

Article

Sustainability and Ecotourism Opportunities: Evaluating the Indicators in a Complex Adaptive System

Riyan Mohammad Sahahiri ^{1,*} , Abdullah Alattas ¹ , Ahmad Fallatah ^{1,2}  and Ammar Mandourah ¹ 

¹ Department of Geomatics, Faculty of Architecture and Planning, King Abdul Aziz University, Jeddah 22254, Saudi Arabia; afalattas@kau.edu.sa (A.A.); amfallatah@kau.edu.sa (A.F.); amsmandourah@kau.edu.sa (A.M.)

² The Center of Excellence in Smart Environment Research, King Abdul Aziz University, Jeddah 22254, Saudi Arabia

* Correspondence: rmsahaheere@kau.edu.sa

Abstract

Assessing sustainability in complex adaptive systems (CAS) is still considerable challenge, due to the prevalence of dynamic non-linear interdependent socio-ecological processes. Traditional assessment approaches often target a single outcome and have a limited ability to model the interactions and feedback loops that influence system behavior. To overcome this limitation, this research proposes a hybrid methodological framework that integrates the Ecotourism Opportunity Spectrum (ECOS), the Delphi method, and key components of CAS theory. The framework allows for the systematic identification, organization, and validation of sustainability indicators in a structured way. It uses a layered approach where indicators are first conceptualized within an integrated framework, then adapted through expert agreement, and subsequently interpreted through the theoretical perspective of CAS to better understand interdependencies and adaptive dynamics. The findings demonstrate strong expert agreement across the identified sustainability indicators and highlight the importance of understanding sustainability dimensions as interdependent rather than isolated assessment components. The CAS-based interpretation further revealed that sustainability indicators operate through adaptive and interconnected relationships, where changes in external environmental, institutional, or socio-economic conditions may influence multiple sustainability dimensions simultaneously. This study contributes to the improvement of sustainability assessment tools and supports decision-making in a more informed, flexible, and context-specific manner by providing a structured but still flexible decision-support approach.

Keywords: ecotourism; sustainability; indicators; opportunities; complex adaptive system



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1. Introduction

Sustainability evaluation has become a critical challenge across multiple domains, characterized by complex and dynamic systems, where traditional linear assessment approaches fail to capture system interdependencies [1,2]. Despite the availability of numerous sustainability assessment approaches, many remain limited in their ability to account for non-linear interactions, feedback mechanisms, and adaptive system behavior [3,4]. Accordingly, there is an increasing need for methodological frameworks that can systematically evaluate sustainability within complex adaptive systems.

Sustainability challenges are particularly evident in a complex system that integrates environmental, social, and economic dimensions, where multiple stakeholders and pro-

cesses interact dynamically [5,6]. Such systems require structured approaches to identify, organize, and evaluate sustainability indicators in a coherent and integrated manner [7,8]. Ecotourism provides a relevant applied context through which these broader sustainability challenges can be observed, as it inherently operates at the intersection of environmental, socio-cultural, and economic systems [2,5,9]. Moreover, many contemporary tourism destinations, including heritage and archeological destinations, increasingly integrate nature conservation, community participation, environmental education, and cultural preservation within their development strategies [10–12]. Consequently, the sustainability challenges associated with ecotourism are not exclusive to nature-based destinations but are also evident in other tourism systems characterized by complex interactions among environmental, cultural, social, and economic dimensions.

Moreover, many contemporary tourism destinations, including heritage and archeological destinations, increasingly integrate nature conservation, community participation, environmental education, and cultural preservation within their development strategies. Consequently, the sustainability challenges associated with ecotourism are not exclusive to nature-based destinations but are also evident in other tourism systems characterized by complex interactions among environmental, cultural, social, and economic dimensions.

Ecotourism is a sustainable and nature-based form of tourism that promotes conservation, education, and local economic benefits [9,13–15]. These opportunities contribute to the tourism industry's long-term sustainability by delivering measurable advantages to local residents and fostering the protection of natural habitats [16–19].

Despite these potential benefits, scholars believe that sustainability outcomes in ecotourism systems may not always be guaranteed due to the complex interactions between stakeholders, environmental conditions, tourism activities, and governance practices [20–22]. So, ecotourism should be subjected to careful planning to ensure sustainability. Thus, there is a need to develop methodological approaches that can systematically evaluate sustainability indicators within complex and interdependent ecotourism systems.

However, evaluating sustainability in complex systems remains challenging due to the absence of standardized frameworks that integrate indicator selection, expert validation, and system-level analysis. A second challenge is the novelty of ecotourism, as it is a relatively new concept and lacks agreed-upon opportunity dimensions that connect with sustainable practices, making it difficult to determine the degree of sustainability within ecotourism opportunities [15,23]. In response to these challenges, previous studies have increasingly employed indicator-based frameworks and expert-driven approaches to support sustainability evaluation in complex tourism and environmental contexts.

Literature Review

In this context, Tsaur et al. [24] evaluated the sustainability of a Taiwanese indigenous ecotourism site. They argued that thorough measurement of all aspects and implications of ecotourism is almost impossible due to the interrelated variables involved. Therefore, they collected sustainability indicators by analyzing the relationships between residents, tourists, and resource administration (resource administration involves managing and governing tourism resources such as natural, cultural, environmental, transportation, and accommodation resources). They applied the Delphi method to identify 47 sustainability indicators, followed by a weighting process to produce a single value indicating the destination's sustainability status. According to their findings, tourism and the community had the most significant impact on natural and cultural resources. In addition, the experts who participated in the Delphi method study were particularly concerned about environmental issues. This suggests that tourism resources such as natural, cultural, environmental, transportation, and accommodation resources are crucial for sustainable tourist development.

Previous studies have proposed a wide range of sustainability indicator systems for assessing ecotourism and sustainable tourism. Ashok et al. [25] evaluated ecotourism sustainability through their Ecotourism Sustainability Assessment (ESA) framework. Initially, they identified four principles and eight criteria through a literature review. Then, 58 indicators and 58 verifiers were confirmed by participatory workshops in Sikkim, India. Verifiers are evidence or data sources used to confirm or support the measured indicators. The Delphi method used at the participatory workshop generated the consensus on principles, criteria, indicators, and verifiers. The authors concluded that ecotourism sustainability depends on four cardinal principles: protection of natural and cultural resources, generation of socio-economic benefits to the local community, generation of environmental awareness and capacity building, and tourist satisfaction. These principles were measured by criteria, indicators, and verifiers.

Barzekar et al. [26] evaluated ecotourism sustainability in the Northern Forest of Iran. They began by reviewing the existing information on sustainability evaluation and used the Delphi method to obtain consensus from respondents on sustainable ecotourism criteria and indicators. Their study identified 61 environmental (ecological), social, economic, cultural, and institutional indicators. Twenty-one indicators pertained to environmental (ecological) indicators, eight indicators to economic, twenty-one to social, six to cultural, and five to institutional aspects.

García-Melón et al. [27] proposed a sustainable National Park (NP) methodology in Venezuela. They applied the Delphi method and the Analytic Network Process (ANP) priority weight method to identify indicators through engagement with the stakeholders (researchers, sustainable development experts, stakeholders of the NP, and NP managers). They consulted with experts and reviewed the literature to formulate thirteen criteria and three sustainable tourism strategies: (a) development of eco-efficient resorts to manage their waste and wastewater in accordance with rules and regulations, (b) development of environmentally friendly activities (such as guided tours, guided diving, fishing, hiking, and windsurfing), and (c) the use of sustainable transportation such as animal-powered transport, row boats, and use of existing trails or roads, as residents of protected areas with the potential for tourism development were highly concerned about this issue. However, the authors concluded that the best tourism strategy to be implemented is environmentally friendly activities followed by sustainable transport, and the worst ranked by far were eco-efficient resorts.

Chávez-Cortés and Maya [28] defined sustainable indicators for a Mexican community and discussed indicators' suitability in the context of tourism development. The authors used Value-Focused Thinking as a framework. The stakeholders' interviews were analyzed, and the authors concluded that tourism sustainability involves aspects from environmental, social, health, educational, economic, and political/institutional dimensions. Tanguay et al. [29] applied selection criteria to 507 indicators from a sustainable tourism indicators database. This allowed them to reduce the list to 20 recognized sustainable tourism indicators in the Gaspésie region in Quebec, Canada. These shortlisted indicators were then used to develop sustainability guiding principles for the Gaspésie region and included principles like safeguarding culture, preservation, heritage development, promoting eco-responsibility, participating in governance and endogenous development, and the sustainability of tourism activities. The authors found that a compromise could be reached between academic and policymaker approaches to indicator formulation using the methods employed in their study.

Miller [30] developed indicators to assist tourists in choosing holidays and promoting sustainability in tourism. The author first identified a list of 74 sustainability indicators from the literature on tourism sustainability. Then, the Delphi method was used to achieve

consensus on indicators that could be used to measure the movement of the tourism product at a company/resort level towards a position of greater or lesser sustainability. The research concluded that although there is general agreement on the need for sustainable tourism to focus on long-term outcomes, there is little agreement on what policies should be employed over this period. However, participation in sustainable tourism promotion is necessary.

Lee and Hsieh [31] identified indicators for sustainable wetland tourism. The initial key dimensions and indicators were identified using the fuzzy Delphi method. Using the Analytic Hierarchy Process (AHP), the relative weights of these dimensions and indicators were then examined. The empirical findings revealed a hierarchy of 141 indicators for sustainable wetland tourism. The stakeholder indicators carried more weight than the environmental dimension at the initial level. The impact on community development was the second level's most crucial factor within the stakeholder dimension. Respect for local cultural heritage, respect for local customs, compliance with destination guidelines, transportation problems, the degradation of the natural environment, presence of crowds at the destination, participation in cultural activities, understanding the culture, assimilation into the local culture, overall effect of tourism, benefit–cost differential, and reduction in environmental impact comprised 7.8 percent of the identified indicators. Several management implications were identified, including the need to encourage stakeholder participation and collaboration to prioritize planning for overall sustainable tourism development and the use of these indicators to manage wetland-based sustainable tourist development.

The literature review also demonstrates that few studies address the multiple ecotourism opportunity dimensions under which sustainable indicators can be developed. For instance, Ashok, Tewari, Behera, and Majumdar [25] employed five dimensions: nature-based, ecologically sustainable, environmentally educative, economically beneficial to the local community, and tourist satisfaction. However, these dimensions do not explicitly address the socio-cultural benefits. Similarly, Barzekar, Aziz, Mariapan, and Ismail [26] also used five dimensions—social, ecological, cultural, economic, and institutional—but these lack a dedicated focus on environmental education and protection, a crucial element of ecotourism. Tanguay, Rajaonson, and Therrien's [29] approach was based on environmental, social, and economic dimensions, despite these dimensions not fully capturing the nature and tourists' satisfaction.

Several international organizations have also developed comprehensive frameworks for monitoring tourism sustainability. The Global Sustainable Tourism Council Destination Criteria (GSTC-D) provides a globally recognized framework covering destination management, socio-economic benefits, cultural heritage, and environmental sustainability [32]. Similarly, the UNWTO Guidebook on Indicators of Sustainable Development for Tourism Destinations offers a systematic approach for identifying and monitoring sustainability indicators at destination level [33]. The European Tourism Indicator System (ETIS) was developed to support destination managers in monitoring economic, environmental, social, and governance dimensions of sustainability. These initiatives demonstrate the growing recognition that sustainability assessment requires multidimensional and integrated indicator systems capable of supporting adaptive destination management [34].

Despite the growing body of research on sustainability indicators, limited attention has been given to their interdependence and adaptive behavior within complex systems. Most existing approaches remain indicator-oriented and context-specific, with insufficient integration between indicator structuring, expert validation, and systems-level interpretation. As a result, current methods often struggle to capture dynamic relationships, feedback mechanisms, and adaptive interactions among system components. Therefore, there is a need for an integrated methodological framework that combines structured

indicator organization, expert-driven consensus, and systems-based analysis within a unified approach.

This research proposes a hybrid methodological framework that integrates the Ecotourism Opportunity Spectrum (ECOS), the Delphi method, and key components of Complex Adaptive Systems theory. It aims to (1) employ the ECOS model to develop a structured methodological framework for organizing sustainability indicators; (2) integrate the Delphi method to establish expert consensus; and (3) apply CAS theory as a conceptual lens to interpret the dynamic and interdependent nature of sustainability indicators within complex systems.

Existing studies have largely focused on identifying sustainability indicators within specific tourism contexts, with limited attention given to how these indicators can be systematically structured and interpreted within complex adaptive systems. In many cases, expert-based evaluation methods are applied without a clear conceptual framework to guide indicator selection and organization. To address these limitations, this study adopts a hybrid methodological framework in which the ECOS model is employed to organize sustainability indicators, the Delphi method is used to validate them through expert consensus, and CAS theory is subsequently applied as an interpretative lens to understand the dynamic interrelationships and adaptive behavior of the validated sustainability indicators. By integrating these approaches, the study contributes a structured and transferable decision-support framework that can support sustainability evaluation across a wide range of complex contexts beyond ecotourism alone.

2. Materials and Methods

2.1. Hybrid Sustainability Assessment Framework

This study proposes a hybrid methodological framework that integrates ECOS, the Delphi method, and CAS theory to support sustainability evaluation in complex systems. The framework was developed to address three persistent challenges in sustainability assessment: (1) the absence of a systematic approach to organizing sustainability indicators, (2) the limited incorporation of expert consensus into indicator validation, and (3) the insufficient consideration of dynamic and interconnected system relationships.

As illustrated in Figure 1, the framework comprises three complementary stages. In the first stage, the ECOS model provides a conceptual structure for identifying and organizing sustainability dimensions and indicators. In the second stage, the Delphi method is used to evaluate and validate the relevance of the identified indicators through iterative expert consensus. In the third stage, CAS theory is applied as an interpretative lens to understand interdependencies, feedback mechanisms, and adaptive relationships among sustainability dimensions and indicators.

The integration of these three components produces a structured yet flexible decision-support framework capable of assessing sustainability in complex and evolving systems. Unlike conventional indicator-based approaches that often examine sustainability components in isolation, the proposed framework recognizes that sustainability outcomes arise from continuous interactions among environmental, social, economic, and institutional processes. Consequently, the framework provides a more holistic approach to sustainability evaluation and has potential applicability beyond ecotourism, extending to other complex sustainability contexts.

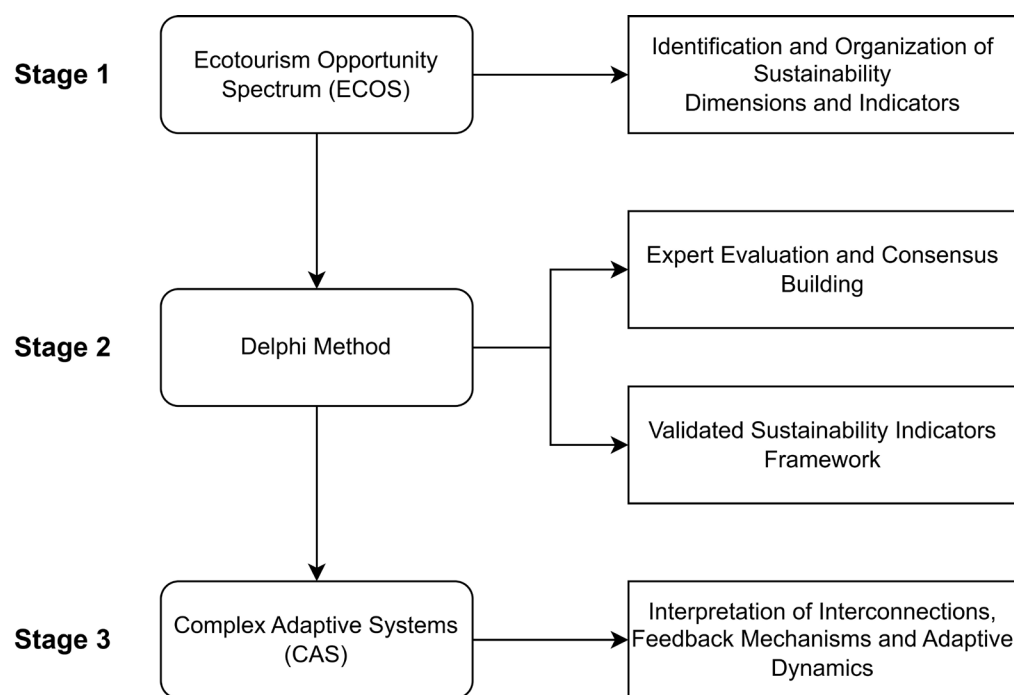


Figure 1. Hybrid sustainability assessment framework integrating ECOS, Delphi, and CAS.

2.2. Research Context

Alula, Saudi Arabia, was selected as the case study due to its rapid transformation into an integrated sustainable tourism destination that combines archeological heritage, cultural resources, nature conservation, and community-based tourism initiatives. Although Alula is internationally recognized for its heritage significance, recent development strategies under Saudi Vision 2030 have strongly emphasized environmental conservation, protected areas, wildlife restoration, and ecotourism development. Therefore, Alula provides an appropriate setting for examining sustainability within a complex adaptive tourism system where natural, cultural, social, and economic dimensions continuously interact. Alula is located on the “Incense Road” in Medina, north-west Saudi Arabia [35,36]. The city holds five historically significant districts: Old Town Alula, Jabal Ikmah, Dadan, Nabataean, and Hegra. Old Town Alula dates to the 12th century and is renowned for its vital role in the incense trade route. In antiquity, the archeological site Dedan served as the capital of the Lihyanite and Nabataean kingdoms. Jabal Ikmah is notable for its abundance of prehistoric rock inscriptions, while the Nabataean area is famed for its unique rock-cut tombs and constructions. Hegra, the first Saudi UNESCO World Heritage site, is the crown jewel of Nabataean architecture and craftsmanship [35–37].

The region experiences a semi-arid climate with Mediterranean features, characterized by hot and dry summers and mild and wet winters. Although the region lacks perennial streams or rivers, it has several valleys or seasonal watercourses that serve as a vital source of irrigation for local agriculture [38,39]. The region’s flora comprises 58 species of vegetation, including low stratum and tussocks, climbing or hanging plants, shrubs and bushes, high trunk trees (palms), shade trees, and moderate-size trees [36,40]. Likewise, Alula is known for its diverse wildlife, including the Nubian ibex, red-necked ostrich, Idmi gazelles, Arabian leopard, Arabian wolf, red fox, and various bird species such as green bee-eaters, laughing doves, crested lark, eagles, harriers, and long-legged buzzards [36,40].

Despite these assets, Alula has been neglected as a tourism spot for years due to remoteness from major towns, strict immigration requirements, religious restrictions, and insufficient tourism infrastructure [36,39]. Saudi Arabia launched “Saudi Vision 2030” in

2016 to move its economic objectives from oil-centric to more sustainable and reliable industries [36,41]. A vibrant society, a thriving economy, and an ambitious nation are the vision's three primary pillars, including strategies to promote tourism, conserve the environment, and improve Saudi Arabia's quality of life [42,43]. The Royal Commission for Alula (RCU) was established by this Vision to promote tourism in Alula and aims to protect the environment, encourage the local residents, and develop ecotourism interpretation and education [36,40].

2.3. The Delphi–ECOS Approach

The ECOS model, developed by Boyd and Butler [44], provides a solid framework for identifying ecotourism opportunities and successful destination management. It introduces eight components for evaluating the ecotourism potential of a specific destination, as depicted in Figure 2. However, the model can be adapted to various contexts with appropriate modifications. Accordingly, as shown in Table 1, five ecotourism opportunity dimensions and 25 sustainability indicators were identified through a comprehensive review of the literature [5,15,18,23,25–27,29,45–47].

Although the tourist satisfaction dimension contains only three principal indicators, the indicator of tourist protection (N25) was conceptualized broadly to incorporate service quality and visitor experience, accessibility of tourism facilities, and interpretation and information services because these attributes collectively contribute to visitor satisfaction and the overall quality of the ecotourism experience.

The Delphi method is a structured communication strategy used to collect and synthesize the opinions of subject matter experts on a specific issue or topic [48,49]. This study employed the Delphi method to reach consensus among experts on sustainable ecotourism indicators. A robust Delphi method requires selecting the expert panel, panel size, number of rounds, and consensus criteria.

At first, the selection of panel members was done based on the criteria that they must have extensive ecotourism knowledge and experience, a diverse range of expertise from various fields, a willingness and availability to actively participate, and strong communication skills to articulate ideas clearly and facilitate productive discussions, as shown in Figure 3 [21,50].

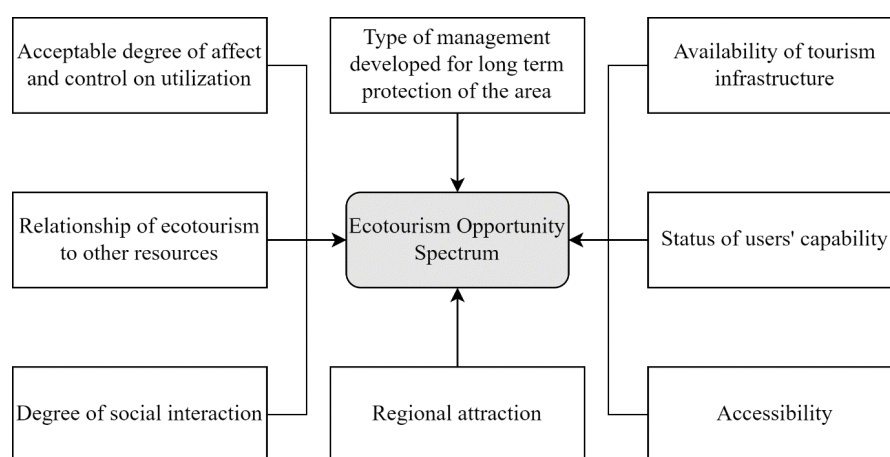


Figure 2. Ecotourism Opportunity Spectrum (ECOS) model [44].

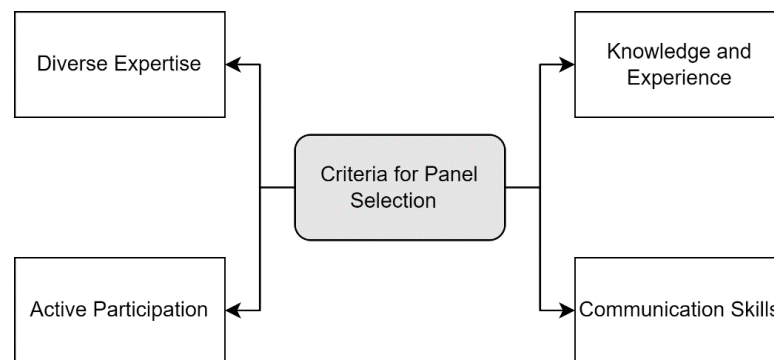


Figure 3. Adopted criteria for panel selection.

Table 1. Dimensions and indicators collected by ECOS.

Dimensions	Indicators
Nature (D1)	Topographical structures (N1) Suitable natural phenomenon (N2) Wildlife saturation (N3) Protected places (N4) Planning to conserve nature (N5) Planning to conserve culture (N6)
Environmental education/ protection (D2)	Environmental protection awareness among local communities (N7) Environmental education (N8) Ecotourism awareness among local communities and visitors (N9) Infrastructural Services (N10) Accommodation opportunities for ecotourists (N11) Government planning to promote tourism (N12)
Sustainability (D3)	Water availability and conservation policies (N13) Practices to conserve the natural environment and people's health (N14) Practices to support sustainable long-term economic growth (N 15)
Socio-cultural benefits (D4)	Planning to conserve historical heritage sites (N16) Protection and promotion of local heritage (N17) Impact assessment indicator (N18) Health facilities (N19) Educational opportunities (N20) Employment opportunities (N21) Local business promotion opportunities (N22)
Tourist satisfaction (D5)	Resilient habitat (N23) Nature-based activities (N24)
	Tourist protection (N25) including service quality and visitor experience, accessibility of tourism facilities, and interpretation and information services.

Secondly, the panel size is also a significant decision for the Delphi method. However, no strict rule is available to determine the panel size. Scholars use different numbers of respondents [30,48,49]. Following the above criteria, 125 experts were contacted for this study. These experts have expertise in different domains, such as engineering, academics, architecture, geology, hospitality, and tourism.

Of the 125 experts invited to participate, 110 completed both Delphi rounds, representing an overall response rate of 88%. The panel comprised experts from academia, government agencies, tourism management, environmental sciences, architecture and planning, engineering, and heritage management. Participants were affiliated with universities, research institutions, tourism authorities, and private-sector organizations (Table 2). The

panel included both Saudi and international experts with professional experience in sustainable tourism, environmental management, and heritage conservation. This diversity was intentionally sought to enhance the reliability and breadth of expert judgment and to minimize disciplinary bias in the evaluation process.

Table 2. Characteristics of the expert panel.

Characteristics	Number	Percentage
Academic Experts	32	29
Government Experts	26	24
Tourism Professionals	27	25
Environmental Experts	15	13
International Experts	10	9

Moreover, scholars recommend implementing two to four rounds for the Delphi method [51–53]. So, this study was implemented in two rounds. In the first round, the researcher distributed a list of 25 sustainable ecotourism indicators among the 125-panel members. Respondents were asked to indicate the degree to which they agreed that the indicators are relevant for sustainability on a 4-point Likert scale from strongly agree (1) to strongly disagree (4), recommended by De Loe [54] and Linstone and Turoff [48]. The precise question posed to the experts was, “Rate the relevance of each indicator to sustainability”. A total of 110 respondent replies was received in the first round; the information was summarized, collated, categorized, and tabulated into the second questionnaire.

The second round started by contacting the 110 members of the first round a second time. All of the Round 1 respondents again replied, taking an interest in this survey. The second-round questionnaire focused on validating the relevance and coherence of the identified sustainability indicators across the proposed dimensions, again on a 4-point scale, from rating the indicators as highly relevant to the dimensions (1) to rating the indicators as highly irrelevant to the dimensions (4).

Among others, the percentage agreement method to evaluate consensus is very commonly used in implementations of the Delphi method [50,55–57]. It typically uses a pre-defined cut-off criterion [58]. Several implementations of the Delphi method [25,50,55,57] have applied a particular level of percentage agreement to measure consensus among an expert panel. The specific percentage used depends upon the importance of the issue which is going to be discussed. In this study, a consensus threshold of greater than 80% agreement was adopted to identify stable and widely accepted sustainability indicators. High consensus was interpreted as evidence of indicator stability and relevance within the proposed methodological framework.

2.4. CAS-Based Interpretation of Sustainability Indicators

It is important to emphasize that CAS theory was not used to generate or select sustainability indicators directly. Instead, the theory was operationalized through three core concepts: interdependence, adaptation, and external disturbances. Interdependence was used to examine how sustainability dimensions and indicators influence one another; adaptation was employed to interpret how sustainability systems respond to changing conditions; and external disturbances were considered to understand how policy, environmental, and socio-economic shocks may reshape sustainability outcomes. Consequently, CAS theory served as an interpretative framework rather than a technique for indicator selection or Delphi questionnaire design.

Following the Delphi evaluation, the qualitative findings obtained from expert responses, sustainability dimensions, and validated indicators were interpreted through the theoretical perspective of CAS. The data used for this interpretation were collected through

the two-round Delphi process, expert feedback, and supporting literature related to ecotourism sustainability and complex systems. CAS theory was then applied as a conceptual lens to examine how sustainability indicators interact across environmental, socio-cultural, economic, and institutional dimensions rather than functioning as isolated assessment elements. In addition, selected external influences relevant to the study context were considered to understand how changing environmental, policy, and socio-economic conditions may shape the adaptive behavior of sustainability systems. This CAS-informed interpretation supported a broader understanding of sustainability evaluation within interconnected and evolving systems.

3. Results

The Results section presents the empirical evaluation of the proposed sustainability indicator system. The two Delphi rounds were undertaken to validate the relevance and coherence of the indicators, while the CAS-based interpretation was subsequently employed to understand their adaptive and interconnected relationships within the sustainability framework.

3.1. Results for the Delphi Method Round 1

A list of 25 sustainable indicators was provided to the expert panel. All the experts replied to all 25 questions, showing the interest of the experts in sustainable indicators. Their ratings for each indicator produced more than 80% agreement (sum of “agree” and “strongly agree”) (Figure 4). The high level of agreement suggests that the selected indicators represent stable and widely recognized components of sustainable ecotourism within the studied system.

3.2. Results for the Delphi Method Round 2

The validated list of 25 sustainability indicators was redistributed to the expert panel for further evaluation of their relevance within the proposed sustainability dimensions. Although response completeness varied among participants, the majority of responses provided sufficient information to evaluate indicator relevance across the proposed dimensions.

The second Delphi round also achieved more than 80% agreement for all indicators based on the combined responses of “highly relevant” and “somewhat relevant,” demonstrating continued consensus among the expert panel. Figure 5 presents the final sustainability framework, including the five sustainability dimensions and the 25 validated sustainability indicators.

3.3. Interpretation of Sustainability Indicators in Context with CAS

The Delphi findings were subsequently interpreted through the theoretical perspective of CAS to better understand the adaptive and interconnected nature of sustainability indicators within ecotourism systems. This interpretation was guided by three operational principles of CAS: interdependence, adaptation, and external disturbances. The principle of interdependence assumes that sustainability dimensions and indicators are connected and that changes in one component may generate cascading effects across other components of the system. The principle of adaptation explains how tourism systems adjust their priorities, management strategies, and development trajectories in response to changing internal and external conditions. The concept of external disturbances highlights how major events, policy interventions, economic transitions, or global crises can trigger system-wide responses and reconfiguration.

Using these principles, four major external influences affecting the sustainability system in Alula were identified: Saudi Vision 2030, inspiration from Petra in Jordan, the COVID-19 pandemic, and the global transition towards sustainability and reduced oil dependency. These external influences demonstrate how sustainability systems continuously adapt to changing environmental, economic, institutional, and social contexts. The findings further indicate that sustainability dimensions and indicators do not operate independently; rather, they are interconnected and capable of influencing one another across multiple dimensions. Consequently, changes in governance priorities, tourism development strategies, environmental conditions, or visitor behavior may simultaneously affect several sustainability indicators. This CAS-informed interpretation highlights the importance of understanding sustainability evaluation as a dynamic and adaptive process shaped by continuous interactions, feedback mechanisms, and responses to external disturbances within complex systems.

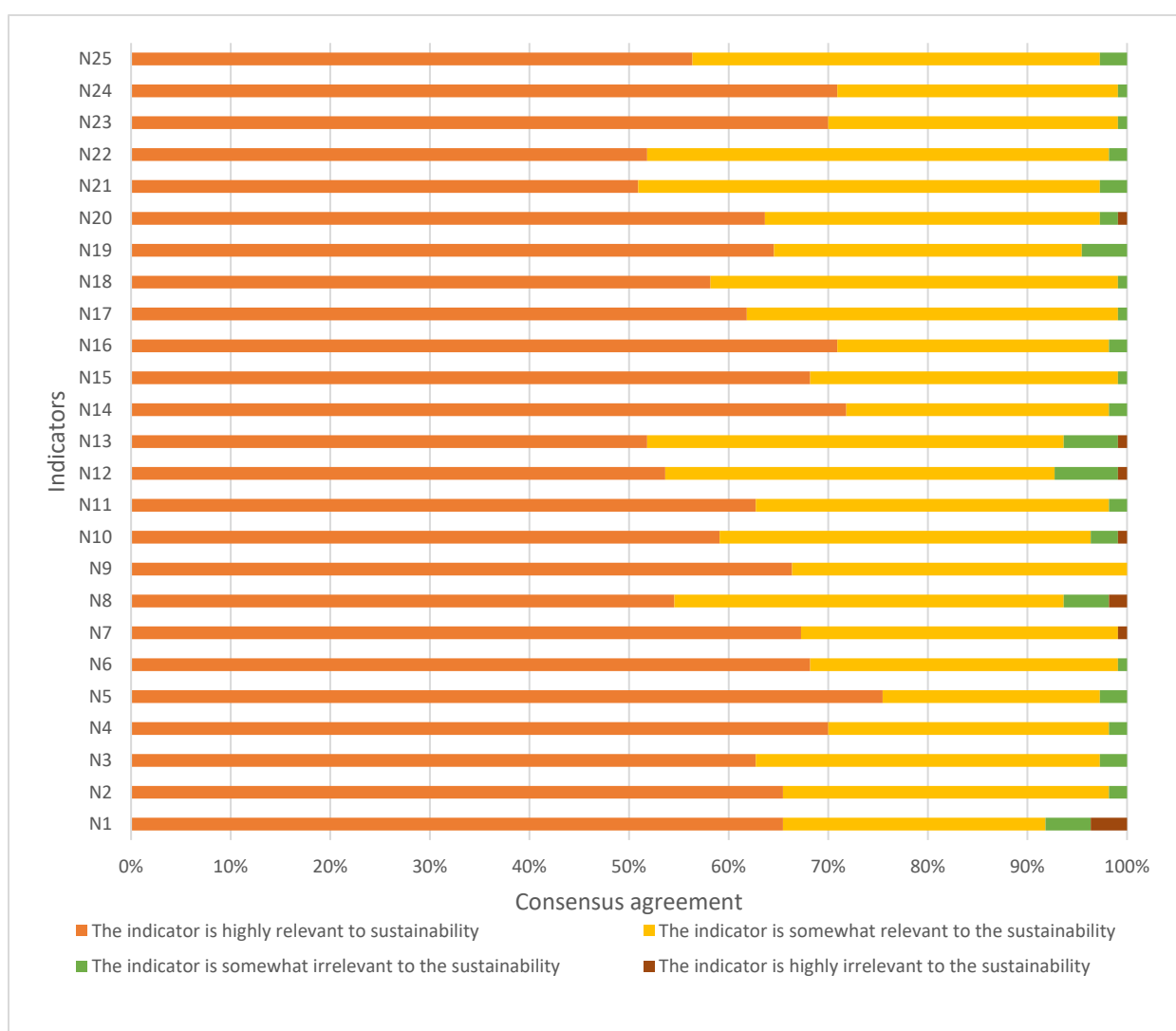


Figure 4. The list of consented sustainable ecotourism opportunity indicators.

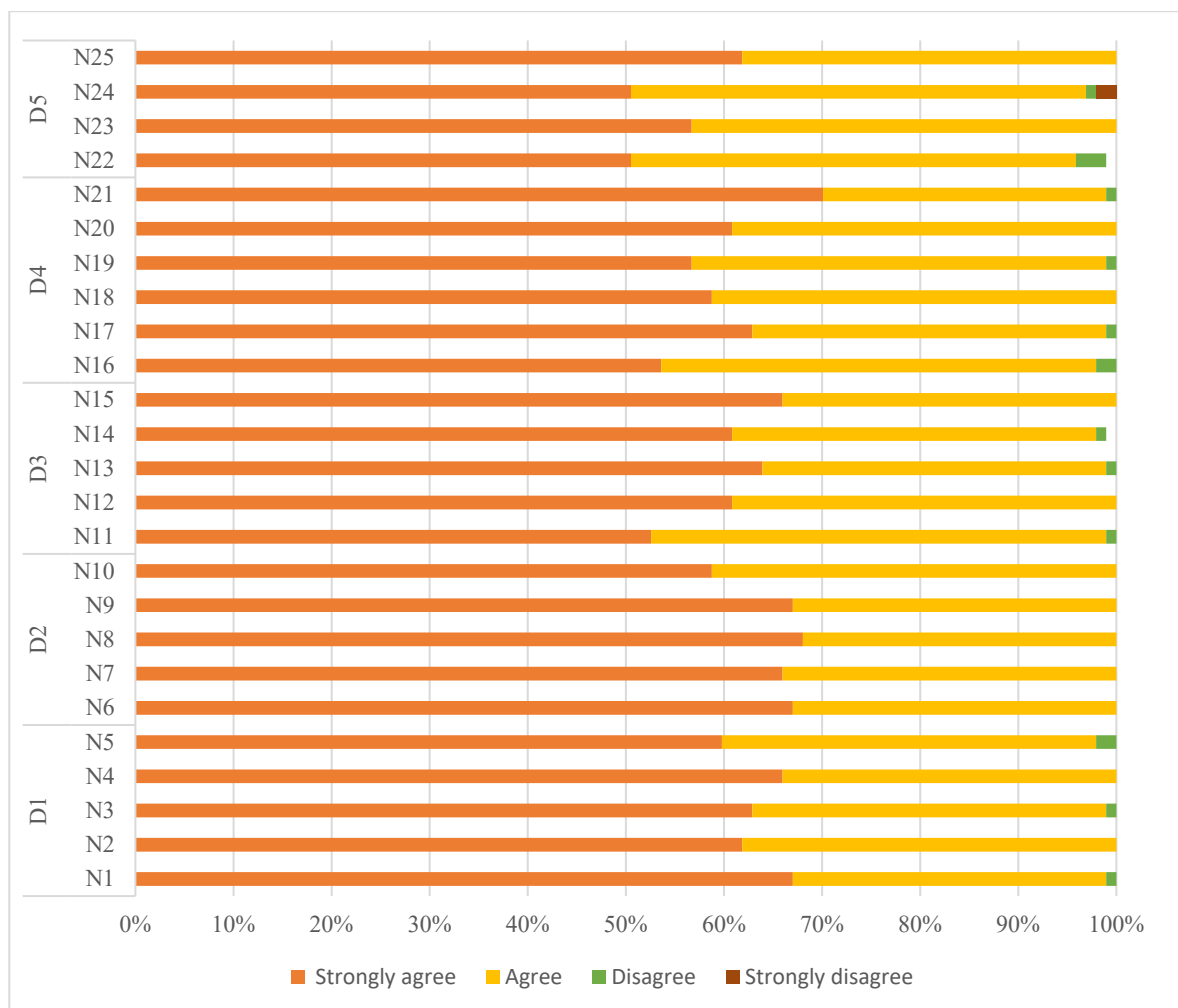


Figure 5. The final sustainability framework, including the sustainability dimensions and the validated sustainability indicators.

- Saudi Vision 2030 is a significant external factor determining Alula's ecotourism potential. This vision seeks to diversify the nation's economy and reduce its reliance on oil by encouraging the sustainability of expanding other industries, including tourism and ecotourism [2,36]. By investing in developing ecotourism opportunities, the vision strongly impacts all dimensions, such as nature, environmental education/protection, sustainability, and socio-cultural benefits [36,40]. For instance, the strategic objective of Vision 2030 to reduce the nation's dependence on oil and promote sustainability is intended to influence the sustainable indicator of long-term economic growth (N15). This purpose has stimulated long-term planning, establishing initiatives such as the RCU. The RCU is devoted to making Alula a global tourist destination, consequently influencing the tourism indicator (N12). This transition requires the collaboration of local and international professionals in archeology, nature conservation (N5), and cultural conservation (N6), all of which contribute to the preservation of historical places (N16) and natural beauty (N5). In addition, the RCU's mandate includes promoting education (such as environmental education (N8) and employment opportunities (N21) for the local community, thereby supporting sustainable economic development (N15). The development of critical infrastructural services (N10) and visitor protection (N25) forms a holistic strategy for achieving sustainable development in tourism and relates back to the basic goal of Vision 2030. So, significant government investment in Alula's ecotourism has developed a connection

between Saudi Vision 2030, ecotourism opportunities dimensions, and sustainable indicators. As a result, ecotourism opportunities have been developed rapidly in Alula. In this context, RCU has started several initiatives, such as developing Sharan Nature Reserve, protecting historical places (such as Old Town Alula and Hegra) and so on [36,40].

- Petra, Jordan, also inspired Alula's ecotourism opportunities. Petra, a UNESCO World Heritage Site in Jordan, is a popular tourist site with sustainable tourism [59–61]. Tourism managers in Alula view Petra as an example of sustainable tourist development, with strong impacts via boosting protection and promoting local heritage indicators (N17). This indicator moderately impacts the dimension "socio-cultural benefits (D4) and other indicators such as promoting cultural heritage, managing cultural events, and planning to conserve historical heritage sites (N16). RCU signed an agreement with the International Council on Monuments and Sites (Saudi ICOMOS) for the protection and promotion of local heritage (N17) [36,40]. RCU and UNESCO also announced a partnership to conserve Saudi Arabia's historical heritage sites (N16) in Alula [36,40].
- The impact of COVID-19 on the worldwide tourism industry also affected Alula's tourism industry. Numerous countries were forced to close their borders due to the pandemic, resulting in a substantial fall in inbound visitors [62,63]. This pandemic strongly impacted tourist satisfaction (D5), which further moderately influences other indicators such as tourists' protection (N25), availability of eating and drinking places, and availability of security for visitors. However, the epidemic has also provided chances for domestic tourism as Alula strives to market itself as a premier destination for domestic tourism [36,40]. In light of the continued travel limitations and public health concerns, Alula modified its tourism initiatives to cater to local tourists by highlighting safety precautions and custom experiences that emphasize the region's distinctive offerings [36,40]. The pandemic also triggered adaptive responses across multiple sustainability dimensions. Increased concern for visitor health and safety strengthened the importance of tourist protection (N25), service quality and visitor experience (N26), and accessibility of tourism facilities (N27). The decline in international arrivals redirected tourism strategies toward domestic markets and stimulated the development of smaller-scale and more flexible tourism experiences. At the same time, reduced visitor numbers affected local businesses (N22), employment opportunities (N21), and tourism-related infrastructure (N10). From a CAS perspective, these cascading effects demonstrate how a single external disturbance may simultaneously influence environmental, social, economic, and institutional dimensions and trigger adaptive responses throughout the tourism system.
- The changing global attitudes about energy and sustainability further impact tourist potential in Alula City. This trend is mirrored in Alula's tourism development as Saudi Arabia, a nation historically dependent on oil, seeks to diversify its energy portfolio in response to the worldwide transition toward sustainable energy sources [64,65]. This external element encourages Alula to join the more extensive sustainability campaign and strongly impacts the dimensions of environmental education/protection and sustainability (D2). The changing global attitudes about energy and sustainability affect other dimensions such as sustainability (D3), which initiate long-ranging planning to promote practices that can support sustainable long-term economic growth (N15). This indicator (N15) can support other indicators, such as employment opportunities (N21) [36,40]. For instance, to support sustainable long-term economic growth (N15), the Saudi government has established RCU to promote sustainable tourism in Alula. For that purpose, RCU aims to attract national and in-

ternational tourists to Alula, and, to improve their satisfaction, they are developing accommodations (such as Sharan Resort, Habitas Alula), transportation (Flyness and Saudi Airlines to Alula and development of Alula airport), and natural, cultural, and historical heritage sites, and these projects are encouraging local business promotion opportunities (N22), thereby creating employment opportunities (N21).

Overall, the CAS-based interpretation demonstrates that sustainability indicators operate as interconnected and adaptive components within complex systems rather than as isolated elements. The findings further suggest that external influences, such as policy shifts, global disruptions, and sustainability transitions, may affect sustainability dimensions differently depending on the adaptability and interdependence of the system. Understanding these interactions can support more informed and context-sensitive sustainability planning and strengthen the long-term resilience of tourism systems.

4. Discussion

This study proposed a hybrid methodological framework for organizing, validating, and interpreting sustainability indicators within complex adaptive systems. The findings demonstrate that integrating the ECOS model with the Delphi method provides a structured approach for identifying and validating sustainability indicators across multiple sustainability dimensions. Unlike many previous sustainability assessment approaches that focus primarily on isolated indicators or context-specific evaluations, the proposed framework integrates conceptual structuring, expert consensus, and CAS-informed interpretation within a unified methodological approach. This integration contributes to the sustainability assessment literature by emphasizing the adaptive and interdependent nature of sustainability indicators rather than treating them as independent assessment elements.

The distribution of indicators across the five sustainability dimensions further highlights the multidimensional character of sustainability evaluation and supports previous studies advocating holistic approaches to tourism sustainability assessment [21,25]. The findings suggest that sustainability indicators are closely interconnected across environmental, socio-cultural, institutional, and economic dimensions, reinforcing the importance of integrated sustainability planning. This interconnection develops a sustainability network that starts from local to worldwide destinations. It can be observed in Alula, where RCU is developing collaboration between local and international professionals to develop ecotourism opportunities in Alula [36,40]. For instance, the RCU signed an agreement with the International Council on Monuments and Sites (ICOMOS) to protect and promote local heritage [36,40]. RCU and UNESCO also announced a partnership to conserve Saudi Arabia's historical heritage sites in Alula [36,40].

The CAS-informed interpretation further demonstrates that sustainability systems are adaptive and sensitive to both internal and external changes. The findings indicate that changes affecting one sustainability dimension may influence other dimensions simultaneously due to the interconnected nature of complex systems. For example, the COVID-19 pandemic influenced tourism-related indicators associated with visitor satisfaction, tourism infrastructure, and local economic activity. Due to COVID-19's impact, in 2020, tourism revenues decreased by \$910 billion to \$1.2 trillion. This had a broader effect, reducing the world GDP by 1.5 percentage points to 2.8 percentage points [66]. These findings reinforce the importance of adaptive and flexible sustainability planning approaches capable of responding to changing environmental, economic, and social conditions.

The proposed framework extends previous sustainability assessment studies by integrating structured indicator organization, expert-driven validation, and CAS-informed interpretation within a single methodological process [25,26,31]. Many previous approaches emphasized indicator identification without sufficiently addressing the adaptive and inter-

connected characteristics of sustainability systems. Ignoring these interdependencies may limit the effectiveness of sustainability evaluation and reduce the ability of planning strategies to respond to changing system conditions. For example, ignoring the interrelationship between local communities and ecotourism awareness among local communities could reduce the local economic benefits and negatively impact tourism sustainability. Similarly, ignoring adaptation, such as to COVID-19's impacts, may result in unproductive, rigid planning that fails to achieve sustainability [1,67].

This study has important implications for ecotourism practitioners, policymakers, and researchers, as it provides a solid foundation for future sustainable ecotourism evaluation, informed decision-making, and the development of effective strategies and policies to ensure the long-term success and sustainability of ecotourism ventures worldwide. In addition, it is valuable to the scientific community because it provides a robust and systematic method for identifying sustainable indicators under multiple ecotourism opportunity dimensions. The framework also contributes methodologically by supporting more systematic indicator organization and expert-driven sustainability assessment across multiple contexts.

Understanding the adaptive relationships among sustainability indicators can support decision-makers in developing more flexible and resilient sustainability strategies capable of responding to changing environmental, economic, and social conditions. From a CAS perspective, sustainability planning should not rely on isolated indicators, but rather consider how multiple sustainability dimensions continuously influence one another within evolving systems. For example, indicators associated with tourist protection and service quality may contribute to improving visitor experiences while supporting long-term tourism resilience. These findings highlight the importance of integrating sustainability practices into tourism infrastructure, hospitality services, and destination management strategies. Improved sustainability practices may enhance visitor satisfaction and strengthen the long-term competitiveness of tourism destinations. Similarly, indicators related to heritage conservation and cultural protection demonstrate the importance of integrating socio-cultural sustainability into tourism planning frameworks. The Alula case further illustrates how heritage-based tourism initiatives can support both cultural preservation and sustainable destination development. These findings reinforce the importance of balancing tourism development with long-term cultural and heritage conservation objectives.

Indicators associated with employment generation and local business development further demonstrate the economic dimension of sustainability within complex tourism systems. This indicator can allow the local stakeholders to monitor the percentage of local employment that can enhance economic empowerment in the community. The Alula case highlights how sustainability-oriented tourism development may contribute to local economic diversification and community participation. From a CAS perspective, economic sustainability is closely interconnected with environmental conservation, institutional planning, and community engagement.

Environmental conservation initiatives such as wildlife protection and habitat restoration also illustrate the interconnected relationship between ecological sustainability and tourism development. In this context, the wildlife saturation sustainable indicator can be used to monitor the changes in animal populations, especially those of reintroduced species, as part of conservation efforts. These conservation efforts may simultaneously support biodiversity protection, destination attractiveness, and sustainable nature-based tourism activities.

The findings of this study also have implications for carrying capacity assessment and adaptive destination management. Previous studies have emphasized that sustain-

able tourism development requires identifying the limits within which tourism activities remain environmentally, socially, and economically sustainable [44,68,69]. However, the usefulness of carrying capacity as a static measure has increasingly been questioned because tourism systems continuously evolve and adapt to changing conditions [4]. Consequently, complementary approaches such as the Limits of Acceptable Change (LAC) framework have been proposed to focus on the degree of change that destinations are willing to tolerate rather than simply determining the maximum number of visitors. From a CAS perspective, the proposed framework may complement LAC approaches by providing a structured set of indicators that can be continuously monitored to identify changes in sustainability conditions and support adaptive decision-making under different development scenarios [70].

The proposed framework may also support scenario-based planning by allowing decision-makers to evaluate how sustainability indicators respond under different development trajectories and external disturbances. Such an approach is particularly valuable in complex adaptive systems where future conditions are uncertain and where management decisions require continuous learning and adjustment. Consequently, the framework may contribute to the development of adaptive strategies that align tourism growth with long-term sustainability objectives and stakeholder priorities.

Another important implication of the proposed framework concerns the development of monitoring and early warning systems. Because sustainability indicators are interconnected and adaptive, continuous monitoring of indicator performance may help identify emerging problems and detect situations where sustainability thresholds are approaching critical levels. Such early warning mechanisms could provide destination managers with timely information to implement corrective actions before environmental, social, or economic conditions deteriorate. Therefore, the framework offers potential not only as an assessment tool but also as a decision-support mechanism for adaptive and preventive sustainability management.

The proposed framework may also support policymakers by providing a structured approach for monitoring sustainability performance across multiple tourism dimensions. Considering the specified ecotourism indicators, government agencies, including the RCU, could actively monitor the sustainable performance of each ecotourism destination. Such an approach can assist decision-makers in identifying sustainability strengths, challenges, and priority areas for future planning. In Alula, Saudi Arabia, for example, the indicator “environmental protection awareness among local communities” may show that the local people need to learn more about how to treat the environment responsibly. The way people treat the environment can make a place more visitor-friendly and increase visitor satisfaction.

The findings further emphasize the importance of collaborative governance, stakeholder participation, and continuous sustainability monitoring within complex tourism systems. Such detailed information is crucial when allocating budgets and shaping policies designed to preserve ecotourism sites and improve the welfare and inclusiveness of local communities. Community engagement also plays a central role in supporting adaptive and inclusive sustainability planning. Indicators associated with local business development and community participation may strengthen both economic resilience and social sustainability. In Alula, the government might aggressively engage local people and RCU in ecotourism site management. RCU can be more significant in promoting and protecting ecotourism resources within its jurisdiction if given the proper authority to engage with local business communities. This may involve providing RCU with incentives based on the performance of their ecotourism sites to encourage them to improve their tourist efforts and also enhance their economies. Lastly, delegating obligations to local government units

could generate a sense of accountability and responsibility for sustainable development. Regular updates on the success of their ecotourism sites help ensure that RCU maintains an active role in managing and enhancing these resources. In conclusion, this research can promote a more systematic, participative, and informed approach to ecotourism management in Alula, Saudi Arabia, thereby contributing to its sustainability and inclusivity.

The proposed indicator system presents several advantages compared with previous ecotourism assessment approaches. First, it integrates environmental, socio-cultural, educational, economic, and visitor-related dimensions within a single framework, thereby providing a more holistic understanding of sustainability. Second, the use of expert consensus improves the reliability and contextual relevance of the selected indicators. Third, the incorporation of CAS theory enables a better understanding of interdependencies among sustainability dimensions that are often overlooked in traditional indicator-based studies [24–27,30].

Nevertheless, several limitations should also be acknowledged. The indicator system remains partially context dependent because expert judgments may vary across geographical and institutional settings. Furthermore, the proposed framework does not quantify the strength of interactions among indicators, and therefore future studies may incorporate systems modeling approaches such as network analysis or system dynamics to examine these relationships more explicitly. Finally, the number and composition of indicators may evolve as sustainability priorities change over time and across destinations.

From a CAS perspective, the external influences identified in Alula can be interpreted more broadly as examples of external disturbances or policy shocks. Policy shocks may include governmental reforms, regulatory interventions, strategic development initiatives, economic crises, geopolitical events, or global environmental changes that alter the behavior of sustainability systems. Consequently, the proposed framework is not restricted to centrally planned or policy-driven destinations such as Alula. Rather, it may also be applied in community-based destinations, mature tourism regions, protected areas, and heritage cities where sustainability outcomes are similarly influenced by changing external conditions.

Beyond the ecotourism context, the proposed framework has potential applicability for sustainability evaluation in other tourism systems characterized by multidimensional interactions, uncertainty, and adaptive change. The framework may be adapted to heritage tourism destinations, cultural tourism, spiritual tourism, protected areas, community-based tourism initiatives, and urban tourism systems where environmental, social, economic, and cultural dimensions continuously interact. Consequently, the methodological contribution of this study extends beyond ecotourism and provides a transferable approach for sustainability assessment across diverse tourism contexts.

5. Conclusions

In conclusion, this study proposed a hybrid methodological framework for organizing, validating, and interpreting sustainability indicators within complex adaptive systems. By integrating the ECOS model, the Delphi method, and CAS theory, the study addressed important challenges associated with sustainability evaluation, including the lack of structured indicator organization, limited integration of expert consensus, and the difficulty of understanding adaptive and interconnected system relationships. The findings demonstrate that sustainability indicators should not be treated as isolated assessment elements, but rather as interconnected components operating within dynamic environmental, social, economic, and institutional contexts. The proposed framework constitutes the principal contribution of this study by integrating conceptual indicator organization, expert-driven validation, and systems-based interpretation within a unified methodological process. By

explicitly combining ECOS, Delphi, and CAS theory, the framework provides a structured and transferable approach that can support sustainability evaluation and decision-making across a wide range of complex systems beyond ecotourism. The framework further offers practical value for researchers and policymakers by facilitating more adaptive, integrated, and context-sensitive approaches to sustainability planning and assessment. The study, however, remains limited by the context-specific nature of expert judgment and the challenges associated with interpreting complex sustainability relationships. Future research may further expand the framework by examining how sustainability indicators evolve under changing environmental, policy, and socio-economic conditions. Such efforts can contribute to more adaptive, context-sensitive, and resilient approaches to sustainability planning and evaluation.

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