

Article

Study on Coupling Coordination Between Ecotourism and Economic Development in Hainan Free Trade Port

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Abstract

Coordinating ecotourism development with economic growth is central to achieving sustainability in regions where natural assets are both a comparative advantage and a binding constraint. This study assesses the ecotourism economy coupling coordination in Hainan Free Trade Port (China) during 2017–2023. Building on sustainable development theory, systems theory, and the tourism-led growth hypothesis, we conceptualize three coordination pathways, industrial structure upgrading, clustering effects, and urban–rural linkages, and operationalize them through an 18-indicator evaluation system covering ecotourism and economic subsystems. Indicator weights are determined using the entropy weight method, and the coupling coordination degree model is applied to quantify the interaction intensity and coordination level. Gray Relational Analysis is further used as a robustness-oriented complement to identify the factors most associated with coordination changes. Results show that both subsystems improved overall with noticeable fluctuations: the ecotourism index rose from 0.239 to 0.719, while the economic development index increased from 0.370 to 0.610. The coupling coordination degree advanced from moderate dysregulation (0.230 in 2017) to near quality coordination (0.995 in 2023), while shock-sensitive years highlight the vulnerability of tourism-related performance. The findings suggest that improving industrial structure and strengthening tourism-related productive capacity and external connectivity are key levers for sustaining coordination without compromising ecological efficiency.

Keywords: ecotourism; free trade port; entropy weight method; coupling coordination degree; gray relational analysis; sustainable development

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1. Introduction

The relationship between tourism development and economic growth has attracted substantial scholarly attention over the past few decades [1,2]. Tourism has been recognized as a significant driver of economic development, contributing to foreign exchange earnings, employment generation, infrastructure development, and regional prosperity across diverse national contexts. As global awareness of environmental sustainability intensifies, ecotourism has emerged as a promising paradigm that reconciles economic development with ecological conservation [3,4]. Unlike conventional mass tourism, which

often prioritizes short-term economic gains at the expense of environmental quality, ecotourism emphasizes responsible travel to natural areas, conservation of the environment, and improvement of local community welfare [5]. This paradigm shift reflects broader societal recognition that long-term economic prosperity depends fundamentally on maintaining healthy ecosystems and sustainable resource utilization patterns. The global ecotourism market has experienced substantial growth, driven by increasing environmental consciousness among travelers and growing demand for authentic nature-based experiences. According to industry reports, the global ecotourism market was valued at approximately 181.1 billion USD in 2019 and is projected to reach 333.8 billion USD by 2027, representing a compound annual growth rate of 14.3%. This growth trajectory underscores the economic significance of ecotourism and its potential contribution to sustainable development objectives. However, realizing this potential requires careful attention to the complex interactions between tourism development and ecological preservation, ensuring that economic benefits do not come at the cost of environmental degradation.

China's tourism sector has experienced remarkable expansion, with the added value of tourism and related industries growing from 2.27 trillion yuan in 2012 to 4.55 trillion yuan in 2021, representing an average annual growth rate of 5.0% [6]. The sector has become an important pillar of the national economy, contributing significantly to employment, consumption, and regional development. However, this rapid development has generated challenges including resource depletion, environmental degradation, and industrial vulnerabilities [7]. Many popular tourist destinations have experienced carrying capacity constraints, with excessive visitor numbers threatening ecological integrity and diminishing visitor experiences. In this context, ecotourism offers a pathway to sustainable development by balancing economic benefits with environmental protection [8]. The Chinese government has increasingly emphasized ecological civilization construction and green development, creating favorable policy environments for ecotourism expansion.

Hainan Province, designated as China's only free trade port in 2020, presents a unique case study for examining ecotourism–economic coordination [9]. Located at the southernmost tip of China, Hainan possesses exceptional natural endowments, including tropical rain forests, pristine beaches, coral reefs, and diverse marine ecosystems. The island's tropical climate, with an average annual temperature of 22–27 °C and abundant sunshine, makes it an ideal destination for year-round tourism activities. The Hainan Free Trade Port Law establishes ecological conservation as a fundamental principle, while simultaneously positioning the island as an international tourism consumption center [10]. This dual mandate creates both opportunities and tensions that merit systematic investigation [11]. On the one hand, the free trade port designation brings unprecedented policy advantages, including zero-tariff imports, simplified customs procedures, and preferential tax treatments that can accelerate economic development. On the other hand, the ecological priority principle requires that all development activities adhere to strict environmental standards, potentially constraining certain economic activities.

The existing literature on ecotourism and regional economic development has predominantly focused on empirical analyses using coupling coordination models [12,13]. These models, derived from physics concepts of system coupling, have been widely applied to examine the interactive relationships between tourism, ecology, and economy across Chinese regions. Studies have examined tourism–ecology relationships in various Chinese regions, including Nanjing [14] and Guiyang [15]. Research has also investigated tourism–urbanization–environment coupling in major urban agglomerations and coastal areas. However, limited research has explored the underlying mechanisms driving ecotourism–economic coordination, particularly in free trade port contexts with explicit sustainability mandates [16]. Most existing studies treat the tourism–economy relationship

as a black box, measuring coordination levels without explaining the pathways through which coordination is achieved or deteriorates.

This study addresses the above gaps by making three interrelated contributions. First, it advances the coupling–coordination literature by reframing coordination analysis as an institutional diagnostic tool rather than merely a descriptive measure of development performance. Drawing on insights from industrial economics, regional economics, and ecological economics, the study conceptualizes ecotourism–economic coordination as an evolving alignment process shaped by industrial structure optimization, clustering dynamics, and urban–rural development pathways within an experimental policy context. Second, the study constructs a comprehensive indicator system tailored to the specific institutional characteristics of the Hainan Free Trade Port. By incorporating external trade indicators and fixed asset investment variables alongside ecological and tourism indicators, the framework captures not only development scale and capacity, but also the structural and institutional conditions under which coordination emerges in free trade port economies. Third, methodologically, the study integrates entropy weighting, coupling coordination degree analysis, and Gray Relational Analysis into a unified analytical framework. This combined approach enables both the identification of coordination trajectories and the diagnosis of indicator-level drivers and structural sensitivities, moving beyond a purely descriptive application of existing models toward a governance-oriented interpretation of coordination dynamics between ecotourism development and economic growth in Hainan from 2017 to 2023.

The remainder of this paper is organized as follows. Section 2 reviews the theoretical foundations and relevant literature, establishing the conceptual framework for understanding ecotourism–economic relationships. Section 3 develops the theoretical framework for understanding ecotourism–economic coupling mechanisms, identifying three primary pathways through which coordination is achieved. Section 4 presents the methodology and data, including the entropy weight method, coupling coordination degree model, and Gray Relational Analysis. Section 5 reports the empirical results, analyzing trends in subsystem development and coordination dynamics. Section 6 discusses the findings and offers policy recommendations for enhancing ecotourism–economic coordination. Section 7 concludes with summary findings and directions for future research.

2. Theoretical Foundations and Literature Review

2.1. Theoretical Foundations

This study draws upon three interconnected theoretical frameworks that collectively provide a comprehensive foundation for understanding ecotourism–economic coordination: sustainable development theory, systems theory, and the tourism-led growth hypothesis. Each framework contributes unique insights while together forming an integrated analytical lens for examining the complex dynamics between ecological conservation and economic development.

2.1.1. Sustainable Development Theory

Sustainable development, defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [17], provides the foundational framework for understanding ecotourism–economic relationships. This seminal definition, articulated in the 1987 Brundtland Commission report, has become the guiding principle for global environmental governance and development policy. The theory emphasizes the interconnection between economic growth, social equity, and environmental protection, recognizing that these dimensions are not mutually exclu-

sive but rather mutually reinforcing when properly managed [18]. The sustainable development framework has evolved significantly since its initial articulation, incorporating insights from ecological economics, environmental science, and development studies. The concept of the “triple bottom line” extended sustainability thinking into business and policy contexts, emphasizing that organizations should pursue economic, social, and environmental objectives simultaneously. More recently, the United Nations Sustainable Development Goals (SDGs) have operationalized sustainability principles into specific targets, with Goal 8 (Decent Work and Economic Growth), Goal 12 (Responsible Consumption and Production), and Goal 15 (Life on Land) particularly relevant to ecotourism development.

In tourism contexts, sustainable development requires balancing immediate economic benefits with long-term ecological preservation [19]. Tourism destinations must manage the tension between maximizing short-term visitor revenues and maintaining the environmental quality that attracts visitors in the first place. This balancing act is particularly challenging in ecotourism contexts, where the natural environment constitutes the primary attraction and any degradation directly undermines the tourism product. Sustainable tourism management therefore requires integrated approaches that consider carrying capacity, visitor management, community participation, and ecological monitoring.

2.1.2. Systems Theory

Systems theory conceptualizes ecotourism and economic development as interconnected subsystems within a larger socio-ecological system [20]. General systems theory, developed by Ludwig von Bertalanffy in the mid-20th century, provides analytical tools for understanding complex phenomena characterized by multiple interacting components and emergent properties. The theory emphasizes that system behavior cannot be fully understood by analyzing individual components in isolation; rather, understanding emerges from examining relationships and interactions among components. This perspective highlights feedback loops, emergent properties, and non-linear dynamics that characterize complex adaptive systems [21]. In ecotourism–economic systems, positive feedback loops can amplify both beneficial and harmful dynamics. For example, successful ecotourism development may generate revenues that fund conservation efforts, which in turn enhance destination attractiveness and generate additional tourism revenues, a virtuous cycle. Conversely, overtourism can degrade environmental quality, reducing destination attractiveness and eventually diminishing tourism revenues, a vicious cycle. Understanding these feedback dynamics is essential for effective policy intervention. The coupling coordination model operationalizes this systems perspective by measuring the degree of harmonious interaction between subsystems [22]. Coupling, a concept borrowed from physics, refers to the degree of interaction or interdependence between system components. High coupling indicates strong mutual influence, while low coupling suggests relative independence. Coordination, meanwhile, captures whether this interaction produces harmonious or conflictual outcomes. A highly coupled but poorly coordinated system may experience amplified instabilities, while a well-coordinated system exhibits synergistic dynamics that enhance overall performance.

2.1.3. Tourism-Led Growth Hypothesis

The tourism-led growth hypothesis (TLGH) posits that tourism expansion can stimulate economic development through multiple channels, including foreign exchange earnings, infrastructure investment, employment generation, and technology transfer [4,5]. This hypothesis emerged from the broader literature on export-led growth, recognizing tourism as a form of export that brings foreign currency into the host economy.

Unlike traditional merchandise exports, tourism exports are consumed at the point of production, creating unique multiplier effects throughout local economies. Empirical studies have largely supported this hypothesis across diverse contexts, finding positive relationships between tourism development and economic growth in both developed and developing countries [23]. The tourism sector creates employment opportunities across skill levels, from high-end hotel management to entry-level hospitality positions, making it particularly valuable for regions with limited industrial bases. Tourism also stimulates investment in infrastructure, airports, roads, telecommunications, and utilities, which benefits the broader economy beyond the tourism sector itself. However, the relationship between tourism and economic growth may be contingent on institutional quality, economic structure, and tourism management practices [24]. Some studies have found that tourism-led growth is stronger in countries with better governance, more diversified economies, and higher human capital levels. Additionally, the type of tourism matters: high-value, low-volume tourism may generate greater net benefits than low-value, high-volume tourism that strains infrastructure and environmental resources. These contingencies underscore the importance of strategic tourism planning that maximizes economic benefits while minimizing negative externalities.

2.2. Literature Review

2.2.1. Ecotourism Concepts and Principles

Ecotourism encompasses multiple dimensions including environmental responsibility, cultural preservation, community participation, and visitor education [2]. The International Ecotourism Society defines it as “responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and involves interpretation and education” [25]. This definition emphasizes three core components: conservation-oriented travel, community benefit sharing, and educational experiences that foster environmental awareness among visitors. The conceptual evolution of ecotourism reflects broader shifts in tourism scholarship and practice. Early formulations emphasized the distinction between ecotourism and conventional mass tourism, focusing on small-scale, low-impact activities in pristine natural settings. More recent conceptualizations have expanded to include cultural dimensions, recognizing that natural landscapes are often intertwined with indigenous and local communities whose traditions and knowledge systems constitute integral elements of the tourism experience [1]. This expanded understanding has important implications for tourism planning and management, requiring attention to both biophysical and socio-cultural sustainability. Core principles of ecotourism include sustainable development, harmonious community–ecology relationships [26], and active stakeholder participation [27]. The sustainability principle requires that tourism activities remain within environmental carrying capacities, avoiding degradation that would undermine long-term viability. Community–ecology harmony emphasizes that local residents and natural ecosystems should coexist in mutually beneficial relationships, with tourism serving as a mechanism to generate conservation incentives. Stakeholder participation recognizes that effective ecotourism governance requires inclusive decision-making processes that incorporate diverse perspectives and interests.

2.2.2. Ecotourism Impacts on Economic Development

Research has documented both positive and negative economic impacts of ecotourism. Positive effects include GDP growth, employment creation, foreign exchange earnings, and infrastructure development [5,28]. Ecotourism can generate significant economic benefits for host communities, particularly in rural and peripheral regions with limited alternative development options. Employment opportunities span multiple skill levels, from specialized guiding and interpretation services to basic hospitality positions,

creating pathways for local economic participation. The multiplier effects of ecotourism expenditures can extend throughout regional economies. Visitor spending on accommodation, food, transportation, and activities generates direct income for tourism enterprises, which in turn purchase supplies from local providers, creating indirect economic impacts. Employees spend their wages on housing, consumer goods, and services, generating induced effects that ripple through the broader economy. Studies have estimated tourism multipliers ranging from 1.5 to 2.5 in various contexts, indicating that each dollar of tourism spending generates additional economic activity. However, scholars have also identified potential negative consequences such as economic leakage, dependency creation, and distributional inequities [29]. Economic leakage occurs when tourism revenues flow out of host communities to external investors, suppliers, or repatriated profits. In some developing country contexts, leakage rates exceed 50%, substantially diminishing the local economic benefits of tourism development. Dependency concerns arise when communities become overly reliant on tourism, exposing them to volatility from external shocks such as economic recessions, natural disasters, or public health crises. Distributional inequities may emerge when tourism benefits accrue primarily to elites or external actors while costs fall disproportionately on marginalized communities.

2.2.3. Coupling Coordination Studies

The coupling coordination model has been widely applied to examine tourism–environment–economy relationships in China [12,13]. This methodological approach, derived from physics concepts of oscillator coupling, provides a systematic framework for measuring the degree of harmonious interaction between complex systems. Studies have analyzed provincial-level panel data [30] and specific regions, including the Yellow River Basin [31]. These studies consistently find improving coordination trends, though significant regional disparities persist [32]. The coupling coordination framework has been applied to diverse regional contexts within China. Coastal areas such as the Bohai Economic Rim and Yangtze River Delta have generally exhibited higher coordination levels, reflecting more developed tourism infrastructure, stronger institutional frameworks, and greater economic diversification. The interior and western regions typically show lower coordination, constrained by limited accessibility, infrastructure gaps, and weaker institutional capacity. These spatial disparities have important implications for regional development policy, suggesting differentiated strategies tailored to local conditions. Temporal analyses have documented general improvement in coupling coordination across Chinese regions over the past two decades, coinciding with national policies emphasizing ecological civilization construction and sustainable development. However, the rate of improvement varies considerably, with some regions experiencing rapid advancement while others show stagnation or even deterioration. Understanding the factors driving these differential trajectories is essential for designing effective policy interventions.

2.2.4. Research Gaps

Despite substantial progress, existing research exhibits several limitations. First, most studies focus on empirical measurement without thoroughly exploring underlying mechanisms [22]. The coupling coordination model provides useful descriptive metrics but does not explain why coordination improves or deteriorates. Second, few studies examine free trade port contexts with explicit sustainability mandates [9]. Hainan’s unique institutional framework, combining trade liberalization with ecological priority, creates distinctive dynamics that existing frameworks may not adequately capture. Third, methodological robustness could be enhanced through supplementary validation techniques such as Gray Relational Analysis [33]. Reliance on single methods limits confidence in findings and may miss important nuances revealed through methodological triangulation. This

study addresses these gaps by providing theoretical mechanism analysis, context-specific indicator development, and methodological triangulation.

2.2.5. From Sustainable Tourism Theory to Coordination Measurement

Sustainable tourism governance theory emphasizes the balanced interaction between environmental carrying capacity, economic viability, and institutional regulation. Translating these abstract principles into empirical assessment requires operational indicators that capture both ecological constraints and development capacity. Accordingly, this study constructs a two-subsystem framework in which eco-tourism development represents the joint foundation of environmental quality and tourism service capacity, while economic development reflects structural transformation and openness. The coupling coordination degree is therefore employed not as a causal estimator, but as an index of systemic alignment consistent with governance-oriented interpretations of sustainability.

3. Mechanisms of Coupling Coordination Between Ecotourism and Economic Development

Understanding the internal mechanisms governing ecotourism–economic coordination requires examining how these two systems interact and influence each other. Drawing on industrial economics, regional economics, and ecological economics, we identify three primary pathways: industrial structure optimization, industrial clustering, and urban–rural coordination.

3.1. Industrial Structure Optimization Pathway

Modern theories of industrial structure reveal evolutionary relationships between economic growth and sectoral labor distribution [34,35]. Clark's law demonstrates the progressive shift of labor from agriculture to manufacturing and eventually to services as economies develop [34]. This structural transformation reflects differential productivity growth rates across sectors, with manufacturing initially exhibiting the highest productivity gains, followed by services in later development stages. Kuznets further established that the industrial and service sectors exhibit higher labor absorption capacity and productivity growth compared to agriculture [35]. These insights have profound implications for understanding how ecotourism development influences broader economic restructuring.

In Hainan, where ecotourism resources are predominantly located in rural areas, ecotourism development can catalyze industrial transformation through several channels. First, ecotourism directly expands the tertiary sector by increasing demand for accommodation, food services, transportation, and recreational activities [13]. Hotels, restaurants, tour operators, and transportation providers constitute the core tourism services sector, generating employment and income directly linked to visitor expenditures. Second, it stimulates secondary sector development through agricultural product processing, handicraft production, and construction activities [36]. Tourism demand for local specialty products incentivizes value-added processing of agricultural outputs, while destination development requires construction of tourism facilities and infrastructure. Third, it facilitates labor migration from low-productivity agriculture to higher-value tourism-related activities [37]. Rural residents who previously engaged in subsistence farming can transition to service sector employment with higher wages and more stable income streams.

The transformation pathway operates through both demand-side and supply-side mechanisms. On the demand side, tourist arrivals create markets for goods and services that did not previously exist at sufficient scale to warrant commercial provision. Local entrepreneurs respond to these market opportunities by establishing businesses that cater

to visitor needs, creating employment and generating tax revenues. On the supply side, tourism development improves productive capacity through investment in physical infrastructure, human capital development, and institutional modernization. Transportation networks, telecommunications systems, and utilities developed to serve tourists benefit local residents and enable non-tourism economic activities. Hainan's historically high dependence on primary industries, combined with underdeveloped secondary industries, has created an imbalanced industrial structure [10]. Agriculture, forestry, and fisheries have traditionally dominated the provincial economy, with limited manufacturing capacity and relatively modest service sector development. This structural imbalance constrains economic growth potential and limits employment opportunities for the island's growing population. Integrating rural and agricultural advantages with ecotourism offers a pathway to transform unique agricultural resources into diversified industrial outputs, extending value chains and fostering green, low-carbon service industries [38]. Tropical fruits, specialty crops, and marine products can be incorporated into tourism experiences through farm visits, agricultural festivals, and culinary tourism, adding value while maintaining connections to Hainan's natural and cultural heritage.

3.2. Industrial Clustering Pathway

Industrial cluster theory posits that geographically concentrated enterprises within specific fields can form interconnected systems through shared resources and complementary capabilities [39,40]. The clustering phenomenon has been observed across diverse industries from manufacturing to services, and tourism destinations frequently exhibit cluster characteristics as related enterprises co-locate to serve visitor demand. Marshall's externality theory suggests that clustering enhances resource utilization and economic output through three mechanisms: labor pooling enables enterprises to draw from shared skilled labor markets; specialized suppliers emerge to serve cluster members efficiently; and knowledge spillovers occur as workers move between firms and ideas spread through informal interactions [39].

Applied to ecotourism, core ecological resources serve as attraction nodes that generate demand and supply chains, drawing related enterprises into regional ecosystems [41]. A pristine beach, national park, or unique ecosystem attracts visitors who require accommodation, food, transportation, and entertainment services. As visitor volumes increase, specialized suppliers emerge to serve tourism enterprises, and a complete destination ecosystem develops around the core ecological attraction. Ecotourism clusters amplify economic effects by integrating downstream industries (hospitality, catering, retail) and horizontally related industries (entertainment, cultural services, health tourism), forming regional tourism hubs anchored by ecological resources [9]. The cluster structure creates multiplier effects as visitor spending circulates among interconnected enterprises before leaking out of the regional economy. However, achieving sustainable ecotourism clusters requires coordinated planning to avoid homogeneity and disorderly expansion [8]. Without strategic guidance, cluster development may result in excessive competition, environmental degradation, and destination decline. In Hainan, abundant coastal and tropical rainforest resources provide foundations for developing ecotourism clusters. Leveraging these resources to create integrated, sustainable tourism systems can yield scale advantages, enhance planning effectiveness, and ensure long-term ecological and economic sustainability [42].

3.3. Urban–Rural Coordination Pathway

Figure 1 illustrates the internal mechanism of ecotourism–economic coupling coordination, highlighting how the ecotourism system—integrating ecological and tourism

subsystems—drives industrial clustering, sectoral transformation, and urban–rural coordination, thereby facilitating coordinated regional economic development. Economic agglomeration effects generated by ecotourism development often promote urbanization, as tourism-related activities attract economic resources to specific regions [37]. Beyond enhancing resource efficiency, ecotourism transforms traditional subsistence agriculture into higher-value economic activities, increasing rural incomes while promoting ecological conservation [36]. Ecotourism also drives improvements in urban and rural infrastructure, narrowing development gaps and fostering urban–rural integration [15]. Transportation networks, telecommunications, and public services developed to support tourism benefit local residents and enable further economic diversification [12]. However, rapid urbanization and increased tourist activity can strain ecological systems and challenge environmental carrying capacity [43]. Balancing these pressures requires robust governance to manage ecological resources effectively while ensuring tourism-driven urbanization delivers equitable and sustainable benefits [19].

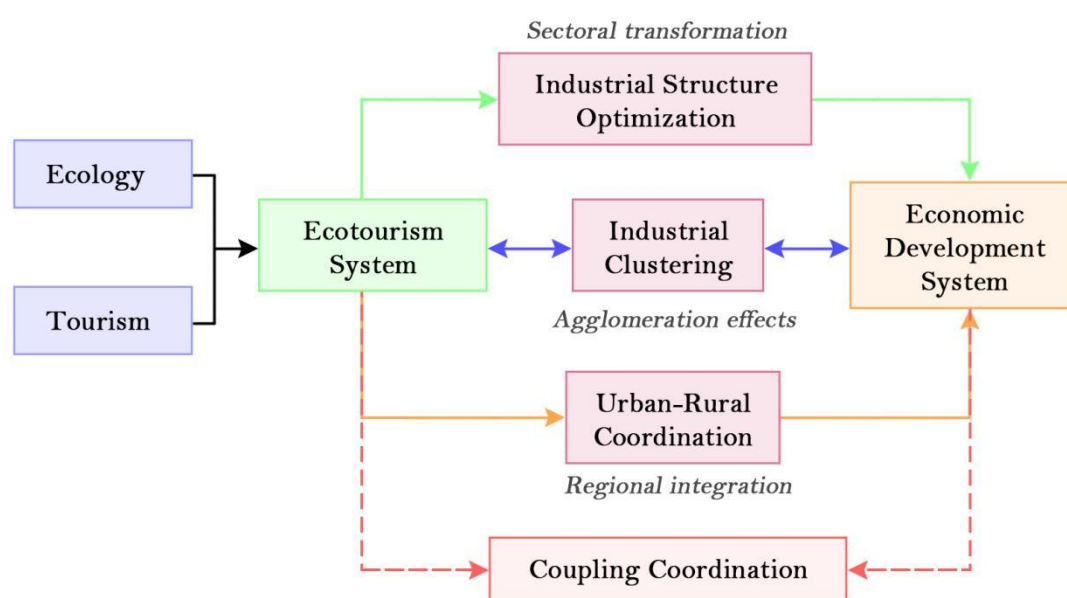


Figure 1. Internal mechanism model of ecotourism–economic coupling coordination. Note: Solid arrows indicate the primary transmission pathways and direct effects among subsystems, while dashed arrows represent feedback and coupling coordination mechanisms.

4. Methodology and Data

4.1. Indicator System Construction

Rational indicator selection is crucial for analyzing eco-tourism–economic coupling coordination. Following principles of systematicity, scientific rigor, and data availability [32], we construct a comprehensive evaluation system comprising 18 indicators across two subsystems. For the eco-tourism development subsystem, we include ecological indicators (ambient air quality, water quality compliance, energy consumption per unit of GDP, total energy consumption) and tourism indicators (tourist arrivals, accommodation and catering value-added, tourism revenue, tourist attractions, and tourist hotels). For the economic development subsystem, we include output indicators (gross regional product, industrial structure proportions), trade indicators (goods imports and exports, services imports and exports), investment indicators (fixed asset investment growth), and welfare indicators (household disposable income and consumption expenditure). Incorporating external trade indicators reflects Hainan’s unique position as a free trade port with a grow-

ing duty-free shopping influence [9]. Fixed asset investment captures infrastructure development critical to both tourism facilities and ecological protection [10]. In constructing the indicator system, careful attention was given to the directional attributes of each variable to ensure consistency with sustainability evaluation principles. Indicators that reflect ecological pressure or resource inefficiency were treated as negative indicators, while those representing ecological improvement or development capacity were treated as positive indicators.

Specifically, total energy consumption and energy consumption per unit of GDP were classified as negative indicators, as higher values indicate increased environmental pressure and lower ecological efficiency rather than improved sustainability performance. This directional assignment is consistent with established practices in ecological efficiency and sustainable development assessment and ensures that the composite index accurately reflects the eco-tourism development conditions of Hainan Province. The indicator properties and weights are reported in Table 1. Here, the eco-tourism development subsystem is intended to capture the structural and environmental conditions that support eco-tourism development, rather than to imply that all tourism activities measured are inherently ecological. While the indicator system emphasizes ecological and tourism-related dimensions, the selection of specific indicators is guided by principles of data continuity, comparability, and policy relevance at the provincial level. Direct measures such as biodiversity indices, land-use pressure, or tourism-related carbon emissions were considered but ultimately excluded due to inconsistent temporal coverage, limited comparability across years, or the absence of standardized tourism-specific accounting at the provincial scale. Instead, environmental quality indicators (e.g., air and water quality) and energy-efficiency measures are employed as second-best proxies that capture ecological pressure and sustainability constraints associated with tourism and economic activities.

Table 1. Indicator system for ecotourism and economic development evaluation.

Subsystem	Indicator	Unit	Property	Entropy	Weight (%)
Ecotourism	Ambient air quality excellent rate	%	+	0.898	5.987
	Urban water quality compliance rate	%	+	0.918	4.831
	Energy consumption per unit GDP	Degree	+	0.758	14.235
	Total energy consumption	Tons std. coal	−	0.913	5.116
	Total tourists received	10,000 persons	−	0.843	9.219
	Accommodation & catering value-added	Billion yuan	+	0.745	15.036
	Tourism revenue	Billion yuan	+	0.749	14.795
	Tourist attractions	Number	+	0.717	16.631
	Total tourist hotels	Number	+	0.760	14.151
	Gross regional product	Billion yuan	+	0.833	9.758
Economic Development	Primary industry proportion	%	+	0.873	7.405
	Secondary industry proportion	%	+	0.643	20.826
	Tertiary industry proportion	%	+	0.903	5.662
	Total goods imports & exports	100 million yuan	+	0.749	14.653

Total services imports & exports	Billion yuan	+	0.758	14.137
Fixed asset investment growth	%	+	0.848	8.853
Household disposable income	Yuan/person	+	0.864	7.913
Household consumption expenditure	Yuan/person	+	0.815	10.792

Note: “+” indicates a positive indicator, where a higher value reflects better system performance; “−” indicates a negative indicator, where a higher value reflects poorer system performance.

This approach aligns with existing empirical studies that operationalize eco-tourism development through observable environmental and efficiency-based indicators when direct ecological metrics are unavailable. It should be emphasized that the indicator system intentionally combines scale-based and efficiency-based variables. Indicators such as tourism revenue and tourist arrivals capture the development capacity and economic scale supporting eco-tourism, whereas indicators such as energy consumption per unit of GDP and total energy consumption reflect resource-use efficiency and ecological pressure. The coupling coordination degree derived from this system, therefore, does not measure sustainable performance in an absolute sense, but rather the degree of alignment between expansion dynamics and efficiency constraints. A higher CCD indicates more synchronized development between scale and efficiency dimensions, not necessarily a lower environmental footprint.

4.2. Data Sources

All indicators are annual series for 2017–2023. Data were collected primarily from the Hainan Statistical Yearbook and the official website of Hainan’s Department of Tourism, Culture, Radio, Television, and Sports. To ensure cross-year comparability, we followed the original statistical definitions reported by these sources and maintained consistent measurement units across the sample period. When sporadic values were missing for individual indicators and years, we applied linear interpolation only for short gaps, and the interpolated values were used solely to preserve the continuity required by the index construction and coupling coordination calculation [12]. The study period spans from 2017 to 2023, corresponding to the accelerated policy implementation phase of the Hainan Free Trade Port. All data were obtained from officially published statistical yearbooks and government reports. For a limited number of indicators with missing observations, each involving no more than one year, linear interpolation was applied to ensure data continuity. Given the relatively short time series, the potential influence of interpolation on coupling coordination degree (CCD) and gray relational analysis (GRA) results is acknowledged and addressed through robustness discussion. To enhance transparency and reproducibility, detailed indicator definitions, measurement units, precise data sources, attribute classifications, and missing data treatment are reported in Appendixes A and B.

4.3. Research Methods

Software. All calculations (including min–max normalization, entropy weights, coupling coordination degree, and gray relational analysis) were performed in Python (available at <https://www.python.org/>, accessed on 23 January 2026).

4.3.1. Entropy Weight Method

The entropy weight method provides objective indicator weights based on information entropy theory [44,45]. For an indicator, smaller entropy values indicate greater dispersion and thus larger influence on comprehensive evaluation [36].

First, data are standardized using min–max normalization:

$$X_{ij} = \frac{X_{ij} - X_{\min}}{X_{\max} - X_{\min}} \quad (\text{positive indicators}) \quad (1)$$

$$X_{ij} = \frac{X_{\max} - X_{ij}}{X_{\max} - X_{\min}} \quad (\text{negative indicators}) \quad (2)$$

Second, the proportion of indicator i in sample j is calculated:

$$L_{ij} = \frac{X_{ij}}{\sum_j X_{ij}} \quad (3)$$

Third, the entropy value is computed:

$$H_i = - \frac{\sum_j (L_{ij} \times \ln L_{ij})}{\ln n} \quad (4)$$

Fourth, information weight is derived:

$$W_j = \frac{1 - H_i}{\sum_i (1 - H_i)} \quad (5)$$

Finally, comprehensive scores are calculated:

$$S = \sum_{j=1}^n W_j X_{ij} \quad (6)$$

Although the entropy weight method is widely used for its data-driven properties, it should be noted that it assigns greater weights to indicators with higher dispersion. In short time series, this mechanism may amplify the influence of volatile variables or external shocks. Accordingly, entropy weights in this study are interpreted as indicative measures of relative informational contribution rather than as objective representations of structural importance.

Where x_{ij} denotes the value of indicator j for sample i , p_{ij} represents the proportion of indicator j , e_i is the entropy value, w_j is the entropy weight, and S_i denotes the comprehensive evaluation score.

4.3.2. Coupling Coordination Degree Model

The coupling coordination degree model measures the harmonious interaction between systems [22]. Coupling degree captures interaction intensity, while coordination degree reflects balanced development levels.

Coupling degree is calculated as:

$$C = \frac{2\sqrt{T_1 \times T_2}}{T_1 + T_2} \quad (7)$$

where T_1 and T_2 represent comprehensive evaluation values of the ecotourism and economic systems, respectively.

The coordination index is:

$$T = \alpha T_1 + \beta T_2 \quad (8)$$

where α and β are typically set to 0.5, indicating equal system contributions [12].

The coupling coordination degree is:

$$D = \sqrt{C \times T} \quad (9)$$

Following established practice [13,16], we classify coupling coordination levels using a ten-interval scheme from extreme disorder (0.0–0.1) to quality coordination (0.9–1.0), as detailed in Table 2.

Table 2. Classification standards for coupling coordination degree.

Coupling Coordination Degree	Level	Type
0.0–0.1	1	Extreme disorder
0.1–0.2	2	Severe misalignment
0.2–0.3	3	Moderate dysregulation
0.3–0.4	4	Mild disorder
0.4–0.5	5	Borderline dysregulation
0.5–0.6	6	Barely coordinated
0.6–0.7	7	Primary coordination
0.7–0.8	8	Intermediate coordination
0.8–0.9	9	Good coordination
0.9–1.0	10	Quality coordination

4.3.3. Gray Relational Analysis

Gray Relational Analysis (GRA) is employed as a supplementary method to validate findings and identify key influencing factors [33]. GRA measures similarity between data series, proving particularly effective for limited samples [46].

The gray relational coefficient between reference sequence X_0 and comparative sequence X_i at point k is:

$$\xi_s(k) = \frac{\min_i \min_k |X_0(k) - X_i(k)| + \rho \max_i \max_k |X_0(k) - X_i(k)|}{|X_0(k) - X_i(k)| + \rho \max_i \max_k |X_0(k) - X_i(k)|} \quad (10)$$

where ρ is the distinguishing coefficient, typically set to 0.5 [33]. The gray relational grade is:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^n \xi_i(k) \quad (11)$$

In this study, the reference sequence in the gray relational analysis is defined as the coupling coordination degree (D), which represents the overall coordination level between the eco-tourism development subsystem and the economic development subsystem. All comparative indicator sequences were standardized prior to gray relational analysis using the same normalization procedures described in Section 4.3.1 to ensure dimensional consistency and comparability. The distinguishing coefficient ρ was set to 0.5 throughout the analysis, following conventional practice in gray system theory, to balance sensitivity and stability of the relational coefficients. Higher relational grades indicate stronger associations between the reference and comparative sequences. (As shown in Table A3).

5. Empirical Results

5.1. Comprehensive Evaluation Analysis

From 2017 to 2023, both the ecotourism and economic development systems of Hainan Free Trade Port exhibited overall improvement with notable fluctuations (Table 3 and Figure 2).

The ecotourism comprehensive evaluation index increased from 0.239 in 2017 to 0.719 in 2023, indicating sustained improvement alongside two notable downturns in 2020 and 2022, which are consistent with shock-induced disruptions to mobility and tourism operations. The subsequent rebounds suggest a relatively strong recovery capacity, but they also confirm that tourism-related performance is more volatile than the economic subsystem. Overall, these fluctuations imply that maintaining coordination requires resil-

ience-oriented arrangements in tourism supply, market structure, and supporting services, rather than relying on trend growth alone. The economic development index showed more stable progression, increasing from 0.370 in 2017 to 0.610 in 2023. The lowest point in 2018 (0.278) reflects pressures from real estate market regulation, as Hainan's economy historically depended heavily on property development [10].

Table 3. Comprehensive evaluation scores (2017–2023).

Year	Ecotourism (T1)	Economic Development (T2)	Comparison	Gap
2017	0.239	0.370	T1 < T2	0.131
2018	0.432	0.278	T1 > T2	0.154
2019	0.497	0.304	T1 > T2	0.193
2020	0.361	0.317	T1 > T2	0.044
2021	0.718	0.465	T1 > T2	0.253
2022	0.462	0.587	T1 < T2	0.125
2023	0.719	0.610	T1 > T2	0.109

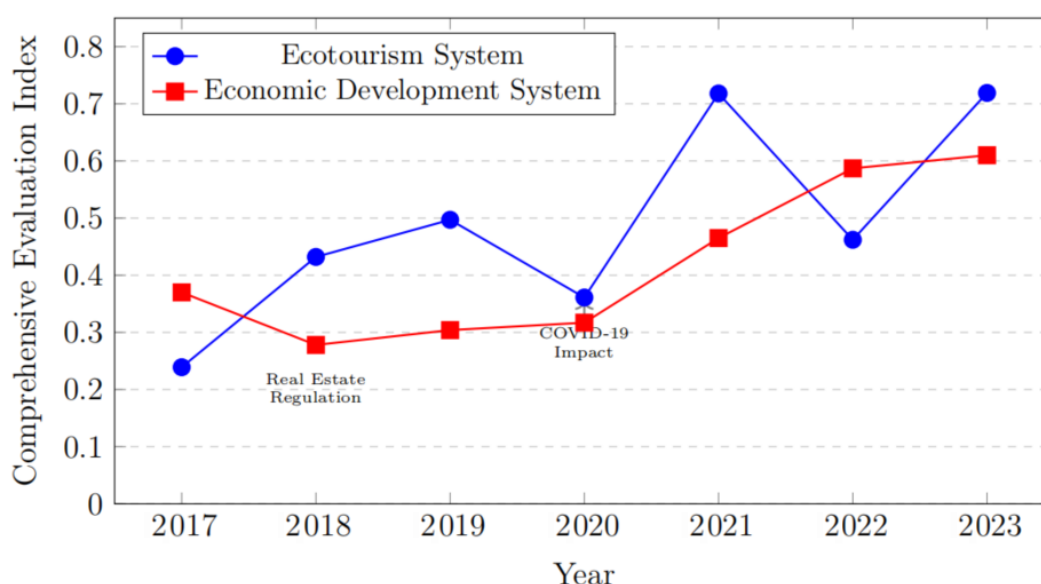


Figure 2. Trends in ecotourism and economic development comprehensive evaluation (2017–2023).

The central government's decision to restrict property speculation in Hainan, while disruptive in the short term, created space for healthier economic development by reducing distortions associated with real estate bubbles. The subsequent recovery, particularly after the 2020 Free Trade Port Master Plan release, demonstrates successful economic restructuring toward the four priority industries: tourism, modern services, high-tech, and tropical agriculture [42]. This restructuring represents a fundamental shift in Hainan's development model, moving away from resource extraction and property speculation toward sustainable, innovation-driven growth. Analysis of indicator weights reveals important insights into the relative importance of different factors in determining subsystem performance. In the ecotourism subsystem, tourist attractions (16.63%), accommodation and catering value-added (15.04%), and tourism revenue (14.80%) carry the highest weights, emphasizing the importance of tourism infrastructure and economic output. These supply-side indicators reflect the capacity of the tourism sector to accommodate and serve visitors, generating economic returns. Energy consumption per GDP (14.24%) also features prominently, reflecting ecological efficiency concerns and the importance of

sustainable resource use in ecotourism development [38]. The relatively lower weights assigned to pure ecological indicators such as air and water quality rates suggest that while environmental quality provides the foundation for ecotourism, tourism development capacity more directly determines the subsystem's comprehensive performance.

In the economic development subsystem, the secondary industry proportion (20.83%) exhibits the highest weight, highlighting Hainan's industrial structure challenges. This exceptionally high weight indicates that manufacturing capacity is a critical constraint on economic development, and improvements in this dimension yield substantial gains in comprehensive evaluation scores. External trade indicators (goods 14.65%, services 14.14%) reflect the free trade port's orientation toward international economic integration, capturing Hainan's growing role in global trade networks. Household consumption expenditure (10.79%) captures domestic demand dynamics, reflecting the importance of local consumption in driving economic activity [9]. The combination of trade and consumption indicators suggests that both external openness and internal demand contribute to economic development performance.

5.2. Coupling Coordination Analysis

Table 4 presents the coupling coordination degree results, revealing a clear progression from moderate dysregulation toward quality coordination.

Table 4. Coupling coordination degree of ecotourism and economic development.

Year	Eco-Tourism Subsystem Index (T ₁)	Economic Development Subsystem Index (T ₂)	Coupling Degree (C)	Coordination Index (T)	Coupling Coordination Degree (D)	Coordination Level
2017	0.239	0.370	0.364	0.146	0.230	Moderate dysregulation
2018	0.432	0.278	0.307	0.207	0.252	Moderate dysregulation
2019	0.497	0.304	0.686	0.311	0.462	Borderline dysregulation
2020	0.361	0.317	0.937	0.191	0.424	Borderline dysregulation
2021	0.718	0.465	0.961	0.775	0.863	Good coordination
2022	0.462	0.587	0.944	0.692	0.809	Good coordination
2023	0.719	0.610	1.000	0.990	0.995	Quality coordination

Note: T₁ represents the composite index of the eco-tourism development subsystem; T₂ represents the composite index of the economic development subsystem; C denotes the coupling degree; T denotes the coordination index; D denotes the coupling coordination degree. Coordination levels follow the classification standards in Table 2.

The coupling degree (C) increased from 0.364 in 2017 to 1.000 in 2023, indicating strengthening interaction between the two systems. In 2017–2018, the coupling degree remained below 0.5, suggesting weak system correlation. From 2019 onward, the systems exhibited progressively stronger interactive dynamics, reaching near-perfect coupling by 2023 [22].

The coupling coordination degree (D) progressed through distinct phases:

- 2017–2018: Moderate dysregulation (Level 3), with D values of 0.230 and 0.252
- 2019–2020: Borderline dysregulation (Level 5), with D values of 0.462 and 0.424
- 2021–2022: Good coordination (Level 9), with D values of 0.863 and 0.809
- 2023: Quality coordination (Level 10), with D value of 0.995

This trajectory demonstrates that free trade port policies have substantially improved ecotourism–economic coordination [10,42]. The national strategic positioning, which scientifically integrates ecological province principles with international tourism consumption center objectives, has created synergies between the subsystems [11]. However, the

results also reveal vulnerabilities. The 2020 decline in coordination (from 0.462 to 0.424) despite high coupling (0.937) illustrates how external shocks can disrupt balanced development even when systems are strongly interconnected [47]. Similarly, 2022 saw reduced coordination despite maintained coupling, highlighting the ecotourism system's sensitivity to pandemic-related disruptions [32].

5.3. Gray Relational Analysis Results

Gray Relational Analysis provides supplementary validation of the coupling coordination findings. Using the coupling coordination degree as the reference sequence and individual indicators as comparative sequences, we calculated gray relational grades to identify factors most strongly associated with coordination outcomes, as presented in Table 5.

Table 5. Gray relational grades between indicators and coupling coordination degree.

Ecotourism Indicators	Grade	Economic Indicators	Grade
Tourist attractions	0.847	Secondary industry proportion	0.891
Tourism revenue	0.823	Goods imports/exports	0.856
Accommodation value-added	0.815	Services imports/exports	0.834
Tourist hotels	0.789	Household consumption	0.812
Total tourists	0.756	Gross regional product	0.798
Energy per GDP	0.734	Fixed asset investment	0.776
Air quality rate	0.698	Household income	0.754
Water quality rate	0.687	Tertiary industry proportion	0.723
Total energy consumption	0.654	Primary industry proportion	0.689

Among economic indicators, the secondary industry proportion exhibits the highest gray relational grade (0.891), corroborating the entropy weight analysis and emphasizing industrial structure optimization as crucial for coordination [35]. External trade indicators (goods 0.856, services 0.834) also show strong associations [9]. In the ecotourism subsystem, tourist attractions (0.847) and tourism revenue (0.823) demonstrate the strongest relationships with coordination, highlighting the centrality of tourism infrastructure and economic output. Ecological indicators show moderate associations, suggesting that while environmental quality matters, tourism development capacity more directly influences coordination outcomes [13].

The GRA results reinforce the mechanism analysis presented in Section 3. Industrial structure optimization (represented by secondary industry proportion) emerges as the most influential pathway, followed by trade openness indicators reflecting clustering and integration effects [40]. More importantly, the Gray Relational Analysis provides a diagnostic complement to the coupling coordination results by clarifying which indicators drive coordination convergence. While the CCD captures the overall alignment between eco-tourism development and economic development, GRA decomposes this alignment into indicator-level associations. The strong relational grades of secondary industry proportion, external trade indicators, and tourism infrastructure variables indicate that the observed rise in coordination is primarily driven by structural and capacity-related factors rather than uniform improvements across all dimensions. At the same time, the comparatively lower relational grades of ecological quality indicators suggest that high coordination scores do not necessarily imply equivalent ecological advancement, thereby qualifying the interpretation of CCD outcomes and underscoring the importance of cautious sustainability assessment.

5.4. Robustness and Sensitivity Analysis

To assess the robustness of the coupling coordination degree (CCD) results, several sensitivity analyses were conducted. First, the weighting parameters in the coordination index were adjusted from the baseline setting of $\alpha = 0.5$ and $\beta = 0.5$ to an alternative specification of $\alpha = 0.6$ and $\beta = 0.4$, assigning greater weight to the eco-tourism development subsystem. The resulting CCD values exhibit similar temporal evolution patterns and coordination classifications, indicating that the main findings are not sensitive to reasonable changes in subsystem weighting. Second, an alternative normalization approach based on z-score standardization was applied to replace the min–max normalization used in the baseline analysis. The CCD trends derived from z-score normalization remain broadly consistent with the baseline results, with no substantive changes in coordination level classification. Third, a leave-one-indicator-out test was performed for both the eco-tourism development subsystem (T1) and the economic development subsystem (T2). Each indicator was sequentially excluded, and CCD values were recalculated. The overall coordination patterns remained stable across these tests, suggesting that the results are not driven by any single indicator. Taken together, these robustness checks confirm the stability and reliability of the CCD findings.

6. Discussion and Policy Recommendations

6.1. Discussion of Findings

The results indicate a clear improvement in ecotourism–economy coordination in Hainan over 2017–2023, with the coordination trajectory moving from dysregulation toward high-level coordination. Importantly, this improvement coincides with a period of intensified institutional arrangements that emphasize both ecological constraints and tourism-oriented economic upgrading. Rather than implying a strict causal effect, our evidence suggests that coordination can rise when (1) tourism-related productive capacity expands, (2) structural upgrading enhances value creation and absorption, and (3) connectivity and clustering mechanisms strengthen linkages between tourism and the wider economy. This interpretation is consistent with the mechanism framework proposed in Section 3; the gray relational analysis further reveals the relative importance of different indicators in shaping the coordination between eco-tourism development and economic growth. Indicators related to tourism infrastructure and service capacity exhibit the highest relational grades, highlighting the role of physical and service foundations in supporting coordinated development. Indicators associated with the economic structure and openness, such as industrial composition and trade-related variables, constitute the second tier and reflect the influence of structural transformation under the free trade port framework. Environmental constraint indicators, while exhibiting comparatively lower relational grades, remain essential baseline conditions that enable sustainable coordination. Together, these results align with the three analytical pathways emphasized in this study, namely infrastructure support, structural upgrading, and institutional openness, providing additional evidence for the mechanism interpretation of the coordination process.

It is important to clarify that the observed improvement in coupling coordination should not be interpreted as direct causal evidence of specific free trade port policy interventions. The analytical framework employed in this study is designed to identify coordination patterns and structural alignment between eco-tourism development and economic growth, rather than to isolate policy treatment effects. While the timing of improved coordination coincides with intensified institutional reforms under the free trade port framework, such temporal co-movement reflects contextual association rather than empirical identification. Accordingly, references to policy influence in this study should

be understood as an interpretive context rather than a causal attribution. Establishing causal effects of individual policy instruments would require counterfactual designs or quasi-experimental methods, which lie beyond the scope of the present analysis. Accordingly, improvements in the degree of coupling coordination should be interpreted as enhanced alignment between tourism–economic expansion and ecological efficiency constraints, rather than as evidence of inherently sustainable outcomes. Rapid expansion accompanied by deteriorating efficiency would not generate high coordination values, just as efficiency improvements without development capacity would not produce coordinated growth. This interpretation avoids conflating scale expansion with sustainability performance. The emergence of coupling coordination degree values approaching unity in the later period (e.g., 0.995 in 2023) warrants careful interpretation. In composite index systems, particularly those based on normalization and aggregation, high coordination scores may partially reflect mechanical effects arising from converging subsystem trajectories rather than perfect real-world harmony. In the context of Hainan Free Trade Port, these elevated CCD values should therefore be understood as indicating a high degree of alignment between eco-tourism development and economic growth trends within the observation window, rather than the resolution of underlying ecological trade-offs or the attainment of an optimal sustainability state. While higher levels of coupling coordination generally indicate improved alignment between eco-tourism development and economic growth, such coordination should not be interpreted as unconditionally desirable. Excessive reliance on tourism-oriented coordination may amplify systemic risks by increasing exposure to demand shocks, external disruptions, or global crises, as evidenced during the COVID-19 pandemic. Moreover, strong coordination trajectories can generate structural lock-in effects, whereby regions become overly specialized in tourism-related activities at the expense of economic diversification and adaptive flexibility. In this context, high coupling may reinforce path dependence and reduce long-term resilience, underscoring the importance of maintaining balance, diversity, and institutional adaptability in coordinated development strategies.

Second, the vulnerability of the ecotourism system to external shocks, evident in the 2020 and 2022 fluctuations, highlights the need for resilience-building measures [21]. Tourism’s sensitivity to public health crises, climate events, and policy changes requires diversification strategies and adaptive management approaches [48,49]. The COVID-19 pandemic provided a stark demonstration of tourism’s vulnerability, with Hainan experiencing sharp declines in visitor arrivals, tourism revenue, and accommodation occupancy rates. While recovery was relatively rapid following the relaxation of mobility restrictions, this episode underscores the importance of building adaptive capacity and diversifying regional economic structures. Economic diversification can reduce overdependence on tourism revenues and limit the cascading effects of external shocks, while product diversification within the tourism sector can mitigate seasonality and stabilize income streams. Institutional capacity for crisis management, including emergency response mechanisms and coordinated communication strategies, also plays a critical role in enhancing resilience. At the same time, the study period (2017–2023) encompasses both accelerated policy implementation and an exogenous systemic shock caused by the COVID-19 pandemic, which introduces volatility into entropy weights and coupling coordination indices, particularly during 2020–2021. Consequently, observed coordination changes during this period should be interpreted as short-term adjustment responses rather than long-run structural equilibrium shifts.

Although robustness checks suggest general stability in coordination patterns, the relatively short time series may amplify the influence of exceptional events, underscoring the need for cautious interpretation. Investment in digital infrastructure and contactless service delivery capabilities can maintain some tourism activity even during periods

when physical mobility is constrained. It should also be noted that the analysis adopts a province-level perspective, which may mask important intra-provincial heterogeneity within Hainan. Coastal areas and major urban centers such as Haikou and Sanya benefit from more developed tourism infrastructure, higher service capacity, and stronger integration into global markets, while inland and ecologically sensitive areas face different development constraints and environmental pressures. As a result, coordination dynamics may vary substantially across coastal, urban, and interior regions. The province-level results therefore reflect aggregate coordination trends rather than uniform spatial outcomes. Future research could incorporate sub-regional or spatially explicit analyses to better capture these intra-provincial variations and their implications for differentiated policy design.

Third, the persistent gap between ecotourism and economic subsystem development suggests incomplete transformation of ecological advantages into economic drivers [11]. Despite Hainan's abundant natural resources and policy support, the economic subsystem consistently lags, indicating structural constraints in translating tourism growth into broader economic prosperity. This finding is consistent with broader patterns observed in resource-rich regions where natural capital does not automatically translate into sustained economic development. The challenge lies in developing institutional frameworks and human capital that enable value capture and retention within the local economy. Several factors may explain this incomplete transformation. First, significant economic leakage may occur if tourism enterprises are externally owned or depend heavily on imported inputs. Second, limited linkages between tourism and other sectors may constrain multiplier effects. Third, human capital constraints may limit the capacity of local residents to participate in high-value tourism activities. Fourth, infrastructure bottlenecks may prevent the full realization of tourism potential. Addressing these constraints requires integrated strategies that strengthen local ownership, develop supply chain linkages, invest in education and training, and continue infrastructure development.

Fourth, the prominence of secondary industry proportion in both entropy weights and gray relational analysis underscores Hainan's industrial structure challenges [10]. Historical over-reliance on real estate and primary industries has created an unbalanced economy requiring sustained restructuring efforts [42]. The exceptionally high weight of the secondary industry proportion (20.83%) in the economic development index reflects Hainan's manufacturing deficit relative to national averages. While some regions have achieved sustainable development through service-dominated economies, most successful cases involve significant manufacturing or high-technology sectors that anchor economic stability and provide high-productivity employment. Hainan's path forward may involve developing niche manufacturing capabilities aligned with its comparative advantages, such as marine biotechnology, tropical agricultural processing, and renewable energy equipment.

6.2. Empirical Interpretation of Mechanism Pathways

While the proposed mechanisms of industrial upgrading, industrial clustering, and urban–rural linkage are not tested through formal mediation models, the empirical analysis provides indirect but informative evidence through proxy indicators and relational patterns. Specifically, industrial upgrading is empirically reflected by the high entropy weight and strongest gray relational grade of the secondary industry proportion, indicating its central role in driving coordination between eco-tourism development and economic growth. Industrial clustering and openness mechanisms are proxies for external trade indicators, including goods and services imports and exports, which consistently exhibit strong gray relational associations with the coupling coordination degree. This

suggests that integration into broader production and service networks enhances coordination by reinforcing tourism-related supply chains and service agglomeration effects. Urban–rural linkage mechanisms are indirectly captured through tourism infrastructure and consumption indicators, such as tourist attractions, accommodation and catering value-added, and household consumption expenditure. Their relatively high relational grades imply that tourism expansion facilitates factor mobility and income circulation between urban service centers and surrounding rural areas, thereby contributing to coordinated development. These proxy-based interpretations do not imply causal mediation but offer empirically grounded support for the proposed mechanism pathways, aligning theoretical arguments with observable coordination dynamics

6.3. Policy Recommendations

To enhance the policy relevance and analytical grounding of the findings, the following recommendations are explicitly derived from the empirical results of the entropy weight analysis, coupling coordination degree model, and gray relational analysis. Indicators exhibiting high entropy weights and strong gray relational grades are interpreted as high-impact leverage points for improving coordination between eco-tourism development and economic growth. Accordingly, policy priorities are aligned with those dimensions that empirically contribute most strongly to observed coordination outcomes. Based on our findings and mechanism analysis, we offer five policy recommendations for enhancing ecotourism–economic coordination in Hainan Free Trade Port.

6.3.1. Prioritize Ecological Efficiency

Ecological priority should remain fundamental to free trade port development, with ecological efficiency at the forefront of all planning decisions [8]. This recommendation reflects the recognition that Hainan’s competitive advantage derives fundamentally from its natural environment, and any development that degrades environmental quality ultimately undermines the foundation of sustainable prosperity. Drawing on Singapore’s experience, Hainan should implement rigorous pre-construction environmental assessment, rejecting projects that fail to meet ecological standards [50]. Singapore’s success in maintaining environmental quality while achieving high levels of economic development demonstrates that ecological protection and economic growth are not inherently contradictory when appropriate governance frameworks are in place. A tourism eco-efficiency evaluation mechanism should scientifically measure environmental performance at micro (routes, products, enterprises) and macro (industry-wide) levels, monitoring resource consumption and carbon emissions [51]. This mechanism would enable identification of best practices that can be disseminated across the tourism sector, as well as detection of underperforming operations requiring improvement. Performance benchmarking, combined with appropriate incentives for high performers and sanctions for poor performers, can drive continuous improvement in ecological efficiency across Hainan’s tourism industry.

6.3.2. Promote Tourism-Plus Industrial Integration

Leveraging comparative advantages through “tourism plus” strategies can optimize industrial structure while enhancing coordination [12]. This integration approach creates value by combining tourism experiences with other economic activities, generating synergies that enhance both tourism attractiveness and broader economic development. First, ecotourism should drive agricultural transformation by integrating rural ecological and cultural resources with tourism development [36]. Agricultural tourism, farm-to-table dining experiences, and agricultural festivals can add value to primary production while creating authentic tourist experiences rooted in local traditions and landscapes. Second,

tourism should be integrated with Hainan's distinctive industries, including marine activities, health services, duty-free shopping, and education, promoting ecological industrialization and industrial ecology [9]. Marine tourism combining recreational activities with ocean conservation education can leverage Hainan's coastal and island resources. Health and wellness tourism drawing on traditional Chinese medicine and spa services can attract high-value visitors seeking holistic experiences. The duty-free shopping sector has experienced explosive growth since policy liberalization, creating important linkages with tourism that drive visitor arrivals and spending. Educational tourism, including study tours, academic conferences, and training programs, can diversify visitor segments and reduce seasonality. This recommendation is empirically supported by the high gray relational grades of tourism-related indicators, including tourist attractions, tourism revenue, and accommodation and catering value-added, which collectively indicate that tourism capacity expansion and service integration play a central role in enhancing coordination between eco-tourism development and economic growth.

6.3.3. Cultivate High-End Ecotourism Clusters

Focusing on premium coastal and tropical rainforest resources, Hainan should attract leading tourism operators and hospitality brands to develop flagship ecotourism projects [40]. The cluster development approach leverages agglomeration economies that emerge when related enterprises locate in geographic proximity, enabling knowledge sharing, labor pooling, and specialized supplier development. Creating ecotourism demonstration zones and clustered industry areas can generate scale advantages and brand effects [41]. Well-designed demonstration zones showcase best practices in sustainable tourism development, serving as models that can be replicated across the province and beyond. Increasing high-quality tourism supply will stimulate market demand, attracting clusters of related upstream, downstream, and horizontally linked enterprises. Upstream enterprises, including tour operators, transportation providers, and booking platforms, enable visitor access to destinations. Downstream enterprises, including restaurants, entertainment venues, and retail establishments, capture additional visitor spending. Horizontally linked enterprises in complementary sectors such as health services, cultural industries, and sports facilities diversify the destination offering and extend visitor stays. The clustering of these enterprises creates a comprehensive destination ecosystem that enhances competitiveness and visitor satisfaction. The importance of clustering-oriented policies is further reinforced by the strong gray relational associations observed for external trade indicators, including goods and services imports and exports. These results suggest that openness and integration into broader service and production networks enhance tourism-related agglomeration effects, thereby strengthening coordination outcomes. Policies promoting international service trade, medical tourism openness, and integrated logistics platforms can therefore serve as effective levers for reinforcing cluster-based development.

6.3.4. Develop Province-Wide Tourism Demonstration

Establishing Hainan as a holistic tourism demonstration province can promote urban–rural coordination through tourism development [15]. The province-wide tourism concept treats the entire island as an integrated destination, breaking down boundaries between urban tourism centers and rural tourism resources. This involves strengthening rural tourism infrastructure, tailoring development to local agricultural products and cultural characteristics, and creating “one village, one product” ecotourism patterns [37]. Each village or community can develop distinctive tourism products based on unique local resources, creating a diverse portfolio of experiences across the province. Encouraging

community-based ecotourism models that enable resident participation in planning, operation, and environmental monitoring can increase incomes while promoting coordinated development [26]. Community participation ensures that tourism development reflects local priorities and values, building social acceptance and long-term sustainability. When residents benefit directly from tourism, they have strong incentives to protect the natural and cultural resources that attract visitors. Participatory approaches also build local capacity for tourism management, reducing dependence on external operators and increasing local value capture.

6.3.5. Optimize Industrial Structure

The empirical results provide strong support for this priority, as the secondary industry proportion exhibits both the highest entropy weight and the strongest gray relational grade with the coupling coordination degree, indicating that industrial upgrading represents the most influential structural driver of coordination outcomes. Continuing industrial structure optimization is essential for sustained coordination [34]. The entropy weight analysis indicates that the secondary industry proportion most strongly influences Hainan's economic development index, reflecting the province's manufacturing deficit relative to national averages and the importance of balanced industrial development. Addressing premature deindustrialization requires breaking from traditional development paths, substantially increasing manufacturing value-added, reducing primary industry dependence, and developing producer services guided by a dual circulation strategy [10]. The industrial structure optimization strategy should focus on sectors aligned with Hainan's comparative advantages and ecological priorities. Marine biotechnology leverages the province's abundant marine resources and growing research capacity to develop high-value products, including pharmaceuticals, nutraceuticals, and biomaterials. Tropical agricultural processing adds value to primary agricultural outputs, including tropical fruits, coffee, and specialty crops, creating manufacturing employment while maintaining connections to the agricultural sector. Renewable energy equipment manufacturing takes advantage of Hainan's exceptional solar and wind resources, positioning the province as a hub for clean energy technology development. These sectors combine manufacturing value-added with sustainability orientation, supporting both economic and ecological objectives.

This strategic approach will form a distinctive free trade port industrial system enabling Hainan's integration into global value chains [9]. The free trade port framework provides preferential policies including reduced tariffs, simplified customs procedures, and tax incentives that can attract manufacturing investment in targeted sectors. By focusing on niches where ecological priorities and economic development align, Hainan can build a manufacturing base that complements rather than conflicts with its environmental protection mandate. At the same time, the relatively weaker empirical associations observed for ecological quality indicators highlight the need for targeted environmental safeguards to ensure that coordination improvements driven by industrial and tourism expansion do not undermine long-term ecological resilience.

6.4. Limitations and Future Research Directions

Regardless of the contributions, this study is confronted with a number of methodological limitations that must be recognized in order to allow the transparent interpretation of the findings as well as guide future studies. To begin with, the analytical model is based on observational time-series data and composite indices, which constrain causal inference. Relationship Coordination degree and gray relational analysis are not intended to realize causal effects of policy and directional relationships, but to reflect the trends of structural conformity and association among economic growth and eco-tourism development. Even

though the trends of coordination are being handled in the context of the free trade port policy, the interpretations are associative and not causative. Future studies may utilize a quasi-experimental type of study like a difference-in-differences, synthetic control or instrumental variable study of interventions that can be applied to better isolate the effects of individual policy interventions and overcome possible endogeneity between tourism development and economic performance. Second, there is a limitation that is associated with building the indicator system. The lack of data availability and consistency at the provincial level precludes the use of direct biodiversity indicators, land-use change indicators, and tourism-induced carbon emission indicators in this study.

Although ecological pressure and sustainability constraints can be well represented by environmental quality indicators and energy-efficiency measures, they do not represent the complexity of the ecosystem or ecological degradation over the long term. Further research is recommended in combining direct ecological measures to enhance knowledge of ecological impacts of eco-tourism on ecological systems as more coarse and standardized ecological data is produced. Third, even though the entropy weight approach offers a data-driven and transparent method of weighting indicators, the method can be biased to overweight more volatile indicators, at least with short samples. This feature can increase the effect of temporary changes or exogenous shocks on composite indices. Further studies might compare the results of entropy-based weights against equal weighting schemes or expert weighting schemes or a combination of both schemes to determine how strong the coordination results are and to minimize volatility sensitivity. Fourth, normalized composite indices and coupling coordination models can be subject to ceiling effects when the subsystem trajectories converge. The high value of coupling coordination that is measured in the later years of the study should be seen as an indication of relative alignment instead of an optimum or completely sustainable equilibrium.

Future studies may investigate other formulations, non-linear coordination schemes or dynamic coupling schemes to reduce mechanical convergence phenomena and enhance interpretive precision. Lastly, the study is rather time-limited (2017–2023), which makes it more vulnerable to fluctuations over time, especially when exogenous shocks like the COVID-19 pandemic are involved. Although the checks on robustness indicate overall stability in coordination patterns, the effects of exceptional events can be exaggerated by short time-series data on entropy weights and coordination indices. Further studies could be improved by extending the time window over which short-term responses to adjustment should be observed, applying a rolling-window analysis, or using dynamic modeling methods to distinguish between the short-term adjustment response and the long-term structural coordination tendency.

7. Conclusions

This study examined the coordination dynamics between eco-tourism development and economic development in the Hainan Free Trade Port using an integrated analytical framework that combines the entropy weight method, the coupling coordination degree (CCD) model, and Gray Relational Analysis (GRA). Rather than treating coordination indices as direct measures of sustainability or policy effectiveness, the study interprets coordination outcomes as indicators of structural alignment between tourism development capacity, economic organization, and ecological efficiency constraints within a context of institutional transformation. The empirical results reveal a clear transition from low-level coordination toward high-level alignment during the study period (2017–2023). This evolution reflects the concurrent expansion of tourism infrastructure and service capacity, gradual industrial structure upgrading, and increasing openness under the free trade port framework. At the same time, the analysis demonstrates that improvements in coordination should not be equated with unconditional sustainability or causal policy impacts.

High CCD values primarily indicate convergence in subsystem trajectories and improved systemic alignment, rather than the resolution of ecological trade-offs or the attainment of an optimal development state.

Methodologically, the study contributes by demonstrating the value of triangulating coordination analysis with diagnostic tools. While the CCD model captures overall interaction intensity and balance between subsystems, Gray Relational Analysis decomposes coordination outcomes into indicator-level associations. The GRA results show that coordination improvements are driven mainly by structural and capacity-related factors, such as secondary industry composition, trade openness, and tourism infrastructure, whereas ecological quality indicators play a necessary but more baseline role. This integrated approach enhances interpretive depth and provides a governance-oriented understanding of coordination dynamics, moving beyond purely descriptive applications of composite indices. From a policy perspective, the findings suggest that coordinated development in free trade port contexts depends less on uniform ecological improvement and more on the balanced interaction between development capacity, structural upgrading, and institutional openness. However, the results also caution against excessive reliance on tourism-led coordination, which may amplify vulnerability to external shocks and create structural lock-in. Sustainable coordination therefore requires not only alignment between subsystems but also economic diversification, institutional adaptability, and long-term ecological safeguards. Overall, this study offers a structured analytical framework for assessing eco-tourism–economy coordination under conditions of policy experimentation and structural transition. By emphasizing cautious interpretation, methodological transparency, and diagnostic integration, the research contributes to a more nuanced understanding of coordination as a relative and dynamic governance outcome rather than a deterministic indicator of sustainability. As free trade ports and tourism-oriented regions worldwide seek to reconcile openness, growth, and ecological responsibility, the analytical insights and interpretive principles developed in this study provide a useful reference for both academic research and policy evaluation.

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Appendix A

Table A1. Indicator Definitions and Data Sources.

Subsystem	Indicator	Definition	Unit	Data Source	Attribute
Eco-tourism development	Ambient air quality excellent rate	Proportion of days with air quality reaching national excellent standards	%	Hainan Statistical Yearbook (2017–2023)	+
Eco-tourism development	Urban water quality compliance rate	Proportion of monitored water bodies meeting quality standards	%	China Environmental Statistics Yearbook (2017–2023)	+
Eco-tourism development	Energy consumption per unit of GDP	Total energy consumption divided by gross regional product	Tons of standard coal / 10,000 yuan	China Energy Statistical Yearbook (2017–2023)	–
Eco-tourism development	Total energy consumption	Total annual energy consumption	Tons of standard coal	China Energy Statistical Yearbook (2017–2023)	–
Eco-tourism development	Total tourists received	Total number of domestic and international tourist arrivals	10,000 persons	Hainan Statistical Yearbook (2017–2023)	+
Eco-tourism development	Accommodation and catering value-added	Value added by the accommodation and catering industry	Billion yuan	Hainan Statistical Yearbook (2017–2023)	+
Eco-tourism development	Tourism revenue	Total tourism revenue	Billion yuan	Hainan Statistical Yearbook (2017–2023)	+
Eco-tourism development	Tourist attractions	Number of officially rated tourist attractions	Number	Hainan Statistical Yearbook (2017–2023)	+
Eco-tourism development	Tourist hotels	Number of star-rated hotels	Number	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Gross regional product	Total regional economic output	Billion yuan	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Primary industry proportion	Share of primary industry in GDP	%	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Secondary industry proportion	Share of secondary industry in GDP	%	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Tertiary industry proportion	Share of tertiary industry in GDP	%	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Total goods imports and exports	Total value of goods trade	100 million yuan	Hainan Statistical Yearbook (2017–2023)	+

Economic development	Total services imports and exports	Total value of services trade	Billion yuan	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Fixed asset investment growth	Annual growth rate of fixed asset investment	%	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Household disposable income	Per capita disposable income	Yuan/person	Hainan Statistical Yearbook (2017–2023)	+
Economic development	Household consumption expenditure	Per capita consumption expenditure	Yuan/person	Hainan Statistical Yearbook (2017–2023)	+

Note: “+” indicates a positive indicator, meaning that a higher value reflects better subsystem development performance; “−” indicates a negative indicator, meaning that a higher value reflects poorer subsystem development performance.

Appendix B

Table A2. Missing Data and Interpolation Treatment.

Subsystem	Indicator	Missing Year(s)	Number of Missing Points	Treatment Method
Eco-tourism development	Tourism revenue	2020	1	Linear interpolation
Eco-tourism development	Urban water quality compliance rate	2019	1	Linear interpolation
Economic development	Fixed asset investment growth	2018	1	Linear interpolation

Appendix C

Table A3. Normalized Indicator Matrix Used for Entropy Weight Calculation.

Year	AQ	WQ	EC/GDP	TEC	TR	ACV	TRV	TA	TH	GRP	PI	SI	TI	GIE	SIE	FAI	HDI	HCE
2017	0.42	0.51	0.68	0.73	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2018	0.45	0.56	0.64	0.71	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2019	0.48	0.59	0.61	0.69	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2020	0.46	0.55	0.65	0.72	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2021	0.52	0.61	0.58	0.67	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2022	0.56	0.65	0.55	0.63	...	...	...	...	...	...	...	...	...	...	...	...	...	...
2023	0.60	0.68	0.52	0.60	...	...	...	...	...	...	...	...	...	...	...	...	...	...

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