

Research

Moderating effects of energy poverty for sustainable tourism, policy, innovation, and environmental resilience: evidence from SEM-ANN approaches

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Abstract

The global tourism sector's rapid growth has exerted significant pressure on environmental resources and ecosystems, underscoring the urgent need for sustainable solutions. While previous studies have explored the roles of sustainable tourism practices, effective tourism policies, and technological innovations in enhancing environmental resilience, there is a notable gap in understanding how energy poverty influences these dynamics. This study addresses this gap by examining the moderating role of reduced energy poverty in strengthening the relationships between Sustainable Tourism (ST), Tourism Policy Effectiveness (TPE), Technological Innovations (TI), and Environmental Resilience (ER). Utilizing data from 378 participants, including tourism stakeholders, policymakers, researchers, and environmental specialists in Bangladesh, this research employs a multi-method approach, integrating Structural Equation Modeling (PLS-SEM) and Artificial Neural Networks (ANN) for robust analysis. The findings reveal that ST, TPE, TI, and Less Energy Poverty (LEP) significantly enhance environmental resilience, with LEP acting as a critical moderator that amplifies the positive impacts of these factors. By highlighting energy poverty as a pivotal barrier and a potential enabler, this study contributes to the global discourse on sustainable tourism and environmental management, emphasizing the transformative potential of improved energy access. This research provides a unique global perspective by demonstrating how reducing energy poverty not only fosters environmental resilience in tourism destinations but also serves as a scalable solution for other developing regions. The integration of SEM and ANN further enhances the methodological rigor and ensures the reliability of the findings. As the first study to explore the moderating role of energy poverty in the nexus of sustainable tourism and environmental resilience, this research offers valuable insights for policymakers, practitioners, and academics, advocating for global strategies to enhance energy access as a catalyst for sustainable environmental outcomes.

Keywords Sustainable tourism · Technological innovation · Tourism policy · Less energy poverty · Environmental resilience

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1 Introduction

The global demand for environmental resilience has reached an unprecedented level due to the accelerating pace of climate change, resource depletion, and biodiversity loss [1–3]. However, a critical yet often overlooked barrier to achieving environmental resilience is energy poverty, particularly in developing and vulnerable regions. Energy poverty, characterized by limited access to affordable, reliable, and clean energy, exacerbates environmental degradation and hinders efforts to build long-term ecological balance. Societies and economies struggling with energy poverty face additional challenges in adopting sustainable practices and resilience strategies, which are essential for mitigating climate impacts and ensuring resource efficiency. Recognizing this, international organizations, governments, and stakeholders have emphasized the need to address energy poverty as a fundamental step toward integrating resilience strategies into economic development, tourism, and urban planning [3–5]. By reducing energy poverty, regions vulnerable to climate change can unlock the potential for sustainable growth, improved livelihoods, and enhanced environmental resilience [2].

Sustainable tourism, environmental quality, and technological innovation are key contributors to strengthening environmental resilience. Sustainable tourism practices are crucial for reducing tourism's adverse environmental effects while simultaneously promoting economic growth and local development [6]. At the same time, less energy poverty is vital for bolstering ecosystem and community resilience, as well as enhancing the well-being of local populations [7]. Technological innovation, encompassing the use of digital technologies and advanced solutions such as AI, IoT, and blockchain, introduces novel opportunities for achieving environmental sustainability [1, 8]. Together, these factors hold the potential to create a synergistic impact on improving environmental resilience, although their interconnections and interactions warrant further investigation.

This study distinguishes itself from existing research by integrating the three key dimensions of sustainable tourism, less energy poverty, and technological innovation into a single comprehensive model. While previous studies have explored the individual effects of these variables, few have examined their interrelationships or how they collectively influence environmental resilience [4, 9–14]. Moreover, existing research often fails to consider the moderating role of less energy poverty, an area where this study offers valuable insights [4–6, 8, 14–17]. By focusing on Bangladesh, a country with unique challenges and opportunities in sustainable tourism and environmental management, this study provides a context-specific analysis that adds depth to the global discourse on environmental resilience.

The innovation of this research lies in the development of an integrated framework that incorporates sustainable tourism, tourism policy effectiveness, technological innovation, and less energy poverty, with less energy poverty serving as a moderating variable. The role of less energy poverty in strengthening the relationships between these factors and environmental resilience has received limited attention in existing literature [3, 4, 11, 18–20]. Additionally, this study addresses a critical research gap by applying this unique model to the context of Bangladesh, a developing nation experiencing rapid growth in tourism alongside significant environmental challenges. By focusing on moderating effects within a region characterized by diverse socio-economic and environmental dynamics, the research makes a valuable contribution to the advancement of knowledge in this field.

The aim of this study is to investigate the effects of sustainable tourism, tourism policy effectiveness, technological innovation, and less energy poverty on environmental resilience, with particular emphasis on the moderating role of less energy poverty. Specifically, the objectives of the study are to: (1) examine the direct relationships between sustainable tourism, tourism policy effectiveness, technological innovation, and environmental resilience; (2) explore the moderating effects of less energy poverty on these relationships; and (3) provide policy recommendations to enhance environmental resilience through integrated, sustainable approaches.

The contribution of this study is twofold. First, it proposes a novel, integrated model that links sustainable tourism, technological innovation, less energy poverty, and environmental resilience. Second, by examining the moderating effects of less energy poverty, the study sheds light on how the quality of the environment can strengthen the effectiveness of tourism policies and technological innovations in promoting resilience. This multi-method approach, combining both PLS-SEM and ANN, offers a robust framework for understanding complex environmental dynamics. Finally, the findings of this study will contribute to the ongoing policy dialogue by providing actionable insights for policymakers in Bangladesh and other similar regions aiming to achieve sustainable development and environmental resilience.

The rest of the paper includes literature review in section two, methodology in section three, results in four, discussions in section five, and conclusions in section six.

2 Literature review

2.1 Sustainable tourism and environmental resilience

Sustainable tourism has become a crucial strategy for balancing the economic advantages of tourism with the need to preserve environmental and social resources. Emerging as a prominent concept in the late 1980s, it aims to minimize the adverse effects of tourism while maximizing benefits for local economies and communities [6]. This approach underscores the necessity of aligning tourism activities with environmental, economic, and societal considerations [21–23]. Studies have demonstrated that sustainable tourism can play a significant role in fostering economic growth and job creation, particularly in developing regions, underscoring its value as a driver of local development [1, 5, 24]. Nevertheless, assessing tourism's impact requires the development of comprehensive sustainability indicators, including environmental accounting measures, which remain a key focus for future research [25]. Moreover, active stakeholder involvement is critical for achieving tourism sustainability, serving as a vital metric of environmental sustainability in tourism-dependent areas [26].

Zheng, et al. [27] investigate the dynamic interaction between tourism, globalization, and environmental quality in the most polluted economies, highlighting the long-term positive environmental effects of sustainable tourism while emphasizing the environmental challenges posed by globalization and economic growth. Similarly, Idroes, et al. [28] analyze the interplay of military expenditure, renewable energy, tourism, and globalization on CO₂ emissions in North African countries, revealing the dual role of these factors in either mitigating or exacerbating environmental degradation. Sikdar, et al. [29] shift the focus to South Asia, examining the environmental consequences of energy poverty, income inequality, and renewable energy adoption. Their findings stress the urgent need for targeted policies to address energy disparities and promote renewable solutions. Meanwhile, Nagarajan, et al. [30] delve into household behaviors in India, exploring how involuntary and deliberate frugality influence the adoption of energy-efficient and energy-generating products, offering valuable insights into consumer-driven sustainability initiatives. Lastly, Idroes, et al. [31] assess geothermal energy's potential in Indonesia, emphasizing its significant role in reducing CO₂ emissions and advancing carbon neutrality.

The COVID-19 pandemic has further underscored the importance of sustainable tourism practices, as it led to a renewed focus on ecological rehabilitation and responsible tourism standards [32, 33]. The pandemic shifted consumer preferences toward sustainable travel options, highlighting the need for destinations to adapt and implement strategies that not only support recovery but also ensure long-term resilience against future environmental challenges [3, 34]. The integration of technological innovations in tourism management, such as the use of digital platforms to promote sustainable practices, is also crucial for enhancing the visitor experience while protecting the environment [3, 14]. Moreover, the emerging concept of "respon-sustainable" tourism, which blends responsible and sustainable practices, is gaining recognition as an effective approach to meeting the needs of both tourists and local communities [35]. Given these considerations, we propose the H1.

H1. Sustainable tourism has a positive effect on environmental resilience.

2.2 Tourism policy effectiveness and environmental resilience

The effectiveness of tourism policies in promoting environmental resilience is a complex issue that involves understanding the interaction between policy frameworks, stakeholder engagement, and sustainable practices [9, 15, 36]. Well-structured tourism policies are crucial for fostering sustainable development, particularly in ecologically sensitive areas and rural communities. As Aslam and Awang [37] emphasize, a comprehensive tourism policy serves as the foundation for sustainable rural tourism development by providing a strategic planning framework that addresses regulatory gaps and promotes responsible resource management. This notion is further supported by Chiwaridzo [4], who highlights the significant role of government policies in shaping tourism supply chains, impacting the sector's social sustainability either by facilitating or hindering sustainable practices.

Moreover, the integration of environmental considerations into tourism policies is essential to mitigate the adverse impacts of tourism on ecosystems. Baloch, Shah, Iqbal, Sheeraz, Asadullah, Mahar and Khan [9] propose a sustainable ecotourism framework, underscoring the importance of governmental interventions such as the Billion Trees

Plantation initiative in Pakistan, which seeks to counteract the negative environmental effects of tourism growth. This is in line with the work of Lampropoulos, Panagiotopoulou and Stratigea [12], who argue that tourism policies must embrace sustainability concerns to balance economic growth and environmental preservation. The United Nations' Agenda 2030 for Sustainable Development further advocates for integrating sustainability into tourism practices to address issues such as overconsumption and pollution, reinforcing the importance of this policy approach.

In addition, multi-level governance plays a pivotal role in promoting sustainable tourism. Anastasiadou [38] explains that the European Union's governance framework encourages stakeholder participation in tourism policy-making, ensuring that policies are more inclusive and sustainable. Scheyvens [14] stresses that such participatory governance structures are vital, as they allow the inclusion of diverse voices, particularly local communities, ensuring that tourism policies reflect the needs and concerns of all stakeholders. This inclusive approach improves the effectiveness of tourism policies by ensuring they are responsive and equitable.

Finally, the implementation of effective tourism policies is influenced by both economic and environmental factors. Chen [39] finds that tourism policies have a positive correlation with sustainable growth, while environmental challenges, such as greenhouse gas emissions, can undermine sustainability. This suggests that tourism policies must incorporate both economic incentives and robust environmental regulations. Torkington, et al. [40] further argue that while many national tourism policies support sustainability, they often fall short of implementing concrete actions to address climate change and manage tourism growth. Given these considerations, we propose the second hypothesis: H2.

H2. Tourism policy effectiveness positively affects environmental resilience.

2.3 Technological innovation and environmental resilience

Technological innovation plays a crucial role in strengthening environmental resilience, particularly through the integration of advanced digital technologies and sustainable practices. The convergence of Artificial Intelligence (AI), the Internet of Things (IoT), and big data is key to the development of smart cities focused on environmental sustainability. Bibri, Alexandre, Sharifi and Krogstie [1] highlight that these technologies can work together to enhance urban sustainability by optimizing resource management and minimizing pollution through data-driven solutions. This integration not only boosts energy efficiency but also supports real-time monitoring of environmental indicators, which is essential for sustainable urban development [15]. By leveraging these innovations, cities can achieve a better balance between growth and environmental conservation.

Moreover, the adoption of innovative environmental technologies is key to addressing pollution and promoting sustainable practices across industries. Chiwaridzo [4] highlight that sustainable technologies, referred to as best available technologies, are designed to minimize environmental impact while ensuring economic viability. This aligns with Grunevald, Kipper and Moraes [11], who link technological innovations to life cycle assessments, demonstrating how such approaches can contribute to sustainable urban environments by efficiently managing waste. The focus on life cycle analysis in environmental technologies emphasizes the importance of a holistic approach in achieving sustainability goals, considering the long-term environmental and economic impacts of technological adoption.

In addition to these developments, blockchain technology has emerged as a powerful tool for enhancing supply chain resilience and sustainability. Munir, Habib, Hussain, Shahbaz, Qamar, Masood, Sultan, Mujtaba, Imran and Hasan [8] explore how blockchain can improve supply chain traceability and transparency, supporting both environmental and social sustainability. Mohamed, Haddad, Barakat and Rosi [19] further reinforce this idea, demonstrating how blockchain adoption can enhance supply chain performance and resilience, particularly in unpredictable environments. These technologies not only optimize operations but also enable organizations to achieve sustainability goals more effectively, ensuring that sustainability is embedded throughout the supply chain.

Within the framework of Industry 4.0, the integration of digital technologies is transforming manufacturing processes to better align with environmental sustainability objectives. Oláh, Aburumman, Popp, Khan, Haddad and Kitukutha [21] suggest that adopting Industry 4.0 technologies can significantly improve environmental performance by enabling eco-friendly manufacturing practices. Guo, Jiang and Li [6] concurs, emphasizing the need for a balance between technological innovation and environmental sustainability to reduce waste and energy consumption. The concept of "twin transition," which refers to the concurrent digital and sustainable transformation, is gaining importance for businesses striving to remain competitive while addressing societal demands for sustainability [41].

Additionally, digital transformation is vital for advancing sustainability efforts. Digital tools enable organizations to optimize resource use and enhance collaboration for sustainable results [42]. This shift is particularly important for small

and medium-sized enterprises (MSMEs), helping them gain a competitive edge and attract stakeholders who prioritize sustainability [42]. The relationship between digital innovation and sustainable entrepreneurship is key to tackling environmental challenges and driving societal progress. Based on these insights, we propose the third hypothesis: H3.

H3. Technological innovation positively impacts environmental resilience.

2.4 Less energy poverty and environmental resilience

Energy poverty and environmental resilience have become critical issues in urban planning and environmental management, particularly as urbanization continues to increase globally. The relationship between urban development and less energy poverty is complex, requiring a comprehensive approach to address both aspects effectively. Urbanization, while providing opportunities for growth, often poses significant challenges to less energy poverty. Sousa, Sales, Silva, Silva and Lourenço [7] emphasize the need for urban less energy poverty indicators to help decision-makers mitigate the negative impacts of urban expansion. These indicators provide a framework for assessing and improving energy access in urban areas, allowing planners to identify critical issues and make informed decisions. One way to enhance urban less energy poverty is through the integration of green spaces, such as vegetation cover, into urban planning, which can help balance development and environmental sustainability [32].

The relationship between economic growth and less energy poverty is complex and context-dependent. Butarbutar, Ananda and Prasetya [10] found that, in some settings, economic development can have a positive effect on less energy poverty. For instance, in Indonesia, the per capita Gross Regional Domestic Product positively influences the Environmental Quality Index (EQI), suggesting that economic growth and environmental improvement can coexist under favorable conditions. However, achieving this balance is not automatic and requires careful planning and management to prevent economic growth from leading to environmental degradation.

Government policies and regulations are crucial in shaping outcomes related to environmental quality. Xu, Xiao, Khiewngamdee and Lin [20] argue that when governments focus on environmental quality rather than short-term economic gains, they can foster investments in environmental initiatives, thereby improving overall environmental conditions. Handoyo and Fitriyah [43] further support this, showing that regulatory quality and political stability are positively linked with environmental sustainability across nations. These findings emphasize the importance of policy frameworks that incorporate environmental objectives into governance to promote sustainable development.

The measurement of environmental quality is another important area of focus. Dang [32] stress the significance of multi-criteria decision-making in evaluating environmental quality, allowing for the inclusion of various factors and viewpoints. Li, Wang and Ji [18] discuss the challenges of assessing environmental quality, noting that a combination of qualitative and quantitative methods is essential to fully understand environmental conditions. This highlights the need for a comprehensive approach to evaluating environmental quality, which can guide effective policy development and enhance resilience.

Finally, public perception and the willingness of individuals to invest in environmental quality are crucial for fostering resilience. Hossain and Lamb [2] provide evidence from Canada that public demand for improved environmental quality is rising, indicating a societal shift towards valuing environmental health. Similarly, Silva, De Keulenaer and Johnstone [16] found that there is a direct correlation between environmental quality and life satisfaction, suggesting that better environmental conditions lead to enhanced quality of life. Given these factors, we propose the fourth hypothesis: H4.

H4. Less energy poverty positively affects environmental resilience.

2.5 Moderating effects of less energy poverty

The moderating effects of energy access are critical for understanding how different factors influence environmental outcomes. Energy access is not an isolated variable; it is shaped by a range of factors including economic policy uncertainty, institutional quality, and renewable energy adoption. For instance, Udeagha and Muchapondwa [17] demonstrate that economic policy uncertainty (EPU) can significantly moderate the relationship between energy intensity and less energy poverty, with higher EPU potentially leading to environmental degradation. This suggests that instability in economic policies can exacerbate environmental challenges, particularly in developing economies like South Africa. Similarly, Silva, De Keulenaer and Johnstone [16] highlight the role of institutional quality in moderating the relationship between

financial development and carbon emissions. Stronger institutions can mitigate negative environmental impacts, underscoring the importance of effective governance in managing energy access.

The impact of institutional quality is further emphasized in the context of the shadow economy and pollution. Dada and Ajide [44] show that better institutional frameworks can reduce the adverse effects of informal economic activities on energy access in Nigeria, suggesting that governance and institutional integrity play a significant role in moderating environmental outcomes. These findings align with the broader understanding that institutional quality can serve as a moderating factor, helping to buffer the negative environmental effects of certain economic activities.

Furthermore, energy access is also influenced by consumer behavior, which is often moderated by economic and psychological factors. Wang, Pham and Dang [22] explore how price sensitivity moderates the relationship between environmental consciousness and organic food purchase intentions. This indicates that consumer perceptions of energy access, and their subsequent behavior, are not solely influenced by environmental factors but are also shaped by economic considerations, demonstrating the multi-dimensional nature of energy access.

In urban contexts, the relationship between energy access and well-being is evident in studies like those by Chen [39], which show that the quality of urban parks can moderate the relationship between environmental perception and well-being among older populations. This highlights the direct impact of energy access on social and psychological outcomes, particularly in urban planning and public health discussions. Given these insights, we propose the following hypotheses to examine the moderating effects of energy access in the context of environmental resilience: H5-H7.

H5. Less energy poverty moderates the relationship between sustainable tourism and environmental resilience, such that the effect is stronger in areas with higher environmental quality.

H6. Less energy poverty moderates the relationship between tourism policy effectiveness and environmental resilience, such that the effect is stronger in areas with higher environmental quality.

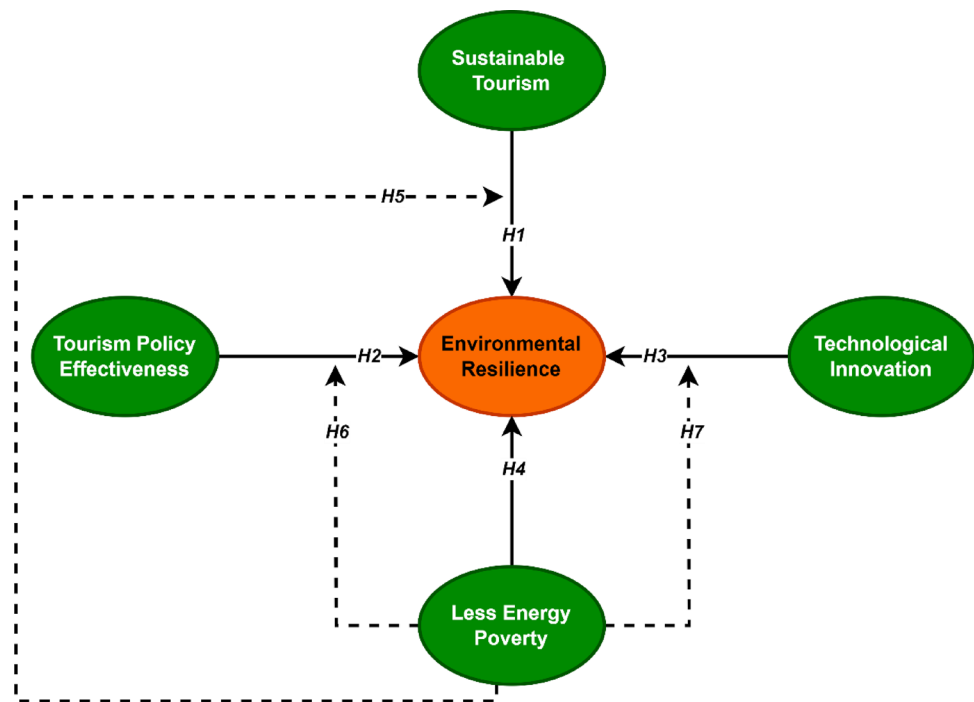
H7. Less energy poverty moderates the relationship between Technological innovation and environmental resilience, such that the effect is stronger in areas with higher environmental quality.

2.6 Theoretical background

The Sustainability Transition Theory (STT) and Resource Dependency Theory (RDT) provide a strong theoretical foundation for this study, enabling a comprehensive understanding of the factors influencing environmental resilience in the context of sustainable tourism, effective tourism policies, technological innovations, and energy poverty [45–48]. STT focuses on the transformative processes that societies and industries undergo to achieve sustainability. It emphasizes the importance of systemic changes in practices, policies, and technological advancements to foster sustainable outcomes. This theory is particularly relevant for the current study as it examines how sustainable tourism practices (ST), tourism policy effectiveness (TPE), and technological innovations (TI) contribute to environmental resilience [45]. Additionally, STT highlights the role of reducing energy poverty as a critical element in facilitating the transition towards more sustainable environmental systems.

On the other hand, the Resource Dependency Theory (RDT) provides a complementary perspective by examining the role of external resource availability and its influence on organizational or sectoral strategies and outcomes [48, 49]. RDT is particularly suited to this study's focus on energy poverty, which represents a significant resource constraint in many developing nations, including Bangladesh. The theory helps explain how reducing energy poverty acts as an enabler, strengthening the relationships between sustainable tourism practices, effective policies, and technological innovations, ultimately enhancing environmental resilience. By framing energy access as a critical resource, RDT underscores the importance of addressing energy poverty to achieve sustainability goals and improve environmental outcomes.

Integrating these two theories offers a holistic framework for understanding the moderating role of energy poverty in fostering environmental resilience [47, 50]. STT provides a macro-level view, focusing on the systemic changes needed to drive sustainability transitions in tourism and beyond, while RDT offers a micro-level lens, emphasizing the critical role of resource availability, such as energy access, in influencing these transitions. Together, these theories not only deepen the study's theoretical contributions but also highlight actionable pathways for policymakers and practitioners to address energy poverty as a catalyst for sustainable development. By applying these frameworks, the study advances the global discourse on environmental resilience and provides valuable insights for developing nations striving to achieve their sustainability objectives.

Fig. 1 Conceptual framework

Based on the related studies and theories, we developed Fig. 1 as conceptual model.

3 Methodology

3.1 Data collection

The data for this study was collected from key stakeholders in the tourism sector of Bangladesh, encompassing five primary groups to ensure a comprehensive understanding of the variables. These groups included Tourism Industry Stakeholders (managers and employees of tourism enterprises, such as hotels, resorts, and eco-tourism operators), Government and Policy Makers (government officials involved in tourism policy development and environmental regulation), Technological Innovators (technology providers and research institutes focused on tourism-related innovations), Community Representatives (media representatives and non-governmental organizations advocating for sustainable tourism and environmental protection), and Environmental Experts (academics and researchers specializing in environmental resilience and sustainability). This diverse mix of respondents was chosen to capture a holistic perspective on the relationships among sustainable tourism, policy effectiveness, technological innovations, energy access, and environmental resilience.

A total of 378 valid responses were collected through a convenience sampling method, which was considered suitable for the exploratory nature of the study and for efficiently reaching knowledgeable respondents. To determine the minimum sample size, the "Ten Times Rule" was applied, which suggests that the sample should be at least ten times the number of measurement items [51, 52]. Given that 20 measurement items were used in the study, the minimum required sample size was 200. To improve the reliability and generalizability of the results, the data collection aimed for 400 respondents, and ultimately, 378 valid responses were included in the analysis. This sample size provides adequate statistical power for the application of PLS-SEM and ANN techniques.

3.2 Construct operationalization

Table 1 presents the operationalization of the study's constructs, each defined through four items measured on a seven-point Likert scale. Sustainable Tourism (ST) is operationalized as the adoption of tourism practices that promote environmental conservation and community well-being, assessed through items measuring eco-friendly practices, resource

Table 1 Constructs, explanations, and items

| Constructs | Explanation | Items |
|------------------------------------|---|---|
| Sustainable Tourism (ST) | Adoption of tourism practices aimed at environmental conservation and community well-being | <ol style="list-style-type: none"> 1. Our organization prioritizes eco-friendly tourism practices 2. Tourism activities focus on minimizing environmental harm 3. Sustainable tourism practices contribute to local community development 4. Resources are managed efficiently to promote environmental sustainability |
| Tourism Policy Effectiveness (TPE) | Perceived success of tourism policies in promoting sustainability and environmental resilience | <ol style="list-style-type: none"> 1. Tourism policies effectively promote sustainable development 2. Regulatory measures ensure environmentally responsible tourism 3. Policy implementation fosters long-term environmental protection 4. Policies encourage collaboration among tourism stakeholders |
| Technological Innovations (TI) | Integration of innovative technologies in the tourism sector to enhance sustainability | <ol style="list-style-type: none"> 1. Technology is used to reduce the environmental footprint of tourism activities 2. Innovative tools help monitor and manage environmental quality 3. Advanced technology enhances efficiency in tourism operations 4. Technological solutions support eco-friendly tourism practices |
| Environmental Resilience (ER) | Ability of the environment to withstand and recover from tourism-related stressors | <ol style="list-style-type: none"> 1. Tourism practices have contributed to the resilience of local ecosystems 2. Environmental degradation due to tourism is effectively mitigated 3. The ecosystem adapts well to changes in tourism intensity 4. Sustainable tourism practices enhance the environment's recovery capacity |
| Less energy poverty | It refers to the improved availability, accessibility, and affordability of reliable and clean energy, which enhances tourism services, supports local communities, and promotes environmental resilience | <ol style="list-style-type: none"> 1. Access to affordable and reliable energy sources has significantly improved in tourism-related areas 2. Increased energy access has enhanced the quality of tourism services and infrastructure 3. Improved access to clean and sustainable energy solutions has contributed to environmental conservation efforts 4. Reduction in energy poverty has positively influenced the livelihoods of local communities involved in the tourism sector |

efficiency, and contributions to local development [14, 25]. Tourism Policy Effectiveness (TPE) captures the perceived success of tourism policies in fostering sustainability and environmental resilience, with items focusing on policy implementation, regulatory measures, and stakeholder collaboration [5, 6]. Technological Innovations (TI) represent the integration of innovative technologies in the tourism sector to enhance sustainability, measured by items related to the use of technology to reduce environmental impacts, improve operational efficiency, and support eco-friendly practices [13, 49]. Environmental Resilience (ER) is defined as the ability of the environment to withstand and recover from tourism-related stressors, with items assessing ecosystem adaptability and mitigation of environmental degradation [5, 27]. Finally, Energy access or less energy poverty (LEP) reflects the baseline condition of the environment in tourism areas, assessed through indicators of air and water quality, biodiversity preservation, and effective waste management [29, 53].

3.3 Common method bias

To address the potential issue of common method bias, Harman's single-factor test was performed. Common method bias occurs when a single factor explains more than 50% of the variance in the data. Using SPSS, an unrotated factor analysis was conducted on all measurement items through a dimension reduction technique. The results showed that the first factor explained 37.21% of the total variance, which is well below the 50% threshold. This indicates that common method bias is not a significant concern in this study, thereby supporting the reliability and validity of the data collected from the respondents.

4 Results

The results section provides an analysis of the findings derived from the combined application of Partial Least Squares Structural Equation Modeling (PLS-SEM) and Artificial Neural Networks (ANN). Initially, PLS-SEM was used to evaluate both the measurement model and the structural model, assessing the reliability and validity of the constructs as well as testing the hypothesized relationships among the variables [54, 55]. The measurement model was first examined to ensure that the indicators appropriately measured their respective constructs, followed by an evaluation of the structural model to test the direct and indirect relationships between the variables. After the PLS-SEM analysis, latent variable scores were derived and subsequently used as input data for the ANN analysis [56, 57]. The ANN analysis aimed to assess model performance by evaluating Root Mean Square Error (RMSE) values, which provide an indication of the prediction accuracy of the model. Additionally, a sensitivity analysis was conducted to determine the relative importance of the independent variables in predicting the dependent variable. This analysis helps identify which factors have the most significant impact on environmental resilience. By integrating PLS-SEM and ANN, this dual-method approach ensures a comprehensive understanding of the relationships and non-linear dynamics among the study's variables.

Figure 2 illustrates the demographic distribution of the 378 respondents across various categories, including gender, age, education, profession, and experience. In terms of gender, the sample comprises 55.56% males and 44.44% females. The age group 30–44 forms the majority (47.62%), followed by 18–29 (31.75%) and 45 and above (20.63%). Educational qualifications show that 47.62% are graduates, 28.57% hold postgraduate or higher degrees, while 23.81% have undergraduate or lower qualifications. Professionally, the largest group is tourism employees (26.46%), followed by tourism managers (21.16%), NGO representatives (18.52%), researchers/academics (17.99%), and government officials (15.87%). Regarding experience, 39.68% of respondents have 0–5 years of experience, 31.75% have 6–10 years, and 28.57% have over 11 years. These demographics highlight a diverse and representative sample of stakeholders involved in the tourism sector in Bangladesh, ensuring varied perspectives in the study.

4.1 Results from structural equation modeling

Table 2 displays the reliability and validity statistics for the constructs used in this study. To evaluate the convergent validity, Factor Loadings (FL) were analyzed, with values ranging from 0.73 to 0.86 across all items. These values exceed the threshold of 0.70, indicating strong correlations between the items and their respective constructs, thereby confirming good convergent validity [54]. In addition, Cronbach's Alpha (CA), a measure of internal consistency, ranged from 0.85 to 0.91 for all constructs, surpassing the acceptable threshold of 0.70 [54]. This suggests that the items within each construct exhibit a high level of consistency and reliability. The Composite Reliability (CR) values also ranged from 0.90

Fig. 2 Demographic profile of the participants

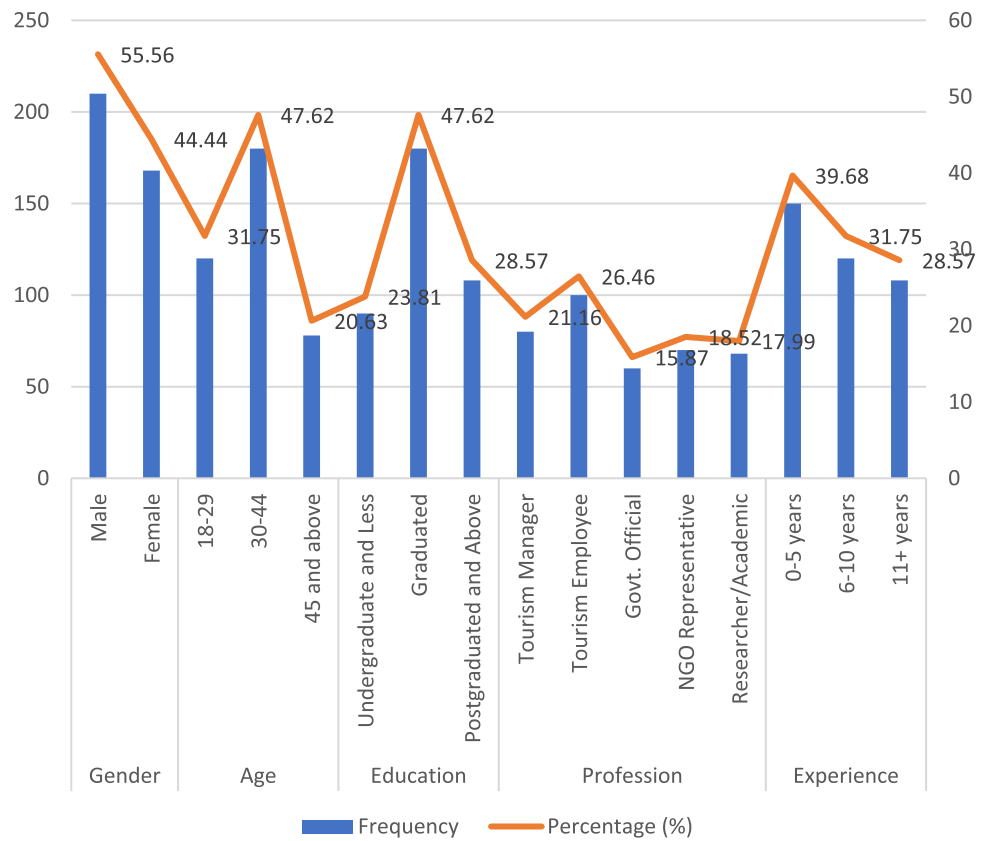


Table 2 Reliability and validity

| Items | FL [> 0.70] | CA [> 0.70] | CR [> 0.70] | AVE [> 0.50] | VIF [< 3.0] |
|-------|----------------------------|-------------|-------------|--------------|-------------|
| ST | 4 [0.78, 0.83, 0.73, 0.86] | 0.87 | 0.91 | 0.67 | 1.132 |
| TPE | 4 [0.76, 0.82, 0.75, 0.79] | 0.88 | 0.90 | 0.64 | 1.148 |
| TI | 4 [0.80, 0.85, 0.77, 0.81] | 0.89 | 0.92 | 0.69 | 1.150 |
| ER | 4 [0.79, 0.84, 0.76, 0.83] | 0.86 | 0.90 | 0.68 | 1.120 |
| LEP | 4 [0.81, 0.79, 0.74, 0.80] | 0.85 | 0.91 | 0.70 | 1.140 |

Table 3 Discriminant validity using HTMT [< 0.85]

| | ST | TPE | TI | ER | LEP |
|-----|------|------|------|------|-----|
| ST | | | | | |
| TPE | 0.68 | | | | |
| TI | 0.62 | 0.57 | | | |
| ER | 0.72 | 0.76 | 0.54 | | |
| LEP | 0.59 | 0.65 | 0.48 | 0.52 | |

to 0.92, which is well above the 0.70 threshold, providing further evidence of the internal consistency and reliability of the constructs used in this study [54].

The Average Variance Extracted (AVE) values, which assess the amount of variance captured by each construct relative to measurement error, ranged from 0.64 to 0.70. All values are above the recommended threshold of 0.50, indicating that each construct explains more than half of the variance in its items, thus confirming convergent validity [54]. Additionally, the Variance Inflation Factor (VIF) values ranged from 1.12 to 1.15, which are well below the threshold of 3.0 [54]. This suggests that there are no concerns regarding multicollinearity among the constructs, further supporting the robustness and validity of the measurement model.

Table 3 presents the discriminant validity results using the Heterotrait-Monotrait ratio (HTMT), which is used to assess whether the constructs in the model are distinct from one another. The threshold for HTMT is typically set at 0.85, with values below this threshold indicating adequate discriminant validity, meaning that the constructs are sufficiently distinct. In this table, all the HTMT values between the constructs are below 0.85, ranging from 0.48 to 0.76, suggesting that each construct is distinct and not highly correlated with the others [54]. For example, the HTMT value between Sustainable Tourism (ST) and Tourism Policy Effectiveness (TPE) is 0.68, which is well below the 0.85 threshold, confirming that these two constructs are separate. Similarly, all other pairs of constructs, such as Sustainable Tourism (ST) and Technological Innovations (TI) (0.62), Tourism Policy Effectiveness (TPE) and Environmental Resilience (ER) (0.76), and Technological Innovations (TI) and Less energy poverty (0.48), also show values below 0.85, indicating that they are distinct and do not overlap excessively. Thus, the results from Table 3 confirm that the constructs in the model exhibit good discriminant validity.

Table 4 presents the results of the model evaluation for Environmental Resilience (ER), showing three key metrics: R-squared, Adjusted R-squared, and Q-squared. The R-squared value of 0.843 indicates that the model explains approximately 84.3% of the variance in ER, demonstrating a high level of explanatory power. The Adjusted R-squared value of 0.829 takes into account the number of predictors, showing that around 82.9% of the variance in ER is explained after adjusting for model complexity, which still indicates strong explanatory power. Lastly, the Q-squared value of 0.442 suggests moderate predictive relevance, meaning that the model not only explains the variance in ER but also has a good ability to predict future outcomes.

Table 5 presents the results of the analysis examining the impact of Sustainable Tourism (ST), Tourism Policy Effectiveness (TPE), Technological Innovations (TI), and less energy poverty on Environmental Resilience (ER). The path from Sustainable Tourism (ST) to Environmental Resilience (ER) shows a standardized coefficient of 0.32, with a t-value of 3.56 and a p-value of 0, indicating a significant positive effect, thus supporting H1. Similarly, the path from Tourism Policy Effectiveness (TPE) to ER has a standardized coefficient of 0.28, a t-value of 3.12, and a p-value of 0.002, signifying a significant positive impact, which supports H2. The relationship between Technological Innovations (TI) and ER shows a coefficient of 0.24, with a t-value of 2.87 and a p-value of 0.004, confirming a significant positive influence, thus supporting H3. Lastly, the path from Less energy poverty to ER has a coefficient of 0.35, a t-value of 4.02, and a p-value of 0, indicating a strong positive effect, which supports H4.

Table 6 presents the results of the moderating effect of Less energy poverty on the relationships between Sustainable Tourism (ST), Tourism Policy Effectiveness (TPE), Technological Innovations (TI), and Environmental Resilience (ER). The interaction term $ST \times LEP \rightarrow ER$ has a standardized coefficient of 0.27, a t-value of 3.21, and a p-value of 0.001, indicating that Environmental Quality positively moderates the relationship between Sustainable Tourism and Environmental Resilience, with the effect being stronger in areas with higher environmental quality, thus supporting H5. Similarly, the moderating effect of LEP on $TPE \rightarrow ER$ shows a coefficient of 0.25, a t-value of 2.98, and a p-value of 0.003, confirming that Environmental Quality strengthens the impact of Tourism Policy Effectiveness on Environmental Resilience, supporting

Table 4 Model evaluation

| | R-squared | Adj. R-squared | Q-squared |
|----|-----------|----------------|-----------|
| ER | 0.843 | 0.829 | 0.442 |

Table 5 Impact of ST, TPE, TI, and LEP on ER

| Relationships | β | T-values | P-values | Supported |
|--------------------------|---------|----------|----------|-----------|
| H1: $ST \rightarrow ER$ | 0.32 | 3.56 | 0.000 | Yes |
| H2: $TPE \rightarrow ER$ | 0.28 | 3.12 | 0.002 | Yes |
| H3: $TI \rightarrow ER$ | 0.24 | 2.87 | 0.004 | Yes |
| H4: $LEP \rightarrow ER$ | 0.35 | 4.02 | 0.000 | Yes |

Table 6 Moderating effect of LEP

| Relationships | β | T-values | P-values | Supported |
|-------------------------------------|---------|----------|----------|-----------|
| H5: $ST \times LEP \rightarrow ER$ | 0.27 | 3.21 | 0.001 | Yes |
| H6: $TPE \times LEP \rightarrow ER$ | 0.25 | 2.98 | 0.003 | Yes |
| H7: $TI \times LEP \rightarrow ER$ | 0.23 | 2.75 | 0.006 | Yes |

Table 7 RMSE-ANN values

| ANN | Training (90%) | | | Testing (10%) | | |
|-------|----------------|-------|-----|---------------|-------|----|
| | SSE | RMSE | N | SSE | RMSE | N |
| ANN1 | 2.930 | 0.281 | 341 | 0.338 | 0.095 | 37 |
| ANN2 | 2.896 | 0.257 | 334 | 0.343 | 0.089 | 44 |
| ANN3 | 3.444 | 0.289 | 337 | 0.203 | 0.070 | 41 |
| ANN4 | 3.060 | 0.262 | 333 | 0.613 | 0.117 | 45 |
| ANN5 | 3.071 | 0.309 | 346 | 0.233 | 0.085 | 32 |
| ANN6 | 3.003 | 0.287 | 342 | 0.397 | 0.104 | 36 |
| ANN7 | 2.865 | 0.249 | 332 | 0.548 | 0.109 | 46 |
| ANN8 | 2.901 | 0.300 | 346 | 0.274 | 0.092 | 32 |
| ANN9 | 3.053 | 0.259 | 333 | 0.336 | 0.086 | 45 |
| ANN10 | 3.044 | 0.280 | 339 | 0.263 | 0.082 | 39 |
| Mean | 3.027 | 0.277 | | 0.355 | 0.093 | |
| SD | 0.157 | 0.019 | | 0.126 | 0.013 | |

Table 8 Sensitivity analysis

| ANN | ST | LEP | TI | TPE |
|---------------------------|-------|-------|-------|-------|
| ANN1 | 0.833 | 1.000 | 0.764 | 0.397 |
| ANN2 | 1.000 | 0.821 | 0.700 | 0.338 |
| ANN3 | 1.000 | 0.930 | 0.842 | 0.351 |
| ANN4 | 0.302 | 1.000 | 0.557 | 0.492 |
| ANN5 | 1.000 | 0.595 | 0.690 | 0.650 |
| ANN6 | 1.000 | 0.760 | 0.780 | 0.483 |
| ANN7 | 1.000 | 0.642 | 0.685 | 0.439 |
| ANN8 | 0.897 | 0.815 | 0.581 | 1.000 |
| ANN9 | 1.000 | 0.650 | 0.710 | 0.165 |
| ANN10 | 0.817 | 1.000 | 0.507 | 0.548 |
| Average Importance | 0.885 | 0.821 | 0.682 | 0.486 |
| Normalized Importance (%) | 100% | 93% | 77% | 55% |
| Ranking | 1 | 2 | 3 | 4 |

H6. Lastly, the interaction between $TI \times LEP \rightarrow ER$ shows a coefficient of 0.23, a t-value of 2.75, and a p-value of 0.006, indicating that LEP moderates the relationship between Technological Innovations and Environmental Resilience, also supporting H7.

4.2 Results from artificial neural network

Table 7 presents the Root Mean Square Error (RMSE) values for 10 Artificial Neural Network (ANN) models during both the training (90% of the data) and testing (10% of the data) phases as following [52] and [58]. The RMSE values during the training phase range from 0.249 to 0.309, with a mean RMSE of 0.277 and a standard deviation of 0.019, indicating that the models performed consistently across the training data. In the testing phase, the RMSE values range from 0.070 to 0.117, with a mean RMSE of 0.093 and a standard deviation of 0.013, suggesting that the models generalized well to unseen data, though with slightly reduced accuracy compared to the training phase. Overall, the results indicate that the ANN models provided reliable and consistent predictions, with low RMSE values reflecting good model performance in both the training and testing phases. The minimal variability in both phases further supports the robustness and reliability of the models.

Table 8 presents the results of the sensitivity analysis, which evaluates the relative importance of the independent variables—Sustainable Tourism (ST), Less energy poverty, Technological Innovations (TI), and Tourism Policy Effectiveness (TPE)—in predicting Environmental Resilience (ER) across 10 Artificial Neural Network (ANN) models [56, 58–60]. The average importance values show that Sustainable Tourism (ST) is the most significant predictor, with an average

importance of 0.885, followed by Less energy poverty at 0.821, Technological Innovations (TI) at 0.682, and Tourism Policy Effectiveness (TPE) at 0.486. When expressed as normalized importance percentages, ST accounts for 100% of the influence, LEP contributes 93%, TI has 77%, and TPE has the lowest contribution at 55%. Based on these values, the ranking of variables in terms of their impact on Environmental Resilience is: ST (1st), LEP (2nd), TI (3rd), and TPE (4th). This analysis clearly indicates that Sustainable Tourism is the most influential factor, followed by Environmental Quality, while Technological Innovations and Tourism Policy Effectiveness have relatively lesser roles.

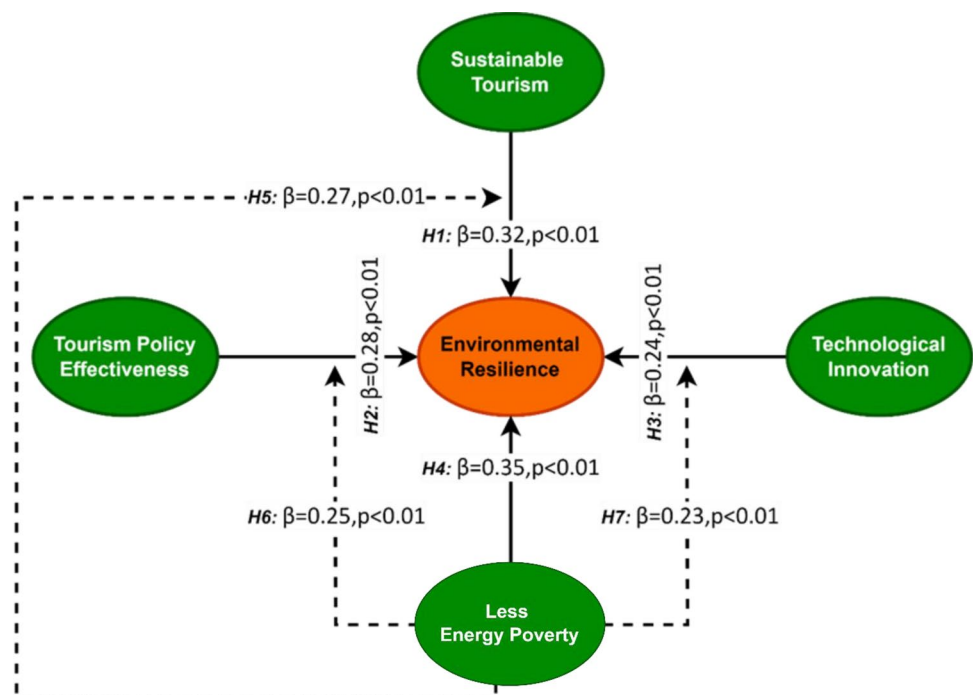
5 Discussions

The findings of this study indicate that Sustainable Tourism (ST), Tourism Policy Effectiveness (TPE), Technological Innovations (TI), and Less energy poverty all have a positive impact on Environmental Resilience (ER) (see Fig. 3). These factors are integral in enhancing the capacity of ecosystems and communities to withstand and recover from the stresses imposed by tourism activities, thereby supporting long-term environmental sustainability. Among these, Sustainable Tourism (ST) emerges as the most influential driver of environmental resilience, as demonstrated by its strong impact in both the Structural Equation Modeling (SEM) and Artificial Neural Network (ANN) analyses. By emphasizing eco-friendly practices, reducing environmental harm, and promoting sustainable resource use, ST plays a key role in preserving ecosystems. Sustainable tourism practices such as waste management, resource conservation, and community engagement help mitigate the adverse effects of tourism, thereby increasing environmental resilience [18, 29, 32]. Furthermore, the adoption of these practices ensures that tourism does not contribute to environmental degradation but instead fosters recovery and regeneration over time, thus enhancing long-term environmental sustainability [24, 61].

Tourism Policy Effectiveness (TPE) also plays a significant role in enhancing environmental resilience. Effective tourism policies that promote sustainable development, regulate tourism activities, and ensure long-term environmental protection create a framework that encourages responsible behavior from all stakeholders [13, 53, 62]. Well-implemented policies, such as regulations on resource use and waste management, contribute to the minimization of tourism-related environmental degradation, allowing ecosystems to adapt and recover from any negative impacts. Furthermore, the collaboration fostered by these policies among stakeholders—such as tourism businesses, governments, and local communities—helps to align efforts toward preserving environmental quality and ensuring that tourism benefits are sustainable.

Technological Innovations (TI) contribute to environmental resilience by providing tools and solutions that help reduce the environmental footprint of tourism activities. Advanced technologies, such as sustainable energy solutions, waste treatment systems, and digital tools for monitoring environmental quality, enable more efficient and

Fig. 3 Impact of sustainable tourism, technological innovation, tourism policy effectiveness, less energy poverty on environmental resilience



eco-friendly management of tourism operations [13, 49, 62]. The integration of technology in tourism also enhances the ability to manage and mitigate the environmental impacts of tourism, such as pollution, resource depletion, and habitat destruction. Through these innovations, tourism operators can minimize their ecological footprint while maximizing the benefits to both the environment and local communities.

Less energy poverty serves as a moderating factor that amplifies the positive impacts of ST, TPE, and TI on environmental resilience. High environmental quality—characterized by clean air, water, and biodiversity—creates a stronger foundation for the sustainability of tourism activities. In areas with better environmental quality, the effects of sustainable tourism practices, effective policies, and technological innovations are more pronounced, leading to greater environmental resilience [29, 53]. For example, in regions with good air and water quality, sustainable tourism practices have a more significant impact on preserving these natural resources, while effective tourism policies are more likely to result in lasting protection of local ecosystems.

6 Conclusions

This study provides valuable insights into the critical factors influencing environmental resilience in tourism destinations. The findings highlight that Sustainable Tourism (ST), Tourism Policy Effectiveness (TPE), Technological Innovations (TI), and Less energy poverty each play a significant and positive role in enhancing environmental resilience. The results confirm that sustainable tourism practices, when effectively implemented, contribute to the long-term preservation and recovery of ecosystems, while well-crafted tourism policies further strengthen these efforts by regulating and encouraging responsible behavior among stakeholders. Technological innovations provide essential tools for reducing the environmental footprint of tourism and improving the management of resources, while environmental quality serves as an important moderator that amplifies the positive effects of these factors in areas with better environmental conditions.

The study also underscores the importance of an integrated approach to sustainable tourism development, where policies, technological advancements, and environmental quality work synergistically to ensure environmental protection and resilience. The moderating role of environmental quality emphasizes the need for targeted interventions in areas with varying environmental conditions to maximize the effectiveness of sustainable tourism initiatives. Furthermore, the findings from both the Structural Equation Modeling (SEM) and Artificial Neural Network (ANN) analyses provide robust evidence that the combined efforts of these factors can significantly enhance environmental resilience.

Building on the study's findings, policymakers should prioritize the development and implementation of comprehensive frameworks that integrate sustainable tourism practices with technological innovations and effective governance. Tourism policies should focus on incentivizing eco-friendly practices among businesses and travelers, such as adopting renewable energy sources, reducing waste, and promoting conservation activities. Governments can also establish partnerships with the private sector to invest in green technologies that minimize the environmental footprint of tourism activities. Additionally, policies should address the disparities in environmental quality across different regions by allocating resources to improve infrastructure and environmental conditions in areas most vulnerable to degradation. Special attention should be given to enhancing the accessibility and affordability of sustainable practices for small and medium-sized tourism enterprises, ensuring their active participation in environmental protection efforts. By incorporating these recommendations, policymakers can create a conducive environment for sustainable tourism to thrive while preserving the natural and cultural assets of tourism destinations.

This study articulates some limitations: First, the data used in the analysis primarily focuses on tourism destinations, which may not fully capture the variations in environmental resilience across non-tourism regions. Future research should expand the scope to include diverse geographical contexts and explore sector-specific dynamics to provide a more holistic understanding. Second, the study employs SEM and ANN methods, which, while robust, may benefit from integration with other advanced analytical tools like longitudinal data analysis or machine learning models to better capture temporal and dynamic effects. Future investigations should also explore the role of cultural, social, and economic factors in moderating the relationship between sustainable tourism and environmental resilience. Additionally, longitudinal studies could be conducted to assess the long-term impacts of tourism policies and technological advancements on environmental sustainability. These extensions will contribute to a deeper understanding and provide actionable insights for improving environmental resilience across diverse settings.

Author contributions M.N.: Conceptualization, write original manuscript, formal analysis. A.O.R.: Conceptualization, write original manuscript. M.A.: write original manuscript, review and editing.

Data availability Data will be available on reasonable request from corresponding author.

Declarations

Ethics approval and consent to participate This study was approved by the school administration and the ethics committee of University of Medical Sciences & Technology, Khartoum, Sudan. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Competing interests The authors declare no competing interests.

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