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Assessment and Suggestions on Sustainable Development of Regional Ecological Economy Based on Emergy Theory: A Case Study of Henan Province

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Abstract: A rapid development in regional economy is often accompanied by an increase in energy consumption and the intensification of environmental pollution, which brings great pressure to the social economy and the natural environment. In order to solve the integrated problem of economic, social, and natural factors, we propose an evaluation method for the sustainable development of the regional economy, based on emergy. By analyzing the statistical data of Henan's economic development from 2010 to 2018, an evaluation index system of regional eco-economic sustainable development was constructed based on four aspects: natural subsystem, economic subsystem, social subsystem, and sustainable development index. The index system was then used to measure and comprehensively evaluate the sustainable development of the ecological economy and the environmental friendliness of Henan Province. The assessment results showed that the emergy self-sufficiency rate decreased, indicating decreased self-sufficiency. Moreover, the environmental load rate was high, indicating high environmental pressure. The emergy currency rate declined with a rise in the emergy investment rate, indicating economic growth. Additionally, the population carrying capacity was consistently > 1, indicating that the population was overloaded. Collectively, the emergy-based evaluation method of regional economic sustainable development in this study provides a comprehensive and scientific evaluation framework, which can help decision makers and researchers better understand and evaluate the problems brought about by the rapid development of regional economy, and provide targeted decision making suggestions. It includes four sub-systems: natural, economic, social, and sustainable, which have important theoretical and practical significances, while also serving as a useful reference for the evaluation of the sustainable economic development of similar regions.

Keywords: emergy; sustainable development; regional ecological economy

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1. Introduction

Sustainable development strategies are an inherent requirement for human economic and social development, and regional resources and environment are the basis for regional economic development. However, regional industrial development policies are oriented toward the pursuit of high growth, with regional economic growth largely based on a high consumption of resources and energy [1]; this traditional development model has inevitably caused environmental pollution. The traditional view of development and long-term path dependence has led to environmental policies being subordinated to economic growth objectives, causing China's existing economic growth and environmental efficiency to become extremely inefficient [2].

Indeed, the extensive growth mode of regional economies around the world has caused acute ecological environmental pollution challenges [3,4], including soil and water loss, as well as resource shortages; thereby, critically affecting the sustainable development of social economy and threatening the living conditions of humans. These problems have provoked widespread concern across global society. In response, the 2022 United Nations High-Level Political Conference on Sustainable Development stressed the need to strengthen international cooperation on climate change, biodiversity protection, and marine pollution control to build a community of shared future for mankind and achieve a harmonious coexistence between man and nature [5]. Therefore, determining a more scientific and objective method of evaluating the sustainable development ability of the ecological economy, so as to realize the harmony and unity of economy, society, and ecology while also promoting the sustainable development of the regional ecological economy, has attracted widespread research attention. From the perspective of sustainable development, the current study analyzes the indicators of the regional ecological economy in one region of China and puts forward targeted policy suggestions based on our findings, with the aim of helping to achieve high-quality economic development.

The pursuit of regional economic sustainability has become an increasingly important agenda for scholars and policymakers worldwide. Researchers from across the world have studied methods by which we can reconcile the relationship between the economy, society, and the environment to achieve sustainable development of the regional economy. For example, Chen et al. constructed an environmental sustainability index and studied China's regional efficiency from 2000 to 2012 [6]. They used the data envelopment analysis model of the multiplicative relation network to analyze the variation trend of acquisition efficiency over time, revealing that overall, environmental sustainability has enormous potential for improvement. Xu et al. constructed an index system to evaluate the sustainable development level of the Yangtze River Delta region, based on sustainable development goals [7]. Martinez et al. employ a life cycle assessment methodology to evaluate the environmental impact of regional economic activities. Their research enables policymakers and stakeholders to identify environmentally damaging processes and develop targeted interventions to mitigate their effects [8]. Liu et al. use pioneering quantitative evaluation models to assess the sustainability of products [9]. Meanwhile, different scholars have adopted unique approaches (Table 1). For example, Moutinho et al. assessed the ratio of gross domestic product (GDP) to carbon dioxide emissions to evaluate the economic and environmental efficiency of Asia and Africa [10]. Anderson et al. explore the significance of social capital in promoting regional economic sustainability. Their study can enhance cooperation, knowledge sharing, and resource mobilization, leading to sustainable economic growth [11]. Johnson et al. delve into the complex interactions between economic growth, social inclusion, and environmental preservation in regional development. They develop a mathematical model that captures the dynamics and interdependencies of these three aspects, allowing policymakers to better understand the trade-offs and synergies when pursuing regional economic sustainable development [12]. Garcia et al. employ a variety of research methods and data analysis techniques to explore the interplay between economic development and sustainability in a regional context [13]. Liu et al. use a data-driven approach to improve resource utilization, minimize waste generation, and increase sustainability [14]. Chen et al. examine the role of innovation by analyzing data from developing countries across various regions, arguing that innovation plays a crucial role in transforming regional economies by promoting productivity, attracting investments, and fostering sustainable growth [15]. Ardashir et al. applied a fuzzy evaluation approach to control the path tracking of autonomous vehicles [16].

Table 1. Sustainable development research methods.

Research Methods	Motivations	Advantages	Disadvantages	Scholar/Year/Ref
DEA model	Assess regional efficiency in China 2000–2012	It is a composite metric that deals with problems that have multiple inputs and outputs	The sample size is too small, the results are unreliable and cannot have too many variables	Chen, 2020 [6]
Panel regression model	To examine the impact of environmental regulations on ecological efficiency	The model is simple and reflects the influence strength of multiple independent variables on a dependent variable	With few parameters, it is only applicable to small samples	Li, 2021 [9]
SFA Technology	Assessing economic and environmental efficiency in Asia and Africa	The results were less affected by the special points	Too many input indicators will affect the reliability of the results	Moutinho, 2021 [10]

By studying the relationship among economy, society, and nature, scholars have promoted the sustainable development of regional ecological economies, and the evaluation index has gradually changed from a single factor to multiple factors. However, given that these methods focus less on the environmental integrity of socio-economic systems, they are unable to comprehensively evaluate the contribution of ecosystems to local economic development, thus limiting their application in policy planning and other aspects. Meanwhile, emergy theory is a concept that proposes a unified unit of measurement for the flow and storage of various materials and energies within a system, based on specific criteria. This theory allows for the conversion of different forms of matter and energy into a common unit, enabling a comprehensive understanding of the interconnections and transformations occurring within complex systems [17]. The theory establishes a scientific theoretical system through indicators, reflecting the characteristics of ecological and economic systems and development models. It not only overcomes the limitation regarding the comparison of energy between different substances under the same standard by traditional analysis methods, but the relationship between the ecological environment and the economy is also objectively expressed. Therefore, it has gradually become an important method to study the sustainable development of regional ecological and economic systems.

The American scholar Odum was the first person to propose the emergy theory [18], which is now widely used in the sustainable development evaluation of distinct types of ecosystems [19–21]. In industrial ecosystems, Babaelahi et al. used emergy to evaluate a two-stage solar gas turbine system [22]. Methods of emergy analysis can help organizations and decision makers with supply chains to manage material procurement and supplier selection, as well as design network and circular economy flow (Table 2) [23]. For instance, Liu et al. used emergy analysis to evaluate remanufacturing processing systems [24], while a separate study applied emergy analysis to assess and improve the sustainability, environmental, and economic impacts of one factory [25]. Sheikh et al. applied emergy analysis to investigate the sustainability of production systems on degraded lands in India [26], whereas Qin et al. used the same method to compare coastal ecosystems [27].

Emergy analysis is also widely employed in the evaluation of agro-ecosystems. For example, David et al. explored the application of emergy in aquaculture systems [28], while Shah et al. established a non-monetary "supply-side" ecosystem services assessment methodology that constructs an emergy-based framework for agro-ecosystem services [29]. The production system of rapeseed was analyzed using an emergy index [30], and Shahhoseini et al. applied emergy analysis to identify factors closely related to the sustainability of potato agro-ecosystems [31].

In the regional ecological and economic system, Wang et al. evaluated the sustainable development of the regional ecological economy in Anhui Province via emergy analysis [32].

Emergy-based methods have also been applied to evaluate the sustainable development of the ecological economy of Qinghai [33], Simao [34], and the Yellow River Basin [35]. Hence, emergy analysis and eco-economic evaluation play a significant role in analyzing regional eco-economic systems [36].

Table 2. Applications of the emergy theory.

Application Areas	Motivations	Advantages	Disadvantages	Scholar/Year/Ref
Industrial ecosystem	To evaluate the sustainability of remanufacturing system	Transformed into a unified unit dynamic analysis area system, more fair, clear and intuitive, easy to calculate and proofread	The calculation of energy conversion rate and energy flow of multi-product or composite product system are complicated	Liu, 2021 [24]
	Compare the ecosystems of coastal cities			Qin, 2020 [27]
Agricultural ecosystem	Evaluate canola production systems			Amiri, 2019 [30]
	Assessing the efficiency of potato agroecosystems			Shahhoseini, 2022 [31]
	The application of emergy in aquaculture system was discussed			David, 2021 [28]
Regional eco-economic system	Evaluate the sustainable development of regional ecological economy			Wang, 2021 [32]
	The sustainability evaluation of 9 cities was analyzed and evaluated			Yuan, 2022 [35]
	Evaluate the ecological efficiency of regional circular economy			Liu, 2018 [36]

The above studies analyzed the eco-economic systems of different fields from the perspective of emergy and put forward targeted policy recommendations according to the evaluation results. It provides reference for regional eco-economic practitioners and decision makers to take into account economic and ecological benefits. Collectively, these research findings are of great significance to the sustainable development of the regional economy; however, certain research gaps remain: (1) The existing research analyzes the emergy of a particular region in a certain year, which reflects the resource utilization and sustainable development of that region to a certain extent but cannot reflect the dynamic characteristics and development trends of the system. (2) There are various elements of regional economic inputs and outputs that are measured in different units. Thus, determining how to measure them more accurately and uniformly is the theoretical basis for the quantitative assessment of ecological sustainable development. (3) Numerous factors influence ecological and economic sustainability, making it difficult to consistently collect, process, and evaluate them. Therefore, an urgent need exists for policymakers and researchers to make comprehensive use of relevant statistical data and combine them with local conditions to assess sustainable development capacity.

Considering these gaps in knowledge, this study proposes a method of emergy theory to evaluate the sustainable development ability of the regional ecological economy. Compared with previous studies, the innovation of this study is reflected in the following aspects: (1) A regional eco-economic emergy index is constructed from four aspects: natural subsystem, economic subsystem, social subsystem, and sustainable development, which is more comprehensive and objective. (2) The modified sustainable development index was used to comprehensively evaluate the regional eco-economic system, taking into account the emergy yield rate (EYR), environmental load rate (ELR), and waste-to-output rate (EWR), thereby producing more scientific evaluation results. (3) Based on the analysis of the current natural economic and social development situation in Henan Province, targeted policy suggestions are proposed.

In order to realize the sustainable development of the regional ecological economy, it is necessary to carry out a scientific evaluation and reasonable planning. Based on emergy theory, some hypotheses are proposed in this study.

(1) We assume that there is a certain relationship between the level of ecological economic development and energy consumption in Henan Province.
(2) We assume that there is a mutually promoting relationship between ecological economic development and social development in Henan Province.
(3) We assume that there are certain contradictions and conflicts between ecological economic development and environmental protection in Henan Province.

In order to verify the above hypothesis, we can use the emergy analysis method in emergy theory to calculate the emergy consumption by a statistical analysis of energy consumption data in Henan Province. This paper analyzes emergy flow from the perspectives of economy, environment, society, and sustainability, evaluates the degree of interaction between the regional eco-economy and social development, and puts forward corresponding policy recommendations.

The findings of this study offer both theoretical and practical significance. Regarding the theoretical significance, from the perspective of emergy, a sustainable development evaluation index system is constructed, revealing the relationship between regional ecological and economic sustainable development and nature, the economy, and society, while also providing theoretical and methodological support for high-quality regional economic development. In the practical context, the relevant data and conclusions provide decision making support for both industrial and governmental managers, as well as provide innovative ideas for relevant sustainable ecological and economic development. The results of this study also provide a reliable reference for decision making and the evaluation of systematic planning for sustainable development.

In order to achieve the above research objectives, the framework of this study is as follows: The second part introduces the methods, constructs the sustainability evaluation indicators, and explains the reasons for choosing Henan Province as an example. The third part takes Henan Province as an example, evaluates the sustainability of the eco-economic system in this region, and draws policy suggestions and management enlightenment. The fourth part summarizes the research, and concludes the research deficiencies and prospects for the future.

2. Materials and Methods

Henan Province (31°23–36°22 N, 110°21–116°39 E) (Figure 1), as a province in central China, has rich economic, social and geographical characteristics, so it becomes the research object of this paper.

First of all, Henan Province has unique features in terms of economy. The GDP of the province reached 48,055.86 billion yuan, and the per capita GDP reached 5015.2 billion yuan. The economic strength of Henan Province ranks among the top five in China and ranks 20th in the world, surpassing more than 100 countries such as Argentina and Sweden. The economic structure of Henan Province shows the coexistence of agriculture and industry, which is different from other regions and countries. Secondly, Henan Province also has unique features in social aspects. As one of the most populous provinces in China, Henan Province has a relatively high population density. By the end of 2020, the total population of the province was 11,526 people, and the permanent population was 99.41 million, with an urbanization rate of 55.43%. This means that Henan Province is facing greater social problems and challenges, such as employment pressure and education resource allocation. Third, the political characteristics of Henan Province are also worthy of attention. As a province of China, Henan Province is under the leadership and guidance of the central government. Understanding the political environment and government policies of Henan Province is of great significance for evaluating and making suggestions. In addition, the geographical location and natural resources of Henan Province are also factors to be considered. Henan Province is located in the middle and lower reaches of the Yellow River in central and eastern China. The region is high in the west and low in the east, with a total area of 167,000 square kilometers. It is rich in natural resources, such as farmland and mineral resources. These natural resources have an important impact on the sustainable development of the regional ecological economy.

Figure 1. Case study area.

A study on the assessment and recommendations of the sustainable development of the regional ecological economy in Henan Province can provide valuable insights into the theoretical basis of the sustainable development of the regional economy, and help to develop a framework and model that can be applied globally to cope with similar challenges faced by other regions, and can provide valuable lessons for global efforts to address climate change and protect natural resources. In addition, the analysis of the ecological economic sustainability in Henan Province can contribute to the current debate on the relationship between social and economic growth and environmental sustainability, providing a deeper understanding of the complex dynamics involved and helping to address the challenges of achieving sustainable development around the world.

2.1. Emergy Method and Evaluation Index

To link human activities with nature, traditional energy studies can only be performed based on the energy produced by one substance and do not allow for the comparison between energies produced by different substances. Thus, to address the shortcomings of existing studies, we have selected the emergy analysis method for our research. Based on Odum's emergy method, various categories of substances and energy flow, which are stored in ecological and economic systems (such as rain, wind, coal, oil, natural gas, capital, technology, and labor), are converted into a unified solar emergy [17] and then quantitatively analyzed. This allows researchers to study the socioeconomic development of ecosystems in terms of their degree of contribution. In this study, the calculation method was chosen for two reasons: First, the data thus calculated will not be affected by the imbalance of economic and social development. Second, the dynamic analysis of regional systems is fairer, clearer, more intuitive, and easier to calculate and calibrate [24]:

$$EME = UE \times W \tag{1}$$

where EME is the emergy value, UE is the emergy conversion rate, and W represents different units.

2.2. Evaluation Indexes

Based on the emergy theory and the actual situation of the eco-economic system in Henan Province, the emergy index of sustainable development for the regional eco-economic system was developed by sorting the actual data of Henan Province and the relevant reference materials of emergencies.

This study analyzed the relationship between the regional ecological economy and sustainable development through strict data calculation. According to scientific, collectable, and quantifiable principles, this study constructed a regional eco-economic evaluation index system including four subsystems and 19 indicators. When constructing the natural subsystem, the views of Wang et al. [32] are primarily applied with the addition of environmental load rate (ELR) and waste-to-output rate (EWR) indicators. When constructing the economic subsystem, the emergy yield rate (EYR) and emergy investment rate (EIR) are applied as the evaluation indexes of the economic subsystem [27], and the emergy currency rate (EDR) and emergy exchange rate (EER) are calculated. In the construction of the social subsystem, the indicators of per capita emergy (EPP), emergy density (EPA), and population carrying capacity (PCC) are mainly used [18]. In the construction of sustainable development indicators, on the basis of considering the sustainability index, the revised emergy-based sustainability index is used for the evaluation of regional ecological and economic sustainability.

2.2.1. Natural Subsystem

(1) The emergy self-sufficiency rate (ESR) is calculated using Equation (2) as the ratio of the local resource emergy input to the total emergy input (EMU) of a region [32].

$$ESR = (EMR + EMN)/EMU \tag{2}$$

where EMR represents renewable resource emergy, and EMN is non-renewable resource emergy. This index describes the degree of economic development and foreign exchange in a region. The development of any country and region is not isolated and is self-reliant, while maintaining contact with the outside world. The higher the ESR, the stronger the system's self-sufficiency ability and the higher the degree of development of internal resources.

(2) The ELR is calculated using Equation (3) and is equal to the ratio of the sum of the economic feedback emergy (EMI) and the EMN to the EMR [33].

$$ELR = (EMI + EMN)/EMR \tag{3}$$

ELR represents the impact of economic development on the natural ecological environment. The greater the impact of the economy on the natural environment, the greater the pressure on the natural environment, and the higher the natural ELR. Therefore, if an area is consistently overloaded, the situation can be expected to become irreversible.

(3) The EWR is equal calculated according to Equation (4) and corresponds to the ratio of the waste emergy (EMW) of the region to the EMU of the region [36].

$$EWR = EMW/EMU \tag{4}$$

The EWR represents the circulatory capacity of the system in that area. The recycling capacity of the system is inversely proportional to the waste output ratio. Therefore, the better the system circulation capability, the lower the EWR.

2.2.2. Economic Subsystem

(1) The EDR is used to evaluate the degree of modernization of the regional economy and to measure whether the regional population is overloaded. The EDR is calculated using Equation (5) and is the EMU divided by the GDP [36].

$$\text{EDR} = \text{EMU}/\text{GDP} \tag{5}$$

Developing countries and rural areas directly use a substantial proportion of unpaid local natural resources, while having a low GDP and high EDR. In contrast, developed countries have a higher GDP, faster capital circulation, and more resources purchased from outside the country, therefore, their EDR is typically lower.

(2) The EER is the ratio of EMI to output emergy (EMO) and is calculated using Equation (6) [32].

$$\text{EER} = \text{EMI}/\text{EMO} \tag{6}$$

The EER refers to the performance of a system when it is trading with the outside world. The more revenue generated during the exchange, the larger the EER and the more advantageous the region is at the time of the exchange.

(3) The EIR refers to the ratio of the EMI to the sum of the EMR in the natural environment and the EMN (Equation (7)) [34].

$$\text{EIR} = \text{EMI}/(\text{EMR} + \text{EMN}) \tag{7}$$

The emergy of the dividend economic feedback is purchased, while the emergy of the divisor is free. Therefore, the EIR is used to measure regional economic development and environmental load. The better the regional economic development, the greater the EIR, indicating a stronger dependence on the environment.

(4) The EYR is equal to the difference between the EMO and the EMW divided by the EMI (Equation (8)) [33].

$$\text{EYR} = (\text{EMO} - \text{EMW})/\text{EMI} \tag{8}$$

The EYR represents the economic performance of a region. Hence, the lower the EYR, the lower the resource utilization rate of this region, the lesser the economic benefit, and the less competitive the economic activities.

2.2.3. Social Subsystem

(1) The EPP is the ratio of EMU to population (P), as demonstrated by Equation (9) [36], and reflects people's living standard. That is, the higher the standard of living, the higher the per capita emergy.

$$\text{EPP} = \text{EMU}/\text{P} \tag{9}$$

(2) The EPA is the ratio of EMU to land area (A), as represented by Equation (10) [36], and reflects the intensity of economic development and the level of economic development. Hence, the greater the EPA, the more developed the economy is and the higher the grade.

$$\text{EPA} = \text{EMU}/\text{A} \tag{10}$$

(3) The PCC is the ratio of EMR plus EMI to EPP (Equation (11)) [32] and is an indicator of the affordability of the urban population in the natural environment. That is, the smaller the PCC, the more stressed the region's economic environment is and the weaker the foundation for sustainable development is.

$$PCC = (EMR + EMI)/EPP \quad (11)$$

2.2.4. Sustainability Index

(1) The emergy-based sustainability index (ESI) is calculated as the ratio of net EYR to ELR, as demonstrated by Equation (12) [32]. Hence, the smaller the ESI, the weaker the sustainability.

$$ESI = EYR/ELR \quad (12)$$

(2) The revised emergy-based sustainability index (ESI′) represents the ratio of the EYR and the ELR, multiplied by the EWR (Equation (13)) [32].

$$ESI' = EYR/(ELR \times EWR) \quad (13)$$

The ESI′ is a comprehensive assessment of society, the economy, and nature. That is, the higher the index, the stronger the sustainable development capacity of the region.

Based on these emergy indexes, the regional eco-economic system emergy evaluation index system was established (Table 3).

Table 3. Emergy evaluation index system of regional ecological economy.

Index	Expression	Definition	Scholar/Year/Ref
	Emergy calculation index		
Renewable resource emergy	EMR	Various renewable emergy from nature	Odum, 1988 [18]
Non-renewable resource emergy	EMN	Various non-renewable emergy from nature	Odum, 1988 [18]
Economic feedback emergy	EMI	Emergy of products, information, technology, and labor services from outside the economic system	Odum, 1988 [18]
Output emergy	EMO	Products and services output by the system	Odum, 1988 [18]
Waste emergy	EMW	Wastewater, waste gas, and solid waste discharged from the system to the environment	Odum, 1988 [18]
Total emergy	EMU = EMR + EMN + EMI	Sum of various emergy input	Odum, 1988 [18]
	Natural Subsystem		
Emergy self-sufficiency rate	ESR = (EMR +EMN)/EMU	Reflect the natural environment support capacity of the region	Wang, 2021 [32]
Environmental load rate	ELR = (EMI + EMN)/EMR	Evaluate the impact of economic activities on the natural environment	Chen, 2018 [33]
Waste-to-output rate	EWR = EMW/EMU	Reflect the pollution degree of economic activities to the natural environment	Liu, 2018 [36]

Table 3. *Cont.*

Index	Expression	Definition	Scholar/Year/Ref
	Economic Subsystem		
Emergy currency rate	EDR = EMU/GDP	Evaluate the development degree of regional economy	Liu, 2018 [36]
Emergy exchange rate	EER = EMI/EMO	Reflect the profit or loss of external transactions	Wang, 2021 [32]
Emergy investment rate	EIR = EMI/(EMR + EMN)	Measure the degree of economic development and environmental load	Pan, 2021 [34]
Emergy yield rate	EYR = EMU/EMI	Measure regional economic benefits	Wang, 2021 [32]
	Social Subsystem		
Per capita emergy	EPP = EMU/P	Reflect the material living standards of the people in the region	Liu, 2018 [36]
Emergy density	EPA = EMU/A	Reflects land use efficiency	Liu, 2018 [36]
Population carrying capacity	PCC = (EMR + EMI)/EPP	The carrying capacity of urban population at the current environmental level	Amiri, 2019 [31]
Population carrying rate	PCR = P/PCC	Measure whether a region is overdrawn	Chen, 2022 [17]
	Sustainability Index		
Emergy-based sustainability index	ESI = EYR/ELR	Measure the status and level of sustainable development	Wang, 2021 [32]
Revised emergy-based sustainability index	ESI′ = EYR/(ELR × EWR)	Comprehensively reflect the level of sustainable development	Wang, 2021 [32]

3. Results and Discussion

Sustainable development, the concept of meeting the needs of the present without compromising the ability of future generations to meet their own needs, is becoming increasingly important in our rapidly changing world. While environmental and social factors play a vital role in achieving sustainability, it is undeniable that economic growth is the driving force behind this process of change. Economic growth is an important component of sustainable development. By generating financial resources, fostering innovation, creating jobs, reducing poverty, and fostering global partnerships, economic progress drives the transition to a sustainable world. The economy plays an important role in achieving a harmonious balance between the natural environment, social, and economic well-being.

To verify the rationality and convenience of the proposed evaluation method and identify problems in the sustainable economic development of Henan Province, a case study for this province was performed. In this study, a regional ecological and economic sustainable development evaluation method was employed based on the energy value theory established in this research, thereby providing a new scientific basis for the adjustment and formulation of regional policies.

3.1. Data Evaluation

This study focused on the period of 2010–2018 by querying the China statistical yearbook, Henan statistical yearbook, government reports, Henan bureau, and Henan Province ecological environment agency raw data (see Supplementary Table S1 for details). Corresponding values were calculated (see Supplementary Table S2 for details) according to the building energy index and the index data of the ecological economic system was calculated (Table 4).

Table 4. Evaluation indexes of ecological and economic system in Henan Province.

Index	2010	2011	2012	2013	2014	2015	2016	2017	2018
Emergy calculation index									
Renewable resource emergy	3.42×10^{21}	3.27×10^{21}	3.08×10^{21}	3.04×10^{21}	3.25×10^{21}	3.22×10^{21}	3.34×10^{21}	3.40×10^{21}	3.30×10^{21}
Non-Renewable resource emergy	6.70×10^{24}	7.62×10^{24}	7.42×10^{24}	7.30×10^{24}	7.36×10^{24}	7.67×10^{24}	7.65×10^{24}	7.67×10^{24}	7.58×10^{24}
Economic feedback emergy	4.01×10^{23}	5.33×10^{23}	6.19×10^{23}	6.86×10^{23}	7.29×10^{23}	7.22×10^{23}	8.08×10^{23}	8.76×10^{23}	9.65×10^{23}
Output emergy	1.95×10^{24}	2.27×10^{24}	2.49×10^{24}	2.72×10^{24}	2.98×10^{24}	3.19×10^{24}	3.47×10^{24}	3.86×10^{24}	4.30×10^{24}
Waste emergy	3.39×10^{23}	4.40×10^{23}	4.58×10^{23}	4.84×10^{23}	4.76×10^{23}	4.46×10^{23}	4.17×10^{23}	4.99×10^{23}	5.35×10^{23}
Total emergy	7.11×10^{24}	8.16×10^{24}	8.05×10^{24}	7.99×10^{24}	8.09×10^{24}	8.40×10^{24}	8.46×10^{24}	8.55×10^{24}	8.54×10^{24}
Population	1.04×10^{8}	1.05×10^{8}	1.05×10^{8}	1.06×10^{8}	1.07×10^{8}	1.07×10^{8}	1.08×10^{8}	1.09×10^{8}	1.09×10^{8}
Natural Subsystems									
Emergy self-sufficiency rate	9.44×10^{-1}	9.35×10^{-1}	9.23×10^{-1}	9.14×10^{-1}	9.10×10^{-1}	9.14×10^{-1}	9.05×10^{-1}	8.98×10^{-1}	8.87×10^{-1}
Environmental load rate	2.08×10^{3}	2.50×10^{3}	2.61×10^{3}	2.63×10^{3}	2.49×10^{3}	2.60×10^{3}	2.53×10^{3}	2.51×10^{3}	2.59×10^{3}
Waste-to-output rate	4.77×10^{-2}	5.39×10^{-2}	5.69×10^{-2}	6.06×10^{-2}	5.88×10^{-2}	5.31×10^{-2}	4.92×10^{-2}	5.84×10^{-2}	6.26×10^{-2}
Economic Subsystems									
Emergy currency ratio	3.14×10^{12}	3.10×10^{12}	2.78×10^{12}	2.53×10^{12}	2.34×10^{12}	2.26×10^{12}	2.10×10^{12}	1.91×10^{12}	1.71×10^{12}
Emergy yield rate	1.77×10^{1}	1.53×10^{1}	1.30×10^{1}	1.17×10^{1}	1.11×10^{1}	1.16×10^{1}	1.05×10^{1}	9.76×10^{0}	8.85×10^{0}
Emergy exchange rate	2.05×10^{-1}	2.35×10^{-1}	2.48×10^{-1}	2.52×10^{-1}	2.45×10^{-1}	2.26×10^{-1}	2.33×10^{-1}	2.27×10^{-1}	2.24×10^{-1}
Emergy investment rate	5.98×10^{-2}	6.98×10^{-2}	8.33×10^{-2}	9.39×10^{-2}	9.90×10^{-2}	9.41×10^{-2}	1.06×10^{-1}	1.14×10^{-1}	1.27×10^{-1}
Social Subsystems									
Per capita emergy	6.81×10^{16}	7.78×10^{16}	7.63×10^{16}	7.54×10^{16}	7.59×10^{16}	7.83×10^{16}	7.85×10^{16}	7.87×10^{16}	7.83×10^{16}
Emergy density	4.26×10^{14}	4.89×10^{14}	4.82×10^{14}	4.78×10^{14}	4.85×10^{14}	5.03×10^{14}	5.07×10^{14}	5.12×10^{14}	5.12×10^{14}
Population carrying capacity	5.93×10^{6}	6.89×10^{6}	8.15×10^{6}	9.14×10^{6}	9.64×10^{6}	9.27×10^{6}	1.03×10^{7}	1.12×10^{7}	1.24×10^{7}
Population carrying rate	1.76×10^{1}	1.52×10^{1}	1.29×10^{1}	1.16×10^{1}	1.11×10^{1}	1.16×10^{1}	1.04×10^{1}	9.72×10	8.82×10
Sustainability Index									
Emergy-Based Sustainability Index	9.06×10^{-3}	6.57×10^{-3}	5.39×10^{-3}	4.85×10^{-3}	4.91×10^{-3}	4.88×10^{-3}	4.58×10^{-3}	4.33×10^{-3}	3.85×10^{-3}
Revised Emergy-Based Sustainability Index	5.21×10^{-2}	3.39×10^{-2}	2.94×10^{-2}	2.73×10^{-2}	3.07×10^{-2}	3.50×10^{-2}	3.80×10^{-2}	3.35×10^{-2}	3.09×10^{-2}

3.2. Evaluation and Analysis of Indexes

According to the emergy evaluation index data, the ecological economic system of Henan Province was evaluated by establishing three subsystems of nature, economy, and society, as well as a sustainable development index.

3.2.1. Analysis of Natural Subsystem Evaluation Indexes

As seen in Table 2 and Figure 2, although the total amount of emergy in Henan province increased from 2010 to 2018 (from 7.11×10^{24} to 8.54×10^{24}), the ESR of emergy decreased year-by-year (from 9.44×10^{-1} to 8.87×10^{-1}), indicating that the supporting capacity of the natural environment in Henan Province was declining. The weaker the self-sufficiency capacity, the more dependent it was on internal environmental resources. The primary cause of this decline was the purchase of resources from outside Henan Province and the use of fewer natural resources directly. Although the emergy structure of resources was more reasonable, the ESR of Henan Province remained high.

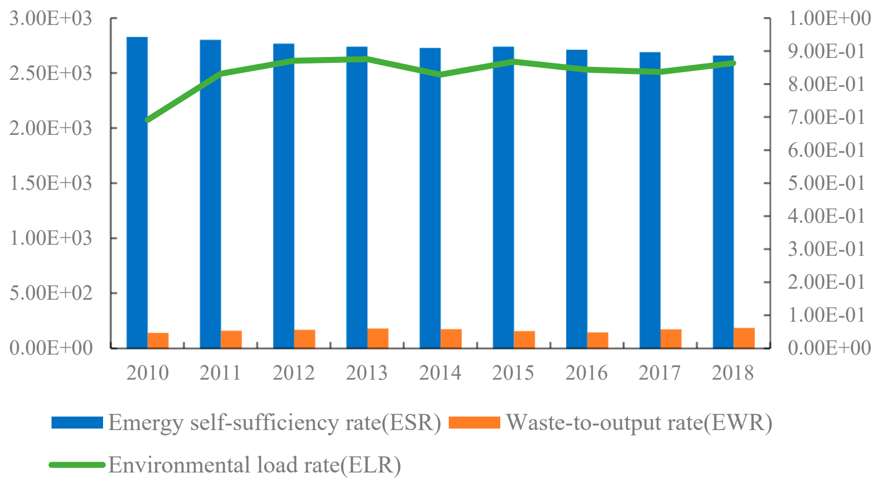

Figure 2. Analysis of natural subsystem evaluation indexes.

The EWR can be used to evaluate the impact of the traditional economic development mode on the environment. The waste emergy value of Henan Province exhibited a fluctuating growth state from 2010 to 2018, and the waste emergy ratio increased from 4.77×10^{-2} in 2010 to 6.26×10^{-2} in 2018 (Figure 2). Due to the rapid development of the economy and waste increase, more pollutants were discharged to the outside world, and the waste recovery rate was low.

The ELR of Henan Province was consistently high and fluctuated around two with no obvious trend change. However, the emergy range of non-renewable resources was larger than that of renewable resources, and the fluctuation of ELR was primarily determined by the emergy of non-renewable resources (Table 2). The emergy value of non-renewable resources was much larger than that of renewable resources, indicating that the economic development of Henan Province primarily depends on non-renewable resources, and the environment system is under great pressure. If the long-term high environmental load condition is not changed, the ecosystem function of Henan Province can be expected to irreversibly decline.

3.2.2. Analysis of Economic Subsystem Evaluation Indexes

As shown in Figure 3, the EIR of Henan Province increased from 0.0598 in 2010 to 0.127 in 2018. Since 2016, the investment value has increased significantly, and the economy has begun to develop rapidly. This suggests that the degree of economic development is improving and the dependence of the environment is decreasing. The EDR of Henan Province has been declining steadily (from 3.14×10^{12} in 2011 to 1.71×10^{12} in 2018) primarily due to the rapid economic growth, a reduction in energy resources purchased by each unit of currency, and a reduction in emergy costs paid by the province. These criteria also imply that the region's economy is developing at a rapid pace.

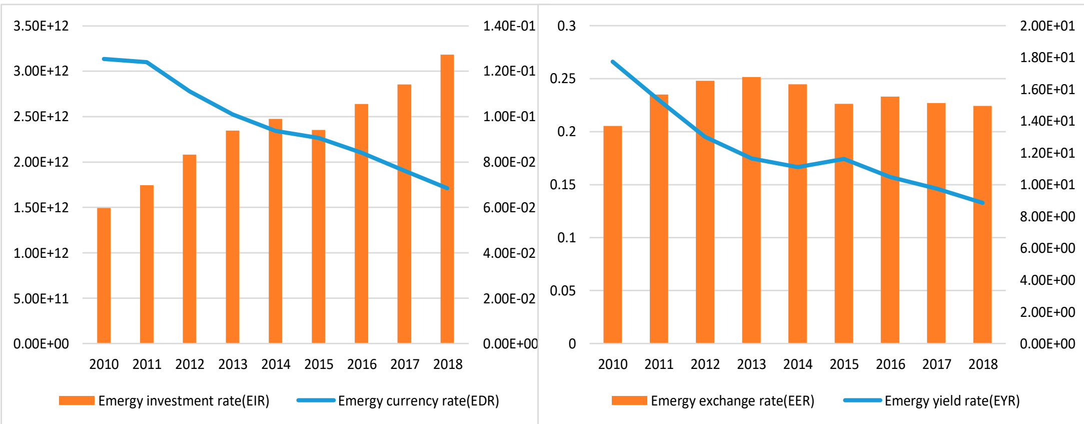

Figure 3. Analysis of economic subsystem evaluation indexes.

After 2014, The EER was a brief increase from the previous years (Figure 3). This is attributable to the central location and geographical limitations of the province, which hinder transportation and result in slower international trade development. Although Henan's import and export volumes have increased, they remain far behind those of developing coastal cities. In addition, the scarcity of customs and inspection agencies has greatly inconvenienced enterprises engaged in the import and export trade, leading to increased costs. This has resulted in many enterprises losing money and no longer engaging in the import and export business. The EYR of Henan Province has gradually declined from 1.77 in 2010 to 0.89 in 2018. The agricultural production efficiency of Henan Province has decreased significantly, as has its production, indicating that Henan Province has been focusing on the total amount and scale of economic development without considering production efficiency.

3.2.3. Analysis of Social Subsystem Evaluation Indexes

Table 2 shows that the total population and emergy of Henan Province have been increasing. The EPA of Henan Province increased gradually from 4.26 $\times$ 10^{14} in 2010 to 5.12 $\times$ 10^{14} in 2018, which further highlights the economic growth of Henan Province. The EPP also showed an upward trend, rising from 6.81 $\times$ 10^{16} in 2010 to 7.83 $\times$ 10^{16} in 2018, although fluctuations occurred (Figure 4). Therefore, it is suggested that the quality of life and living standards of the citizens are also improving.

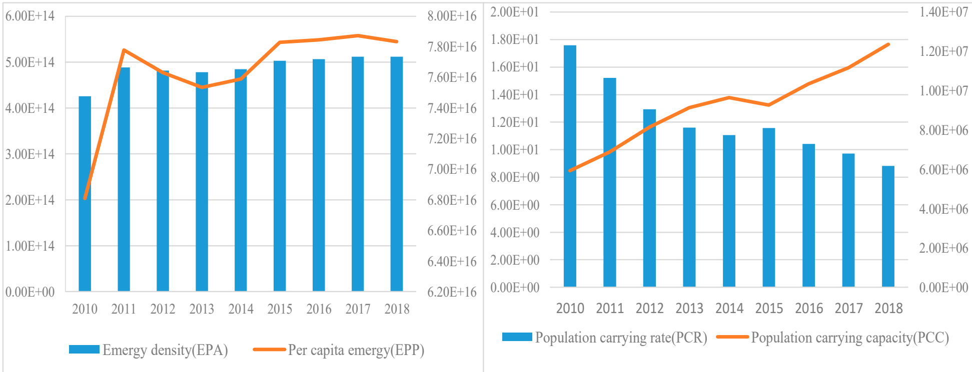

Figure 4. Analysis of social subsystem evaluation indexes.

The PCC of Henan Province improved from 5.93 $\times$ 10^6 in 2010 to 1.24 $\times$ 10^7 in 2018 (Figure 4). The population carrying capacity (PCR) is the regional population to PCC ratio. When this indicator is less than one, the regional population is not overloaded, whereas when it is greater than one, the population of the region is overloaded, implying greater population pressure. Although the PCR of Henan Province has been declining, it remains far greater than one, suggesting that the population of Henan Province is in a state of disbalance with the economy and the environment, which can be expected to eventually impact the stability of the social system.

3.2.4. Analysis of Sustainability Index

The trend of ESI and ESI′ in Henan Province from 2010 to 2018 was gradually decreasing (Figure 5). Meanwhile, the ELR of Henan Province has remained consistently high; however, the sustainability index has remained <1. Studies have shown that if the sustainable development index is too small and exhibits a downward trend, the environmental load is too large, which is reflected as a consumer city [36]. The economic system is in a state of lack of vitality and sustainable development, mainly due to the excessive use of non-renewable resources.

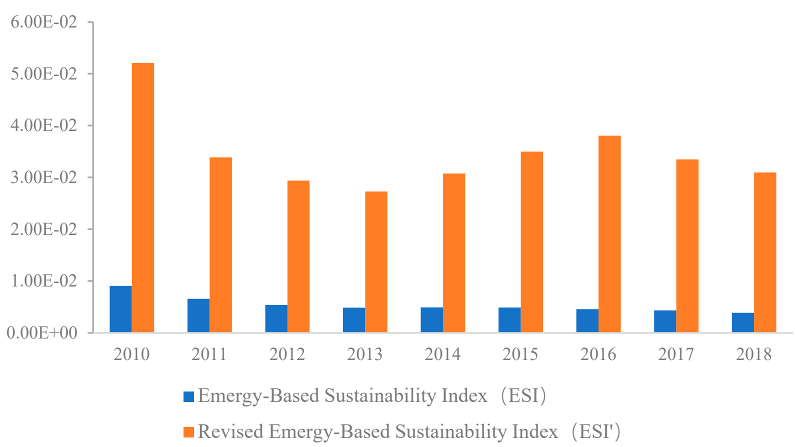

Figure 5. Analysis of sustainability index.

3.3. Policy Suggestions

According to the above emergy analysis results and the situation of Henan Province, several suggestions are herein put forward to promote the sustainable economic development of Henan Province.

3.3.1. Optimizing the Emergy Structure and Promoting Structural Upgrades

It can be seen from Table 4 that the EDR has been gradually decreasing from 2011 to 2018, indicating the rapid economic development of the Central Plains and the increasing consumption of energy resources. Henan Province is an important energy province in China, with its energy sources primarily represented by raw coal, petroleum, and natural gas; however, its rough industrial structure and production methods have led to an increasing demand for energy. Moreover, the ELR of Henan Province has been relatively high, mainly due to the excessive use of non-renewable resources and a neglect in developing and utilizing renewable resources. Therefore, it is necessary to strengthen the development of new energy and improve the utilization rate of resources, as well as to carry out a multi-level resource transformation and implement a low-carbon transformation of emergy structures. Overall, it would be beneficial to accelerate the high-end, intelligent, and green transformation of traditional industries and explore typical models of green development.

3.3.2. Reducing Waste Emissions and Developing a Circular Economy

Waste emissions have a profound impact on the ecological environment and regional sustainable development. Furthermore, it can be seen from Table 4 that the EWR in Henan Province has been dynamically increasing from 2010 to 2018; the ELR has been high and the environment has been in a high-load state for a long time. The government needs to actively promote the slogan, "protecting the environment is protecting our homeland". In addition, the government should establish the concept of sustainable development, strengthen the supervision of environmental protection, and criticize the behavior of those who disobey laws and regulations and destroy the environment. Manufacturers should be expected to reduce the amount of materials used in their products and remodel their manufacturing processes to reduce waste emissions and conserve resources. In addition, it is beneficial to recycle and utilize the waste generated in the production process, popularize the knowledge of a circular economy, develop good thrifting habits, and cultivate the responsibility of caring for the environment.

3.3.3. Optimizing the Industrial Structure and Changing the Economic Growth Model

The overall economic strength of Henan Province has been increasing—as shown by Table 4, showcasing the EDR and EIR from 2011 to 2018—and the transformation from a large agricultural province to a large economic and cultural province has been successfully realized. However, the long-established industrial structure is of low level and poor efficiency, with small industrial enterprises and low industrial concentration. The energy value output rate has been reduced significantly, as has the production efficiency of Henan Province. Therefore, it is necessary to optimize the industrial structure and promote sustainable economic development. Further consolidation of the position of agriculture as the foundation, implementation of the input of active fiscal policy, increased support for the planting industry, and increased incomes for farmers should all be achieved. In addition, it would be beneficial to promote open economic development actively, adhere to the combination of "going out" and "bringing in," and build a new pattern of export-oriented regional economic development.

3.3.4. Controlling the Rate of Population Growth and Improving the Living Standards of Residents

It can be seen from Table 4 that the PLR has been >1 from 2011 to 2018, indicating that the population pressure in Henan Province is relatively high. On the one hand, to reduce the population carrying rate, it is necessary to prevent excessive population growth. On the other hand, it is important to increase the development and utilization of renewable energy to reduce environmental pressure on urban ecosystems and improve the regional population carrying capacity. The growth rate of per capita emergy value in Henan Province is lower than that of per capita GDP. Therefore, in subsequent development processes, it will be necessary to focus on aspects such as strengthening the importance of the residents' livelihoods; improving urban public service capabilities; increasing investment in medical care, education, culture, and pensions; strengthening environmental protection; improving water and air quality; and improving residents' satisfaction and sense of gain.

3.4. Management Implications

Several previously published studies provide results similar to those of the current study. For instance, Liu et al. [37] revealed the relationship between wastewater ecological damage and economic development, where China's economic development began to show a decoupling of ecological damage from wastewater. The primary drivers of this decoupling are the strict formulation and implementation of China's environmental policies, as well as the green upgrading of industrial structures, with weak correlation to economic slowdown. Although the experience and achievements of the Chinese government in wastewater pollution control are demonstrated, only ecological impacts are discussed. Meanwhile, the current study explores environmental, economic, and social issues, with implications for sustainability. Moreover, Xu et al. [38] developed a decision making model for a centralized and decentralized supply chain consisting of a manufacturer and retailer from a game theory perspective. They found that the government should effectively reduce carbon emissions through a carbon emissions trading system to achieve economic and environmental harmony. Our study found similar results, and that green and low-carbon development is an inevitable requirement for sustainable development. Compared with the existing studies [39,40], this study has many advantages. First, emergy theory converts the energy that cannot be compared into the same unit, which directly reflects the relationship between the energy flow of each element in the system. Second, considering the environmental, economic, and social problems of the regional eco-economic system, the sustainable development ability of the region is analyzed. Lastly, the regional system is dynamically analyzed to intuitively reflect the historical path and development trend of its regional sustainable development.

Based on our results, the following management insights can be summarized:

First, the emergy analysis approach successfully provides a bridge between the economy and ecosystems, while also providing a measure of the true contribution of natural resources to economic development. Moreover, this approach overcomes the limitation whereby traditional methods cannot calculate the value of different material resources on a unified scale. This approach also provides a more comprehensive solution over current methods for the analysis of natural and human social systems as a whole.

Second, while developing the economy, we must improve the utilization rate of resources, reduce unnecessary waste, and protect resources and the ecological environment. The sustainable development of regional economic systems can be accomplished based on the protection of resources and the ecological environment.

Third, ecosystems involve natural, economic, social, and other related subsystems. Therefore, the interaction between these internal subsystems affects the level of sustainable development which can be achieved, so it is necessary to quantitatively evaluate the level of sustainable development and analyze each subsystem as much as possible.

The novelty and contributions of the study are summarized as follows: (1) The emergy model for sustainable regional economic development was studied, and the developed indicators highlight the primary issues to a greater extent. (2) The policy recommendations are focused and provide a solid foundation for promoting the sustainable economic development of Henan Province. (3) This research method reflects the structure, function, and evolutionary mechanisms of cities as composite ecosystems and can effectively compensate for the shortcomings of general and untargeted sustainable development countermeasures in urban sustainable development research. Hence, this study provides a reference for the sustainable development of other regions.

4. Conclusions

In today's society, the contradiction between rapid economic development and the preservation of the natural environment has placed considerable pressure on society. Hence, the design of strategies to promote the balance between economic development and social and ecological environmental optimization has become a research hotspot. In addition, the identification of the sustainability of regional economies and the targeting of policy recommendations remains challenging.

In this study, an emergy-based assessment method for regional eco-economic sustainable development is proposed, a case study of Henan Province is conducted, and policy recommendations are proposed based on the assessment results. It can be seen from Table 4 that the case study results show that the ESR of Henan Province decreased year-by-year, and the ability of self-sufficiency was weaker. The ELR was consistently high, indicating that the system environment is under great pressure. The EYR showed a downward trend, indicating that the production efficiency was decreasing. The PLR was consistently far greater than one, indicating that the population of Henan Province is overloaded.

This work provides a method for studying regional economic development and a reference for government decision making. However, the following shortcomings remain: (1) Owing to the influence of a large amount of data and other objective conditions, certain specific numerical calculations may have relatively small deviations; nevertheless, they do not affect the conclusions drawn from the key findings of the study. (2) This study only investigates the sustainable development status of one region in Henan Province, which is not comparable and cannot provide more comprehensive policy suggestions. Future research directions will include how to minimize the possible error reduction, as well as a comparative analysis of sustainable development across multiple regions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151612495/s1, Table S1: Raw data of Henan Province from 2010 to 2018; Table S2: Emergy data of Henan Province from 2010 to 2018.

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