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SUSTAINABILITY ANALYSIS OF DATA-DRIVEN AGRICULTURAL ECOLOGICAL ECONOMIC SYSTEMS: A CASE STUDY OF NORTHERN ANHUI

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Abstract: The agro-eco-economic system (AEES) is a fundamental system underpinning human survival. To improve the evaluation of regional AEES performance, this study proposes an emergy-based framework for assessing sustainable development and constructs a corresponding evaluation index system. Applying this framework, we analyzed AEES data from the Northern Anhui from 2014 to 2023. Key findings reveal: The average total emergy input was 6.04×10^{22} solar emjoules (sej), while the average total emergy output was 5.08×10^{23} sej. The average emergy self-sufficiency ratio (ESR) and net emergy yield ratio (EYR) were 0.13 and 9.72, respectively, showing no significant temporal trend over the decade. The emergy investment ratio (EIR) and environmental loading ratio (ELR) exhibited a declining trend post-2017, indicating substantial yet gradually decreasing environmental pressure on the AEES. The average emergy sustainability index (ESI) was 1.15, with a moderate upward trend observed over the past five years, suggesting developing sustainability potential. Based on these results, the study provides targeted decision-making insights and management implications for advancing high-quality agricultural development in Northern Anhui. This research holds significant theoretical and practical relevance for sustainable AEES management.
Keywords: Data-driven; Emergy; Agricultural eco-economic system; Sustainaxbility; Northern Anhui

1 INTRODUCTION

In 1987, the World Commission on Environment and Development, in its report "Our Common Future," first articulated the concept of sustainable development. Today, eliminating hunger, achieving food security and improved nutrition, and promoting sustainable agriculture are among the United Nations' 17 Sustainable Development Goals. Therefore, the sustainable development of the AEES is both an effective pathway to solving hunger and an important integral component of global sustainable development.

To better understand AEES sustainability, scholars have employed diverse methods and tools for assessment [1-4]. However, a key issue with these evaluation methods is the difficulty in unifying indicator selection. The root cause is the inability to convert economic, material, and energy flows into a unified standard. The emergence of emergy analysis has changed this situation. Furthermore, emergy analysis allows for the quantification and comparison of energy flows across different systems. Emergy, pioneered by the renowned ecologist Odum, posits that all energy on Earth originates from solar energy. Therefore, inputs and outputs (materials or energy) of the AEES can be uniformly converted into solar emergy based on specific ratios, measured in solar emjoules (sej) [5]. Emergy analysis uses emergy as a baseline, converting different types of otherwise incomparable energy within a system into a common standard for measurement and analysis, enabling the quantitative analysis of AEES sustainability. Currently, emergy analysis is widely applied in the sustainability evaluation of ecological economic systems [6-8]. Research on emergy analysis applications in agricultural ecosystem sustainability primarily focuses on two main areas: comparing sustainability across different AEES [9] and studying regional AEES sustainability [10-11].

This study takes the AEES of Northern Anhui as its object and employs emergy analysis for quantitative evaluation. It constructs a sustainable development evaluation index system for the Northern Anhui AEES. By collating and calculating basic AEES data for Northern Anhui from 2014 to 2023, it evaluates the sustainable development capacity of the region's AEES.

2 RESEARCH METHODS AND INDEX SYSTEM

2.1 Research Methods

The AEES is an organic whole. To scientifically and comprehensively evaluate its operational status and development characteristics, selected evaluation indicators should possess relative independence. This paper divides the AEES energy flow into Total Emergy Used (Input, E) and Total Emergy Yield (Output, Y). System input emergy is categorized by source into Renewable Environmental Resource Input (R), Non-renewable Environmental Resource Input (N), Renewable Organic Emergy Input (T), and Non-renewable Industrial Auxiliary Emergy Input (F). System output emergy is categorized by agricultural sector into crop farming, animal husbandry, forestry, and fishery.

According to the emergy calculation method, the emergy values for the input and output items are calculated separately using the following formula:

$$B_i = \sum_i O_i E_i Tr_i \qquad i = 1, \ldots, n \tag{1}$$

Where B_i is the solar emergy of the *i*-th input or output item, O_i is the actual collected data for the *i*-th item, E_i is the energy conversion coefficient for the i-th item, and Tr_i is the solar transformity for the *i*-th item. After calculation using Formula 1, the emergy units for all input and output items are unified into solar emjoules (sej).

2.2 Index System

To understand the operational status of the regional AEES, this paper, from the perspectives of resources, environment, economy, and sustainability, and drawing on relevant literature, introduces five evaluation indicators: Emergy Self-Sufficiency Ratio (ESR), Emergy Investment Ratio (EIR), Net Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and Emergy Sustainability Index (ESI). This establishes the regional AEES emergy evaluation index system.

Emergy Self-Sufficiency Ratio (ESR) evaluates the system's self-sufficiency (Formula 2). A higher value generally indicates a greater contribution of natural resources to the system's inputs and stronger self-sufficiency. Renewable resources include solar radiation, wind energy, rain potential energy, and rain chemical energy. As wind, rain potential, and rain chemical energy ultimately derive from solar energy, the maximum value among renewable resources is used as the system's renewable resource emergy input.

$$ESR = (R + N) / E \tag{2}$$

Environmental Loading Ratio (ELR) characterizes the magnitude of environmental pressure borne by the AEES (see Formula 3). A higher ELR value indicates more non-renewable resource inputs (e.g., fertilizers, pesticides), leading to excessive dependence on artificial resources, significant environmental pressure, and hindering sustainable AEES development.

$$ELR = (F + N) / R \tag{3}$$

Emergy Investment Ratio (EIR) is the ratio of the sum of non-renewable industrial auxiliary emergy (F) and organic emergy (T) to the natural environmental input emergy (R + N). This indicator measures the development level of the AEES and its resource and environmental pressure. A higher EIR value indicates a higher level of economic development but also greater environmental pressure (see Formula 4).

$$EIR = (F + T) / (R + N) \tag{4}$$

Net Emergy Yield Ratio (EYR) is the ratio of output emergy (Y) to the sum of non-renewable industrial auxiliary emergy (F) and organic emergy (T) inputs (see Formula 5). This index reflects the system's sustainability. A higher value indicates higher efficiency, stronger sustainability, and higher price competitiveness of agricultural products.

$$EYR = Y / (F + T) \tag{5}$$

Emergy Sustainability Index (ESI) was proposed by Italian scientist Ulgiati and American ecologist Brown in 1997 (Formula 6) [12]. A region with a high EYR and a low ELR has a high ESI, indicating good sustainability; conversely, it indicates unsustainability. An ESI between 1 and 10 suggests the system is vigorous with development potential. ESI > 10 indicates weak ecosystem sustainability, while ESI < 1 indicates a consumer-oriented economic system.

$$ESI = EYR / ELR \tag{6}$$

Based on the above emergy indicators, the regional AEES emergy evaluation index system is constructed, as shown in Table 1.

Table 1 Sustainability Evaluation Index System for the Agricultural Ecological Economic System in Northern Anhui

Index Category	Expression	Indicator Description
Basic Indicators		
Renewable Natural Resources	R	Renewable resources from nature, e.g., solar, wind, rain energy
Non-renewable Natural Resources	N	Non-renewable resources from nature, e.g., topsoil loss
Non-renewable Industrial Auxiliary Emergy	F	Non-renewable industrial products in input emergy, e.g., fertilizer, pesticide, diesel, etc.
Organic Emergy	T	Organic emergy input to the system, including labor, seeds, organic fertilizer, etc.
Total Input Emergy	E=R+N+F+T	Sum of all input emergy items
Total Output Emergy	Y	Total emergy output of the system
Sustainability Indicators		
Emergy Self-Sufficiency Ratio (ESR)	ESR = (R + N) / E	Natural resource endowment and contribution to AEES development
Environmental Loading Ratio (ELR)	ELR = (F + N) / R	Pressure on the environment
Emergy Investment Ratio (EIR)	EIR = (F + T) / (R + N)	Level of regional agricultural economic development and environmental pressure
Net Emergy Yield Ratio (EYR)	EYR = Y / (F + T)	Ecosystem operational efficiency
Emergy Sustainability Index (ESI)	ESI = EYR / ELR	Sustainable development capacity of the regional agricultural ecosystem

3 SUSTAINABILITY EVALUATION OF THE AGRICULTURAL ECOLOGICAL ECONOMIC SYSTEM IN NORTHERN ANHUI

3.1 Study Area Overview

Northern Anhui Province is located in the northern part of Anhui, encompassing six prefecture-level cities: Bengbu, Fuyang, Bozhou, Suzhou, Huaibei, and Huainan. It features a warm-temperate semi-humid monsoon climate with distinct seasons, moderate temperatures, and average annual precipitation of 845mm. Annual solar radiation ranges from 5200 to 5400 MJ/m², with 2303.1 sunshine hours annually. In 2023, the grain sown area in Northern Anhui was 4123.72 thousand hectares, accounting for 56.22% of Anhui Province's total. The total grain output reached 40.5075 million tons, representing 54.96% of the provincial total. The permanent population was 26.47 million (43.24% of Anhui), with a rural population of 12.906 million (54.78% of Anhui's rural population). The gross output value of agriculture, forestry, animal husbandry, and fishery was 296.7 billion yuan, constituting 47.48% of Anhui's total. Northern Anhui is a crucial agricultural region in Anhui Province. To enhance its agricultural sustainability and promote high-quality development, this study selects Northern Anhui as the research area.

3.2 Data Sources and Calculation Results

The relevant agricultural basic data used in this paper mainly come from the Anhui Statistical Yearbook(2015-2024) compiled by the Anhui Provincial Bureau of Statistics, supplemented by the author's field surveys. Field survey items mainly included organic fertilizer application, seed usage, and labor input. Climate data (temperature, precipitation, sunshine) for Northern Anhui were obtained from the Meteorological Data Center of the National Meteorological Information Center. Energy conversion coefficients and emergy transformities primarily came from relevant literature [13-15]. The calculation method and process refer to the literature [15]. Based on the AEES emergy flow data for Northern Anhui and Formula 1, 35 input and output items that significantly impact the calculation results were retained. The calculation results are shown in Table 2 and Table 3.

Table 2 Emergy Input Analysis of the Agricultural Ecological Economic System in Northern Anhui (2014-2023) (sej)

	Project	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	Renewable Resource Input (R)(×10^{21})	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
1	Solar Energy(×10^{19})	5.27	5.79	5.79	5.79	5.93	6.01	5.78	5.88	5.98	6.00
2	Wind Energy(×10^{20})	7.62	8.34	8.34	8.34	8.60	8.76	8.33	8.52	8.71	8.75
3	Rainwater Chemical Energy(×10^{21})	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
4	Rainwater Potential Energy(×10^{20})	7.83	8.47	7.83	8.08	9.14	6.43	8.27	9.95	7.91	8.32
	Non-renewable Resource Input (N) (×10^{21})	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
5	Topsoil Loss(×10^{21})	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
	Non-renewable Industrial Auxiliary Input (F)(×10^{22})	4.58	4.67	4.74	4.79	4.86	4.92	4.95	3.92	3.89	3.56
6	N Fertilizer(×10^{21})	7.06	7.07	7.04	7.00	6.95	6.95	6.83	6.69	6.41	5.29
7	P Fertilizer(×10^{21})	8.45	8.43	8.40	8.30	8.30	8.37	8.26	8.05	7.70	4.26
8	K Fertilizer(×10^{20})	7.78	7.94	8.00	8.06	8.24	8.29	8.30	8.20	7.89	7.10
9	Compound Fertilizer(×10^{21})	2.50	2.68	2.79	2.91	2.97	3.08	3.17	3.19	3.10	4.20
10	Pesticides(×10^{20})	1.40	1.37	1.34	1.37	1.40	1.40	1.35	1.32	1.26	9.95
11	Agricultural Film(×10^{15})	3.46	3.45	3.60	3.69	3.96	4.01	4.01	4.03	3.73	3.19
12	Agricultural Machinery(×10^{22})	2.66	2.73	2.79	2.84	2.91	2.95	2.99	1.99	2.04	2.08
13	Electricity(×10^{20})	2.78	2.93	3.20	3.40	3.53	3.61	3.50	3.44	3.52	2.89
14	Fuel Oil(×10^{17})	1.99	1.97	1.84	1.92	1.94	1.92	1.93	1.44	1.48	1.43
	Organic Emergy Input (T)(×10^{21})	8.03	7.95	7.82	7.75	7.63	7.59	7.50	7.48	7.41	7.40
15	Organic Fertilizer(×10^{20})	2.59	2.55	2.57	2.57	2.61	2.62	2.61	2.60	2.60	2.58
16	Labor(×10^{21})	7.77	7.69	7.56	7.49	7.37	7.33	7.23	7.22	7.15	7.14
17	Seeds(×10^{17})	6.30	6.52	6.99	7.19	7.49	7.46	7.53	7.90	8.00	7.73
	Total Input Emergy (E)(×10^{22})	6.13	6.28	6.27	6.34	6.50	6.30	6.49	5.62	5.39	5.10

Table 3 Emergy Output Analysis of the Agricultural Ecological Economic System in Northern Anhui (2014-2023) (sej)

	Project	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
	Crop Farming(×10^{22})	6.80	6.85	7.21	7.13	7.14	7.14	7.03	6.55	6.61	6.51
1	Wheat(×10^{21})	6.91	6.94	7.22	7.59	7.90	8.04	8.26	8.24	8.38	8.08
2	Rice(×10^{20})	4.41	4.14	4.56	3.75	4.40	4.00	4.01	4.01	3.90	4.11
3	Corn (Maize)(×10^{22})	1.34	1.42	1.55	1.58	1.64	1.62	1.62	1.73	1.73	1.65
4	Beans (Legumes)(×10^{21})	2.08	1.90	1.94	1.67	1.53	1.63	1.32	1.37	1.43	1.94
5	Tubers (Potatoes)(×10^{19})	1.64	2.03	2.14	2.36	2.38	2.06	2.08	3.17	3.61	3.98

6	Peanuts(×10^{21})	4.76	4.64	4.46	4.37	4.47	4.14	4.03	4.03	4.05	3.86
7	Cotton(×10^{21})	11.4	10.7	12.2	10.5	8.46	7.74	6.34	4.69	4.71	4.69
8	Vegetables(×10^{21})	2.76	2.90	3.04	3.17	3.25	3.35	3.38	3.39	3.41	3.47
9	Fruits & Melons(×10^{22})	2.62	2.68	2.72	2.78	2.90	3.00	3.04	2.61	2.64	2.61
	Livestock Products(×10^{23})	4.48	4.36	4.26	4.35	4.38	4.49	4.39	4.11	4.14	3.95
10	Pork(×10^{22})	5.49	5.49	5.34	5.61	5.74	6.09	5.95	5.74	6.31	6.20
11	Beef(×10^{21})	8.52	8.95	8.40	8.52	8.06	8.07	8.20	8.37	8.57	8.71
12	Mutton (Sheep/Goat)(×10^{21})	8.17	8.49	8.29	8.38	8.49	8.87	9.25	9.46	8.78	8.90
13	Poultry Eggs(×10^{22})	6.08	5.85	5.87	5.93	6.00	6.30	6.50	6.77	6.57	6.47
14	Dairy (Milk)(×10^{22})	6.55	6.38	6.63	6.80	6.61	7.04	6.83	6.34	6.60	6.65
15	Other Meats(×10^{22})	3.09	2.85	3.00	3.37	3.43	3.48	3.43	3.46	3.40	3.34
16	Wool(×10^{23})	2.19	2.13	2.01	2.01	2.04	2.03	1.95	1.70	1.68	1.51
	Forestry(×10^{19})	4.96	6.09	6.09	6.38	7.23	7.70	6.87	7.03	6.72	7.46
17	Forest Products(×10^{19})	4.96	6.09	6.09	6.38	7.23	7.70	6.87	7.03	6.72	7.46
	Fishery(×10^{21})	9.01	9.63	10.1	10.6	11.0	10.6	10.7	11.2	7.06	6.56
18	Aquatic Products(×10^{21})	9.01	9.63	10.1	10.6	11.0	10.6	10.7	11.2	7.06	6.56
	Total Output Emergy (Y)**(×10^{23})**	5.25	5.14	5.09	5.17	5.21	5.31	5.20	4.87	4.87	4.67

Based on the relevant emergy data in Tables 2 and 3 and the calculation methods, and using the emergy evaluation index system constructed in Part 2, the indicator values for the AEES in Northern Anhui from 2014 to 2023 were calculated, as shown in Table 4.

Table 4 Sustainability Indicator Values for the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

	Project	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Basic Indicators	R(×10^{21}sej)	5.19	5.61	5.19	5.36	6.06	4.26	5.48	6.60	5.25	5.52
	N(×10^{21}sej)	2.31	2.50	2.31	2.39	2.70	1.90	2.44	2.94	2.34	2.46
	F(×10^{22}sej)	4.58	4.67	4.74	4.79	4.86	4.92	4.95	3.92	3.89	3.56
	T(×10^{21}sej)	8.03	7.95	7.82	7.75	7.63	7.59	7.50	7.48	7.41	7.40
	E(×10^{22}sej)	6.13	6.28	6.27	6.34	6.50	6.30	6.49	5.62	5.39	5.10
	Y(×10^{23}sej)	5.25	5.14	5.09	5.17	5.21	5.31	5.20	4.87	4.87	4.67
Sustainability Indicators	ESR	0.12	0.13	0.12	0.12	0.13	0.10	0.12	0.17	0.14	0.16
	EIR	7.17	6.74	7.35	7.18	6.42	9.22	7.19	4.89	6.10	5.39
	EYR	9.76	9.40	9.22	9.28	9.26	9.35	9.13	10.5	10.5	10.9
	ELR	9.26	8.77	9.56	9.39	8.46	12.0	9.47	6.38	7.86	6.90
	ESI	1.05	1.07	0.96	0.99	1.09	0.78	0.96	1.64	1.34	1.57

3.3 Results and Analysis

3.3.1 Basic indicator analysis

From 2014 to 2023, the average renewable resource emergy input into the AEES in Northern Anhui was 5.45×10^{21} sej, remaining relatively stable. Variations were primarily caused by changes in rainwater chemical energy due to annual precipitation fluctuations. The input of non-renewable industrial auxiliary emergy (F) increased from 4.58×10^{22} sej in 2014 to 4.95 × 10^{22} sej in 2020 (see Fig. 1). After 2020, F input gradually decreased. The reduction in industrial auxiliary energy input helps decrease fertilizer and pesticide residues, improve the AEES environment, and enhance farmers' quality of life. Since 2014, the organic emergy input (T) showed a significant declining trend. This is mainly due to migrant workers typically returning only during busy farming seasons and their farming practices increasingly relying on mechanization. Additionally, the number of large livestock decreased from 962,000 head in 2014 to 786,000 head in 2023, contributing to the reduction in organic emergy input.

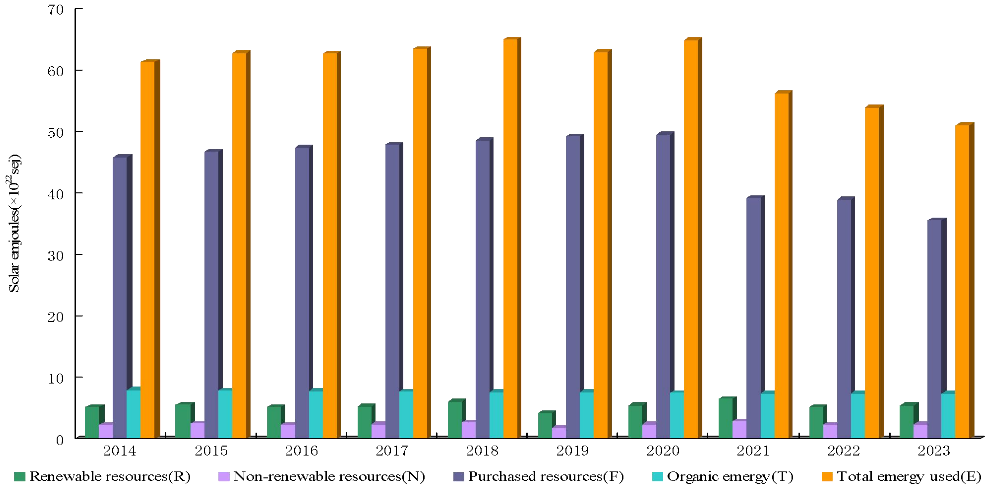

Figure 1 Emergy Inputs of the Agricultural Ecological Economic System in Northern Anhui Region (2014-2023)

The average total emergy input (E) for the Northern Anhui AEES from 2014 to 2023 was 6.04 $\times$ 10^{22} sej. Renewable resources (R), non-renewable resources (N), non-renewable industrial auxiliary emergy (F), and organic emergy (T) accounted for 9.03%, 4.02%, 74.28%, and 12.67% of the total input, respectively (see Table 2, Fig. 2). Over the past decade, fertilizers and pesticides accounted for 30.74% of the total input emergy, indicating they still dominate industrial emergy input in Northern Anhui, exerting significant pressure on the soil and water environment.

The average total emergy output (Y) from 2014 to 2023 was 5.08 $\times$ 10^{23} sej. The lowest output was in 2023 (4.67 $\times$ 10^{23} sej), and the highest was in 2020 (5.31 $\times$ 10^{23} sej). Output fluctuated noticeably from 2015 to 2020 but showed a declining trend after 2020, decreasing from 5.31 $\times$ 10^{23} sej in 2020 to 4.67 $\times$ 10^{23} sej in 2023 (see Table 3). Among the output sectors, livestock products contributed the most emergy, followed by crop farming. The average outputs were 4.29 $\times$ 10^{23} sej for livestock and 6.90 $\times$ 10^{22} sej for crops, accounting for 84.50% and 13.58% of total output, respectively. This indicates that agricultural output in Northern Anhui is still dominated by animal husbandry and crop farming. Due to forests being primarily ecological reserves and limited freshwater areas, forestry and fishery outputs were minor, together accounting for only 1.91% of total output emergy.

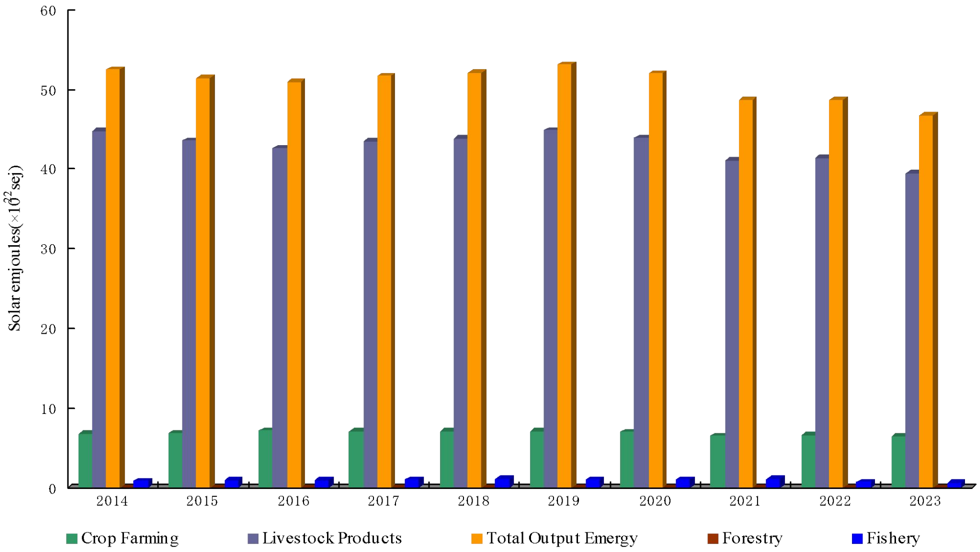

Figure 2 Major Output Emergy of the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

3.3.2 Sustainability indicator analysis

Based on the emergy data analysis results, this study analyzes and evaluates the AEES in Northern Anhui from four dimensions: resources, environment, economy, and sustainability indicators.

(1) Emergy Self-Sufficiency Ratio (ESR)

Since 2014, the ESR of the Northern Anhui AEES ranged from a maximum of 0.17 to a minimum of 0.10, showing little change over the decade (see Fig. 3a). This reflects the relative stability of renewable natural resource input (R), non-renewable natural resource input (N), and total input emergy (E). It also indicates that the proportion of natural resource input within the total input is small, showing relatively low dependence on natural resources, high dependence on industrial inputs, and a relatively high level of agricultural intensification.

(2) Emergy Investment Ratio (EIR)

The average EIR from 2014 to 2023 was 6.76. The highest value was 9.22 in 2016, and the lowest was 4.89 in 2021. After 2016, it showed a declining trend (see Fig. 3b). This indicates high inputs of non-renewable industrial auxiliary emergy (F) and organic emergy (T), meaning a large proportion of purchased emergy input, imposing a certain degree of resource and environmental pressure on AEES sustainable development.

(3) Net Emergy Yield Ratio (EYR)

The average EYR was 9.72. The highest value was 10.86 in 2023, and the lowest was 9.13 in 2020. There was little change from 2014 to 2020, but values increased steadily after 2020 (see Fig. 3c). This indicates high efficiency in converting input emergy within the Northern Anhui AEES, good overall functionality of the agricultural ecosystem, and relatively good sustainability.

(4) Environmental Loading Ratio (ELR)

The ELR fluctuated significantly from 2014 to 2023 and remained at a relatively high level, averaging 8.80. The highest was 11.99 in 2016, and the lowest was 6.90 in 2023 (see Fig. 3c). This indicates that the development of the AEES in Northern Anhui is subject to high environmental pressure, adversely affecting its sustainable development.

(5) Emergy Sustainability Index (ESI)

The average ESI from 2014 to 2023 was 1.15. The highest value was 1.64 in 2021, and the lowest was 0.78 in 2019 (see Fig. 3d). The ESI showed little change from 2014 to 2018 but exhibited a clear upward trend after 2019, increasing from 0.78 in 2019 to 1.57 in 2023. This suggests that the Northern Anhui agricultural ecosystem possesses strong sustainable development potential, showing an increasing trend.

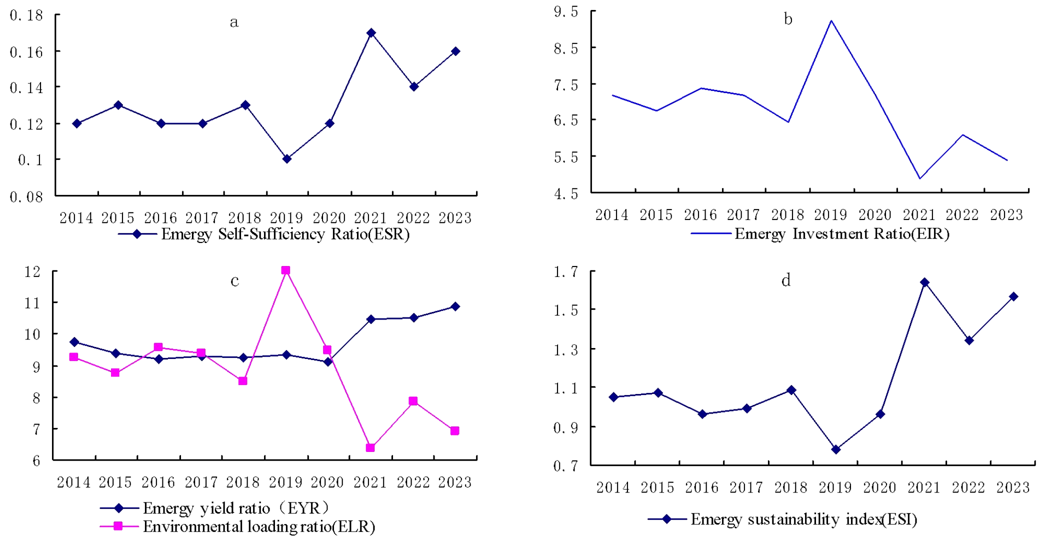

Figure 3 Sustainability Indices of the Agricultural Ecological Economic System in Northern Anhui (2014-2023)

3.4 Management Implications

Based on the quantitative evaluation and research findings, promoting sustainable development of the AEES in Northern Anhui requires multi-faceted solutions. This study proposes the following recommendations:

3.4.1 Reduce non-renewable resource input

Within the AEES inputs of Northern Anhui, non-renewable resources (N) are consumptive and environmentally damaging. Topsoil loss is a major component of N inputs. Therefore, vigorous efforts are needed to prevent soil erosion and soil pollution.

3.4.2 Improve the utilization efficiency of non-renewable purchased resources

Non-renewable purchased resources (F) hold a unique position. While they are artificial inputs, they are also crucial for agricultural production. Thus, reliance on technological advancement is essential to improve the utilization efficiency of F resources, thereby reducing the required input volume. For example, precise measurement of soil nutrient content can enable targeted fertilizer application. Simultaneously, increasing organic fertilizer input and promoting straw return to fields can help reduce chemical fertilizer usage.

3.4.3 Develop ecological agriculture

Encourage the development of ecological planting and breeding, strengthen the certification and management of green food and organic agricultural products. Promote ecological circular agriculture, enhance the resource utilization of livestock and poultry manure, advance comprehensive utilization of crop straw, and strengthen the control of agricultural plastic film pollution. Reinforce the protection and improvement of cultivated land quality and advance the comprehensive management of degraded farmland. Given water scarcity in Northern Anhui, vigorously promote agricultural water conservation and adopt efficient water-saving technologies. Implement healthy aquaculture practices. Conduct actions to reduce pesticide and herbicide usage while enhancing their efficacy.

4 CONCLUSIONS AND DISCUSSION

With the reduction and outflow of rural labor, farming practices have shifted towards efficiency-driven methods, leading to persistently high application rates of fertilizers, pesticides, herbicides, and mechanized farming. This has resulted in increased non-point source pollution and high energy consumption. A critical challenge is how to increase AEES output while reducing its environmental footprint and creating highly sustainable systems under certain input levels. Evaluating regional AEES sustainability and proposing targeted improvement measures are fundamental for transforming agricultural ecosystem development modes and enhancing the quality and efficiency of agricultural development.

This study deepens the understanding of agricultural ecosystem inputs and outputs from an emergy perspective. It establishes a unified measurement model and proposes an evaluation framework integrating economic, environmental, and social benefits. This research provides valuable insights for regional AEES sustainable development, offers theoretical and methodological support for high-quality agricultural development, and furnishes policymakers with effective solutions.

COMPETING INTERESTS

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