainability of geoparks. These elements contribute not only to the conservation and management of geoparks but also to their promotional activities. In particular, fostering a sense of belonging and ownership of heritage elements among local people, as well as raising visitors' awareness through educational activities, supports the conservation and sustainable management of geoparks (Gordon et al. 2018). Therefore, the criteria under

Table 7 Weighted decision matrix of important Geoparks in Türkiye

	Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Alternatives	A1- Nemrut (Caldera) Geopark	0.059	0.052	0.048	0.026	0.032	0.032	0.013	0.024	0.022	0.014	0.013	0.02
	A2-Cilo-Sat Geopark	0.059	0.052	0.036	0.026	0.024	0.022	0.006	0.012	0.017	0.009	0.013	0.02
	A3-Kula-Salihli Geopark	0.047	0.039	0.06	0.04	0.04	0.043	0.025	0.036	0.028	0.018	0.017	0.02
	A4-İda-Madra Geopark	0.047	0.052	0.036	0.04	0.032	0.032	0.019	0.024	0.022	0.014	0.013	0.02
	A5- Denizli Travertine Geopark	0.036	0.039	0.06	0.053	0.04	0.032	0.025	0.024	0.022	0.018	0.017	0.02
	A6- Cappadocia Geopark	0.036	0.039	0.048	0.04	0.04	0.043	0.032	0.036	0.028	0.023	0.017	0.02
	A7- Narman Geopark	0.036	0.039	0.036	0.04	0.024	0.022	0.019	0.024	0.022	0.014	0.013	0.02
	A8-Zonguldak Coal Geopark	0.024	0.052	0.024	0.013	0.024	0.022	0.019	0.012	0.011	0.009	0.01	0.02

Table 8 Ranking of sustainability levels of important geoparks in Türkiye according to the TOPSIS method

Alternatives	Si+	Si-	Ci+	Ranking
A3-Kula-Salihli Geopark	0.023343233	0.068547342	0.745967059	1
A6- Cappadocia Geopark	0.032367188	0.062864475	0.660121573	2
A5- Denizli Travertine Geopark	0.033274342	0.064359819	0.65919365	3
A1- Nemrut (Caldera) Geopark	0.040937201	0.052152097	0.560237303	4
A4-İda-Madra Geopark	0.039899467	0.046994224	0.540824353	5
A7- Narman Geopark	0.052171335	0.037923244	0.420927036	6
A2- Cilo-Sat Geopark	0.060216557	0.042328933	0.412782004	7
A8- Zonguldak Coal Geopark	0.078573	0.018188	0.187966	8

the cultural and educational dimensions in the model should be considered not as limited elements of the evaluation process, but as complementary and fundamental components of sustainability assessments. Studies by Kelley and Salazar (2016) and Mikhailenko et al. (2024) have identified geoparks as a resource for educational and tourism purposes. In addition, in the long term, preserving cultural memory in geoparks, strengthening awareness of geographical identity, and raising awareness through education contribute to making environmental and socio-economic gains more permanent and sustainable in society.

The ranking results from the case analysis applications of the model within the scope of the research show significant advantages and differences in the sustainability related criteria structure. The higher sustainability scores of geoparks with protected status (e.g., UNESCO Global Geoparks) are consistent with findings that natural resource conservation plays a critical role in sustainable management. Indeed, based on these characteristics, the Kula-Salihli Geopark ranks among the strongest areas. In addition to having numerous geosites, the area is notable for being managed in accordance with sustainable principles and prioritising the socio-cultural and economic development of the local population. In this respect, the Kula-Salihli Geopark ranks first among the evaluated areas in terms of sustainability level, which is consistent with the literature (Kırlar Can and Usta 2021; Aytaç and Demir 2023). In the developed model, this area is included in the classification of geoparks of global importance according to the sustainability prioritization of experts.

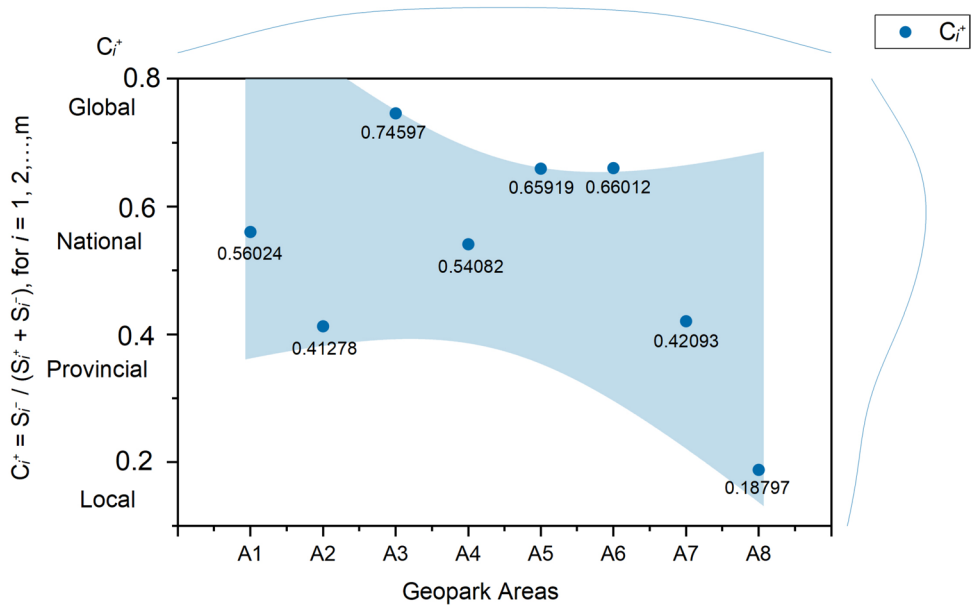


Fig. 6 Distribution of sustainability levels of significant geoparks in Türkiye

Other areas of global significance include the Cappadocia Geopark and the Denizli Travertine Geopark. The importance of these two geoparks is particularly linked to their strong conservation status, integration of local communities and the geopark, and the sustainability of their economic and social values. Furthermore, these attractive features are sustained through a sustainable balance between conservation and utilization, despite intense tourism pressure and increasing visitor demand in these areas. This situation can essentially be considered a reflection of the high level of tourism investment in these areas and their advanced tourism planning and marketing (Akgöz et al. 2022; Türk 2022). Both the site rankings and the importance levels constitute distinctive features that differentiate this geopark from others, including sites listed on the UNESCO World Heritage List, and are consistent with existing research (Kaygılı et al. 2018; Doğan et al. 2018; Özkul et al. 2024; Öztürk 2025).

The low level of importance of Nemrut (Caldera) Geopark, Ida-Madra Geopark, Narman Geopark and Cilo-Sat Geoparks at the regional level within the scope of sustainability and Zonguldak Coal Geopark, which is important at the local level, are mainly characterized as the lack of development of tourism activities in these areas. Although these areas contain rich environmental, educational, and cultural features, including geological heritage and geotourism, they are also sites that require planning for socio-economic sustainability. Indeed, the study by (Dede et al. 2025) highlighted a general lack of policy and planning tools for the sustainable use of local and regional elements in Türkiye. In particular, even if these areas are declared nature parks, they reflect domestic tourism like other protected areas, and hold no meaning for geotourists or the local population. According to experts, these areas are seen as weaknesses in the prioritization of sustainable geoparks and as areas that need improvement.

Indeed, the framework of the sustainability model developed for geoparks in this study includes different results compared to traditionally implemented approaches: (a) a comprehensive geopark assessment based on sustainability-related indicators, (b) the importance and prioritization of these indicators in sustainability dimensions, and (c) a sustainable prioritization model that can be developed according to various location examples as a result of the comparison.

While this study offers important outcomes that address sustainable development goals for geoparks, it also has some limitations. Due to the lack of geographically and thematically based geopark applications, digital tourism applications, climate change indicators, and current data statistics, these criteria were not included in the analysis process. Another limitation of the study is the lack of records in many geoparks related to this trend, despite the absence of participatory structures within geoparks' local identities. Geoparks lack a data network within a sustainable framework that integrates data, supports conservation, and enables use. Furthermore, Türkiye, with its geological history and tectonic dynamism, possesses geopark qualified areas in nearly all of its areas. However, considering data accessibility and evaluation constraints, case studies were provided for selected areas.

For future studies, it is recommended that climate change indicators, digital tourism applications, and migration data within geoparks be incorporated into the criteria structure, particularly regarding sustainability dimensions. Including these variables will enable the model to analyze geoparks in terms of climate vulnerability and population mobility. Furthermore, mixed design studies that reflect the motivations and demands of local communities will allow for the development of social

sustainability dimensions alongside environmental and economic trends. The use of alternative fuzzy approaches across geoparks, reflecting the diverse perspectives of decision makers with expertise in these areas, could have implications for future studies. Following the implementation of this model, the development of sustainability compatible risk and planning models within geographic information systems will offer new perspectives on geopark research.

Conclusion

This study holistically assessed the sustainability levels of Geoparks in Türkiye, considering environmental, socio-economic, and cultural-educational criteria, and revealed the decisive roles of these criteria in geopark performance. Within the scope of geopark assessments, experts concluded that among the environmental dimensions of sustainability, endemic species and habitat sensitivity (C1), geological/hydrological risks (C2), and conservation status (C3) had a greater impact on geoparks than other criteria. In the study, socioeconomic factors such as local development, local community participation, tourism pressure, and infrastructure were found to be the most prominent factors in determining the sustainability levels of geoparks, following environmental criteria.

Overall, the findings indicate that a comprehensive analysis of the model components developed to determine the sustainability levels of geoparks reveals that geopark sustainability cannot be explained solely by environmental criteria. In addition to environmental factors, socio-economic and cultural-educational parameters must be considered to protect geoparks as geotourism areas effectively. Therefore, management plans that prioritize the development of all aspects of geopark sustainability must be developed and implemented.

In conclusion, this approach, developed within the context of sustainable development goals and based on relevant literature and expert opinions, encompasses three dimensions (environmental, socioeconomic, and cultural-educational). This approach offers a holistic model for geoparks. The model, using case studies, demonstrates the need for a holistic approach to such assessments by analyzing selected geopark areas in Türkiye for sustainability. Given that geoparks are sustainable geotourism destinations, it follows that sustainable management of these areas cannot be achieved solely through the protection of natural values. While the protection of geoparks is of paramount importance for sustainability, their use as a sustainable tourism tool necessitates consideration of socioeconomic and cultural-educational factors. Therefore, sustainability trends for geoparks and their protection should be considered within a framework encompassing three main axes. Indeed, it is important to recognize that the 17 sustainable development goals and their integrated sub-criteria can be linked to the values and functions of geological diversity and geological heritage (Kubalíková et al. 2023b). The research presents a developable approach that assesses the sustainability levels of geoparks against specific parameters, in the context of their preservation use balance and their transfer to future generations. Finally, this research will ensure more effective and sustainable geoscientific heritage protection and will be a guiding model for determining priorities for this purpose.

Data Availability

The basic data supporting the findings of this study are presented in the article. The authors can be contacted for more detailed data or additional information requests; assistance will be provided upon request.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12371-026-01286-7.

Author Contributions Yusuf Kızılkan: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Visualization, Writing-original draft, Writing-review & editing, Supervision. Salih Birinci: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing-original draft, Writing-review & editing. Aykut Camcı: Conceptualization, Methodology, Validation, Resources, Writing-original draft, Writing- review & editing. Çağlar Çakır: Conceptualization, Methodology, Validation, Investigation, Resources, Writing-original draft, Writing- review & editing.

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Declarations

Ethical Approval and Informed Consent This study was conducted in accordance with ethical principles, and the necessary approval was obtained from the relevant institution's ethics committee (Session Number: 14, Decision Number: 304). All participants were informed about the purpose and scope of the study beforehand, and their consent was obtained voluntarily. The experts were selected from different disciplines to ensure representation and independent evaluation. Collected data was kept confidential, used only for scientific evaluations, and no personal information was shared.

Competing interests The authors declare no competing interests relevant to the content of this article.

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