sustainability

MDPI

Article

Emergy-Based Evaluation of the Sustainability of Agricultural Ecosystem in Dazhou, China, from 2002 to 2022

Yun Liu [1,2,*], Johan Afendi Bin Ibrahim [2] and Yen Sin Foo [2]

[1] School of Teacher and Education, Northwest Normal University, Lanzhou 730070, China
[2] School of Tourism, Hospitality and Event Management, Universiti Utara Malaysia, Sintok 06010, Malaysia; afendi@uum.edu.my (J.A.B.I.); foo.yen.sin@uum.edu.my (Y.S.F.)
* Correspondence: liuyunlianxi@163.com

Abstract: Our aim is to analyze the emergy evaluation indicators of the agricultural ecosystem in Dazhou, northeastern Sichuan, and provide practical and effective recommendations for sustainable agricultural development. Using emergy analysis, the emergy inputs and outputs of an agricultural ecosystem from 2002 to 2022 were calculated. Five emergy indicators were selected for evaluation: emergy yield ratio (EYR), emergy self-sufficiency ratio (ESR), emergy input ratio (EIR), environmental load ratio (ELR), and emergy sustainable indices (ESI). The total emergy input of the agricultural ecosystem showed an upward trend from 2002 to 2017, thus the industrial auxiliary emergy input decreased, somewhat curbing its continued rise from 2017 to 2022. The structure of emergy inputs, in descending order, is as follows: industrial auxiliary > organic emergy > renewable environmental resources > non-renewable environmental resources. The total emergy output of the agricultural ecosystem was highest in 2007, reaching 2.31×10^{22} Sej, and lowest in 2012, at 1.83×10^{22} Sej. The structure of emergy outputs, in descending order, is as follows: livestock > planting > fishery > forestry. The emergy yield ratio fluctuated down from 3.12 to 2.51, with an average of 2.88, below the provincial average of 3.07. The emergy self-sufficiency ratio fluctuated down from 0.30 to 0.26, with an average of 0.27, above the provincial average of 0.13. The emergy input ratio fluctuated up from 2.31 to 2.91, with an average of 2.66, above the provincial average of 1.86. The environmental load ratio fluctuated from 3.8 to 4.75, with an average of 4.40, which is higher than the provincial average of 1.68. The emergy sustainable indices fluctuated down from 0.81 to 0.53, with an average of 0.67, below the provincial average of 1.17. The efficiency of resource utilization in the agricultural ecosystem of Dazhou has decreased, economic inputs have increased, and it is in a consumptive production process. The pressure on the local natural environment is increasing, and the capacity for sustainable development remains at a low level over the long term.

Keywords: agricultural ecosystem; emergy analysis; Dazhou; sustainable development

check for updates

Citation: Liu, Y.; Ibrahim, J.A.B.; Foo, Y.S. Emergy-Based Evaluation of the Sustainability of Agricultural Ecosystem in Dazhou, China, from 2002 to 2022. *Sustainability* **2024**, *16*, 9156. https://doi.org/10.3390/su16219156

Academic Editors: Mrittika Basu and Rajarshi Dasgupta

Received: 9 August 2024
Revised: 14 October 2024
Accepted: 19 October 2024
Published: 22 October 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Agricultural ecosystems (AE) are vital to human survival and the health of our planet [1]. These ecosystems, where agricultural activities and natural processes interact, serve a key function in furnishing food, raw materials, and economic equilibrium [2]. They are fundamental to sustaining global food security, offering a steady supply of crops and livestock that feed billions of people worldwide [3]. One key aspect of AE is their contribution to biodiversity [4]. Traditional farming practices, such as rotational cropping and polyculture, promote a diverse range of species, which help maintain ecosystem stability and resilience [5]. This biodiversity is essential for pollination, pest control, and soil health, ensuring that agricultural systems remain productive over time [6]. Moreover, AE are integral to the carbon cycle. Through photosynthesis, crops capture carbon dioxide from the atmosphere, helping to mitigate climate change [7]. Sustainable farming practices, such as conservation tillage and agroforestry, further enhance carbon sequestration and reduce

greenhouse gas emissions [8]. AE also support rural communities and economies [9]. They provide livelihoods for millions of farmers and workers, fostering economic development and social stability [10]. In many regions, agriculture is a cornerstone of cultural heritage and traditional knowledge, contributing to the social fabric of societies [11]. However, these ecosystems face significant challenges, including climate change, soil degradation, and loss of biodiversity [12]. Therefore, it is crucial to adopt sustainable agricultural practices and policies that protect and enhance the resilience of these ecosystems. By doing so, we can ensure that AE continue to provide essential services for future generations, while also preserving the health of our planet.

In recent years, China has placed significant emphasis on agricultural ecological protection, implementing various measures to promote sustainable farming practices and environmental conservation [13]. These efforts are aimed at addressing challenges like soil deterioration, water crisis, and pollution, while ensuring food security and the health of rural communities. One of the key measures China has adopted is the promotion of eco-friendly agricultural practices [14]. This includes the widespread implementation of organic farming, integrated pest management, and the reduction of chemical fertilizer and pesticide use. By encouraging farmers to adopt these methods, China aims to enhance soil health, improve crop quality, and reduce environmental contamination. China has also invested heavily in the restoration of degraded lands [15]. The country has launched large-scale afforestation and reforestation projects (e.g., the Grain for Green program), which converts marginal farmlands into forest and grasslands. This initiative has helped to reduce soil depletion, improve water retention, and increase biodiversity. In addition, the Chinese government has implemented policies to protect water resources. Measures include the construction of efficient irrigation systems, the promotion of water-saving technologies, and the strict regulation of agricultural runoff to prevent water pollution. These efforts have contributed to the maintenance of vital water supplies and the improvement of water quality in agricultural regions [16]. The results of these measures have been significant. China has seen improvements in soil fertility, increased agricultural productivity, and a reduction in the use of harmful agrochemicals [17]. Additionally, the restoration projects have enhanced the resilience of ecosystems and reduced the impact of natural disasters such as floods and droughts. Overall, China's commitment to agricultural ecological protection has led to positive environmental and economic outcomes, demonstrating the importance of sustainable practices in ensuring long-term agricultural sustainability and environmental health.

Emergy analysis (EA) is a method used to evaluate the energy efficiency and sustainability of systems by accounting for all the energy inputs required to produce a product or service [18]. This approach, developed by Howard T. Odum, considers not just the direct energy inputs but also the indirect energy embedded in materials, labor, and environmental services [19]. Emergy is measured in units called emjoules, which represent the amount of energy that has been used directly and indirectly in generating a product [20]. In the context of AE, EA has been increasingly applied to assess the sustainability and environmental impact of various farming practices [21]. By calculating the emergy inputs (EI) required for agricultural production, researchers can compare different farming systems and identify those that are more energy-efficient and sustainable [22]. For instance, EA can be used to estimate the efficiency of organic versus conventional farming methods. Organic farming often shows higher emergy efficiency due to lower inputs of manufactured fertilizers and biocides, and a greater reliance on natural processes [23]. This approach underscores the advantages of organic agriculture regarding energy efficiency and diminished ecological footprints. EA is also used to assess the sustainability of agroecosystems by considering the renewable and non-renewable resources involved [24]. It offers an in-depth view of the ecological expenses linked to farming practices, including soil degradation, water use, and biodiversity loss [25]. This holistic view is crucial for developing strategies that enhance the sustainability of agricultural systems [26]. Moreover, policymakers and farmers can use EA to make informed decisions about resource allocation and management practices [27].

By identifying practices with lower EI and higher sustainability, EA supports the transition towards more resilient and environmentally friendly agricultural systems [28]. Overall, EA provides crucial perspectives on the energy flows and viability of agricultural systems, aiding in the development of practices that promote ecological balance and resource conservation.

In the early 1990s, Professor Lan pioneered the introduction of EA theory in China, applying it to the study of AE [29]. Since then, the theory has evolved and become a prevalent method for evaluating the sustainability of AE in the country [30]. EA is extensively used in China to evaluate energy performance, resource management, and the ecological effects of different farming methods [31]. Researchers and policymakers employ this approach to grasp the full ecological and economic impacts of farming systems, directing the creation of more sustainable agricultural practices [32]. One significant application of EA in China is in the comparison of traditional and modern farming methods [33]. By evaluating the EI and outputs of these systems, studies have shown that traditional farming practices often have higher emergy efficiency due to their reliance on renewable resources and lower dependence on synthetic inputs [34]. This has provided valuable insights for promoting sustainable agricultural practices that align with ecological principles [35]. EA is also employed to evaluate the viability of various cropping systems and livestock operations [36]. For instance, it has been utilized to assess energy consumption and the ecological effects of rice–wheat rotation, organic agriculture, and integrated crop–livestock systems. These studies have highlighted the benefits of diversified and integrated farming practices in terms of energy savings and reduced environmental degradation [37]. EA supports the development of policies aimed at sustainable agriculture [38]. By offering a comprehensive perspective on resource utilization and ecological effects, it helps in devising strategies to improve the sustainability of agricultural systems [39]. For example, it has been instrumental in the promotion of conservation agriculture, agroforestry, and other operations that better soil health and biodiversity [40]. The application of EA in China has significantly advanced the understanding of agricultural sustainability [41]. It continues to be a vital tool for researchers and policymakers, fostering the development of resilient and environmentally friendly agricultural systems that can meet the challenges of the future [42].

Scholars have conducted emergy studies on the AE of several cities, including Chizhou, Dingxi, Loudi, Tangshan, Harbin, Chengde, and Yancheng. These studies provide valuable references for emergy research in other cities. Dazhou is a major agricultural city and has ranked first in grain production in Sichuan Province for 11 consecutive years. Dazhou is actively exploring pathways for sustainable agricultural development, offering a notable contribution in Sichuan. This paper utilizes emergy theory and analysis methods to conduct an empirical study of the AE emergy of Dazhou from 2002 to 2022, and offers recommendations for advancement.

2. Materials and Methods

2.1. Study Area

Dazhou (30°19′ N—32°20′ N, 106°39′ E—108°32′ E) is located in the northeastern part of Sichuan Province, at the southern foothills of the Daba Mountains. It stretches 177.5 km from east to west and extends 223.8 km from north to south. The terrain is higher in the north and lower in the south, sloping from the northeast to the southwest, with a total area of 16,600 km^2. The northern part is the mountainous area of the Daba Mountains, the southeastern part consists of the parallel ridge–valley system of eastern Sichuan, and the western part adjoins the hilly areas and low mountainous regions of the Sichuan Basin. Between the mountains and hills, there are broad valleys and gently sloping plains. The highest elevation is 2458.3 m, while the lowest elevation is 222 m. Dazhou is located in a subtropical monsoon climate zone, with unevenly distributed precipitation. The average annual temperature is 16.6 °C, and the average annual precipitation is 1193.3 mm. The rivers within the region belong to the Qujiang River system and the Hanjiang River system. The Qujiang River system has a drainage area of 14,966 km^2 within the region, while the

Hanjiang River system has a drainage area of 512 km^2. As of December 2022, Dazhou administers 2 districts and 5 counties. Dazhou is a populous city, a major agricultural hub, and a resource-rich area in Sichuan Province. In recent years, Dazhou has actively promoted green farming and livestock recycling, exploring new paths for ecological agriculture development to boost sustainable agricultural growth.

2.2. Data Collection

AE data, including inputs, outputs, meteorological information, and other relevant data, were systematically classified and archived [2,13]. Figure 1 was created to elucidate the energy transfer dynamics within the primary components of the system. This figure analyzes the interactions between the system's elements and their surrounding environment.

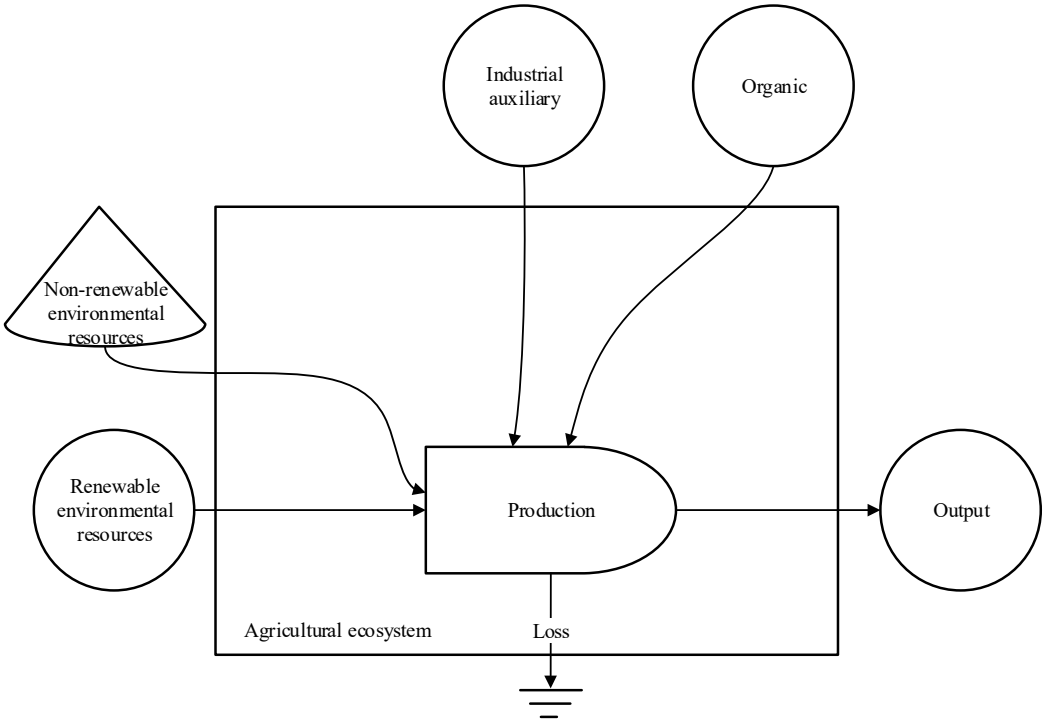


Figure 1. Energy flows in the agricultural ecosystem in Dazhou.

Based primarily on the "Statistical Yearbook on Dazhou (2002–2022)", "Government Work Reports on Dazhou (2002–2022)", and "National Economic and Social Development Statistical Bulletins (2002–2022)", as well as on-site visits, surveys, and measurements, the basic data for input and output projects required for emergy calculations have been compiled. The emergy conversion rates are mainly derived from research by Odum [29–32] and Lu [33,34], among others [35,36], as shown in Table 1.

Table 1. The emergy conversion rates of items in the agricultural ecosystem.

Types	Items	Transformity (Sej/J or Sej/g)
Renewable environmental resources (R)	Solar energy	1.00 Sej/J
	Wind energy	1.50×10^3 Sej/J
	Rainwater potential	8.88×10^3 Sej/J
	Rainwater chemical energy	1.50×10^4 Sej/J
	Earth rotation energy	2.90×10^4 Sej/J
Non-renewable environmental resources (N)	Topsoil energy loss	6.35×10^4 Sej/J

Table 1. *Cont.*

Types	Items	Transformity (Sej/J or Sej/g)
Industrial Auxiliary (T)	Fertilizer	1.78×10^{10} Sej/g
	Pesticide	1.62×10^{9} Sej/g
	Agricultural film	3.80×10^{8} Sej/g
	Fuel oil	6.60×10^{4} Sej/J
	Electricity	1.59×10^{5} Sej/J
	Total power of agricultural machinery	7.50×10^{7} Sej/J
Organic (F)	Seed	6.60×10^{4} Sej/g
	Organic fertilizer	2.70×10^{9} Sej/g
	Labor	3.80×10^{5} Sej/J

Note: Transformity was determined as an average value without considering the differences between farms.

2.3. Measured Parameters

The raw data of each item need to be calculated after determining the emergy conversion rates. Referring to relevant materials [29–36], the energy calculation formulas for each project are compiled as shown in Table 2.

Table 2. The calculation of the raw data.

Items (Sej)	Calculation
Solar energy	Solar constant (1367 W/m^2) × sunshine duration (h) × (1 − albedo) × area (m^2)
Wind energy	Average elevation (m) × air density (kg/m^3) × eddy diffusion coefficient (m^2/s) × wind speed gradient (m/s) × area (m^2)
Rainwater potential	Average elevation (m) × annual precipitation (m) × rainfall density (10^3 kg/m^3) × gravitational acceleration (9.8 m/s^2) × area (m^2)
Rainwater chemical energy	Annual precipitation (m) × gibbs free energy of rainwater (10^3 J/mol) × rainfall density (10^3 kg/m^3) × area (m^2)
Earth rotation energy	Heat flux (J/m^2) × area (m^2)
Topsoil energy loss	Soil erosion rate (kg/m^2) × soil organic matter content (g/kg) × organic matter energy (J/g) × area (m^2)
Fuel oil, electricity, total power of agricultural machinery, and labor	Annual consumption (kg) × energy conversion factor (J/kg)
Fertilizer, pesticide, agricultural film, organic fertilizer, seed, organic fertilizer, and output	Can be directly obtained from the statistical yearbook

Emergy refers to the value of the energy consumed, directly or indirectly, in the formation of resources, products, or services [43]. It is measured using solar emergy as the standard, with Sej as the unit of measurement [44]. Energy transformations and storage in AE adhere to the principles of energy conservation and the law of diminishing energy returns [45]. Renewable resources such as solar radiation, wind, and precipitation are harnessed by the AE through its production functions [46]. To maintain the agricultural ecological environment's capacity to consistently provide necessary materials and energy, feedback from human society is imperative [47]. This feedback is crucial for updating and enhancing the functional and industrial support within the agricultural ecology [48]. Higher tiers in the energy hierarchy exhibit elevated energy conversion rates, necessitating greater energy input to sustain high energy quality and enhanced control capabilities, which are pivotal for the system [49]. The fundamental expression for solar value in terms of

matter or energy conversion is in Formula (1), and E is for emergy (Sej), S is for transformity (Sej/J or Sej/g), and A is for available energy (J or g).

$$E = A \times S \quad (1)$$

2.4. Assessment Metrics

The emergy input of an agricultural ecosystem is composed of four parts: renewable environmental resources (R), non-renewable environmental resources (N), industrial auxiliary inputs (T), and organic inputs (F) [50]. The emergy outputs of an agricultural ecosystem consist of four sectors: crop farming, forestry, animal husbandry, and fisheries [51].

Five emergy indicators were selected: emergy yield ratio (EYR), emergy self-sufficiency ratio (ESR), emergy input ratio (EIR), environmental load ratio (ELR), and emergy sustainable index (ESI) [52]. The rationale behind choosing these specific indicators over others commonly used in EA lies in their ability to provide a comprehensive evaluation of sustainability [53]. These indicators offer insights into both the productivity and environmental impact of the agricultural system, as well as its long-term sustainability [54]. Specifically, the EYR and ESR reflect the system's efficiency and reliance on local resources, while the ELR and EIR address the environmental pressures and dependency on external inputs [55]. The ESI combines these factors to give an overall measure of sustainability [56]. These indicators were chosen to provide a balanced evaluation of the performance of agricultural ecosystem across different dimensions, ensuring a well-rounded assessment.

2.4.1. Emergy Yield Ratio

The emergy yield ratio (EYR) is the ratio of the total emergy output to the economic emergy input, reflecting the efficiency with which an AE utilizes purchased emergy [57]. The efficiency of this utilization depends on the level of agricultural technology and productivity [58]. The more advanced the agricultural technology and the higher the productivity level, the greater the EYR value. Generally, if EYR > 2, this indicates that the agricultural technology is relatively advanced, the productivity level is high, and the conversion rate of the AE is high [59]. Conversely, if EYR < 2, this suggests that the agricultural technology is relatively outdated, the productivity level is low, and the conversion rate of the AE is low [60].

2.4.2. Emergy Self-Sufficiency Ratio

The emergy self-sufficiency ratio (ESR) is the ratio of the EI from environmental resources to the total EI [61]. It reflects the contribution of natural resources and the system's dependency on them [62]. In regions with favorable natural resource conditions, such as excellent water, heat, and soil conditions, the contribution to the AE is higher [63]. At the same time, less emergy is needed to improve agricultural production conditions, indicating a higher dependency on natural resources [64]. A higher ESR value indicates a greater contribution of environmental resources and a higher level of dependency on them [65].

2.4.3. Emergy Input Ratio

The emergy input ratio (EIR) is the ratio of economic EI to environmental resource emergy, reflecting the level of agricultural economic development [66,67]. In regions with higher levels of agricultural economic development, more economic input is made, resulting in a higher EIR value [68]. On the one hand, investments in agricultural infrastructure, innovation in agricultural technology, improved seeds, enhanced labor quality, and increased organic fertilizers will increase the EIR value, which supports sustainable agricultural development [69]. On the other hand, increased investments in pesticides and chemical fertilizers to control pests and enhance soil fertility will also raise the EIR value but may hinder sustainable development [70].

2.4.4. Environmental Load Ratio

The environmental load ratio (ELR) is the ratio of the sum of economic EI and non-renewable resource emergy to renewable resource emergy, reflecting the pressure exerted by the system on the local ecosystem [71]. Generally, as more economic resources are invested in agriculture, the utilization of environmental resources increases, leading to higher agricultural output and a greater ELR value [72]. A higher ELR indicates greater environmental pressure from the system, which may lead to ecological issues such as soil fertility decline, soil erosion, vegetation damage, and water and soil loss [73].

2.4.5. Emergy Sustainable Indices

The emergy sustainable index (ESI) is the ratio of EYR to ELR, reflecting the management level in balancing agricultural output with ecological protection and indicating the system's sustainable development capability (SDC) [74]. A higher EYR and a lower ELR result in a higher ESI, demonstrating stronger SDC [75]. If the ESI value is less than 1, it indicates low agricultural output energy benefits, excessive environmental pressure, and weaker SDC [76]. If the ESI value is between 1 and 10, it indicates higher agricultural output energy benefits, lower environmental pressure, a vibrant system, and stronger SDC, representing an ideal development state [77]. If the ESI value is greater than 10, it suggests lower levels of agricultural economic development, a stronger dependency on natural resources, a weaker capacity to alter natural conditions, and a lower SDC [78]. Formula of assessment metrics are listed in Table 3, and R is for renewable environmental resources, N is for non-renewable environmental resources, T is for industrial auxiliary, F is for organic, and Y is for output.

Table 3. Emergy evaluation index.

Index	Formula
EYR	$Y \cdot (T + F)^{-1}$
ESR	$(R + N) \cdot (R + N + T + F)^{-1}$
EIR	$(T + F) \cdot (R + N)^{-1}$
ELR	$(N + T + F) \cdot R^{-1}$
ESI	$EYR \cdot ELR^{-1}$

3. Results

3.1. Emergy Inputs of Agricultural Ecosystem in the Study Area

The total EI for AE increased from 8.51×10^{21} Sej to 1.10×10^{22} Sej from 2002 to 2017, and the system's total EI remained at 1.10×10^{22} Sej from 2017 to 2022. Specifically, the EI from R increased from 1.75×10^{21} Sej to 1.92×10^{21} Sej, while the EI from N rose from 8.24×10^{20} Sej to 9.04×10^{20} Sej from 2002 to 2022. The EI from F increased from 2.72×10^{21} Sej to 3.23×10^{21} Sej. The EI from T rose annually from 3.22×10^{21} Sej to 5.05×10^{21} Sej from 2002 to 2017, but it slightly decreased to 4.98×10^{21} Sej from 2017 to 2022. This indicates that the total EI for AE showed an upward trend from 2002 to 2017, and the reduction in T input somewhat curtailed its continued increase from 2017 to 2022. These data of EI of AE in the study are listed in Table 4.

In terms of the proportion of EI, the order from largest to smallest is as follows: T > F > R > N, as seen in Figure 2. Although the EI from T shows a decreasing trend, it remains the highest proportion type. Among these, fertilizers and labor are the projects with the highest proportion of input. Due to the location on the edge of the Sichuan Basin, with a predominantly hilly and mountainous terrain, agricultural land is dispersed and large-scale production is difficult to achieve, making it challenging to promote large machinery. The AE primarily relies on abundant labor and small machinery for development. People have improved agricultural production conditions and enhanced land productivity by increasing the use of fertilizers and pesticides, and actively developed characteristic agriculture suited to the hilly and mountainous terrain.

Table 4. Emergy input of agricultural ecosystem in Dazhou from 2002 to 2022.

Types	Items (Sej)	2002	2007	2012	2017	2022
Renewable environmental resources (R)	Solar energy	3.48×10^{19}	3.66×10^{19}	3.62×10^{19}	3.72×10^{19}	3.81×10^{19}
	Wind energy	3.25×10^{20}	3.42×10^{20}	3.38×10^{20}	3.48×10^{20}	3.56×10^{20}
	Rainwater potential	6.24×10^{20}	6.56×10^{20}	6.49×10^{20}	6.68×10^{20}	6.84×10^{20}
	Rainwater chemical energy	5.50×10^{20}	5.79×10^{20}	5.73×10^{20}	5.89×10^{20}	6.04×10^{20}
	Earth rotation energy	2.15×10^{20}	2.26×10^{20}	2.24×10^{20}	2.31×10^{20}	2.36×10^{20}
	Subtotal	1.75×10^{21}	1.84×10^{21}	1.82×10^{21}	1.87×10^{21}	1.92×10^{21}
Non-renewable environmental resources (N)	Topsoil energy loss	8.24×10^{20}	8.67×10^{20}	8.58×10^{20}	8.82×10^{20}	9.04×10^{20}
Environmental resource input (R + N)		2.57×10^{21}	2.71×10^{21}	2.68×10^{21}	2.76×10^{21}	2.82×10^{21}
Industrial auxiliary (T)	Fertilizer	2.79×10^{21}	3.10×10^{21}	3.52×10^{21}	3.90×10^{21}	3.67×10^{21}
	Pesticide	6.09×10^{18}	6.11×10^{18}	7.20×10^{18}	7.39×10^{18}	6.68×10^{18}
	Agricultural film	2.28×10^{18}	3.16×10^{18}	4.09×10^{18}	4.30×10^{18}	3.92×10^{18}
	Fuel oil	1.44×10^{19}	2.02×10^{19}	2.99×10^{19}	3.61×10^{19}	3.75×10^{19}
	Electricity	1.92×10^{20}	2.91×10^{20}	3.81×10^{20}	4.72×10^{20}	5.12×10^{20}
	Total power of agricultural machinery	2.11×10^{20}	3.07×10^{20}	4.20×10^{20}	6.30×10^{20}	7.52×10^{20}
	Subtotal	3.22×10^{21}	3.73×10^{21}	4.36×10^{21}	5.05×10^{21}	4.98×10^{21}
Organic (F)	Seed	4.33×10^{18}	4.45×10^{18}	5.33×10^{18}	5.40×10^{18}	5.56×10^{18}
	Organic fertilizer	1.61×10^{19}	1.88×10^{19}	1.93×10^{19}	2.15×10^{19}	2.42×10^{19}
	Labor	2.70×10^{21}	2.66×10^{21}	2.97×10^{21}	3.16×10^{21}	3.20×10^{21}
	Subtotal	2.72×10^{21}	2.68×10^{21}	2.99×10^{21}	3.19×10^{21}	3.23×10^{21}
Economic input (T + F)		5.94×10^{21}	6.41×10^{21}	7.36×10^{21}	8.24×10^{21}	8.21×10^{21}
Total input		8.51×10^{21}	9.12×10^{21}	1.00×10^{22}	1.10×10^{22}	1.10×10^{22}

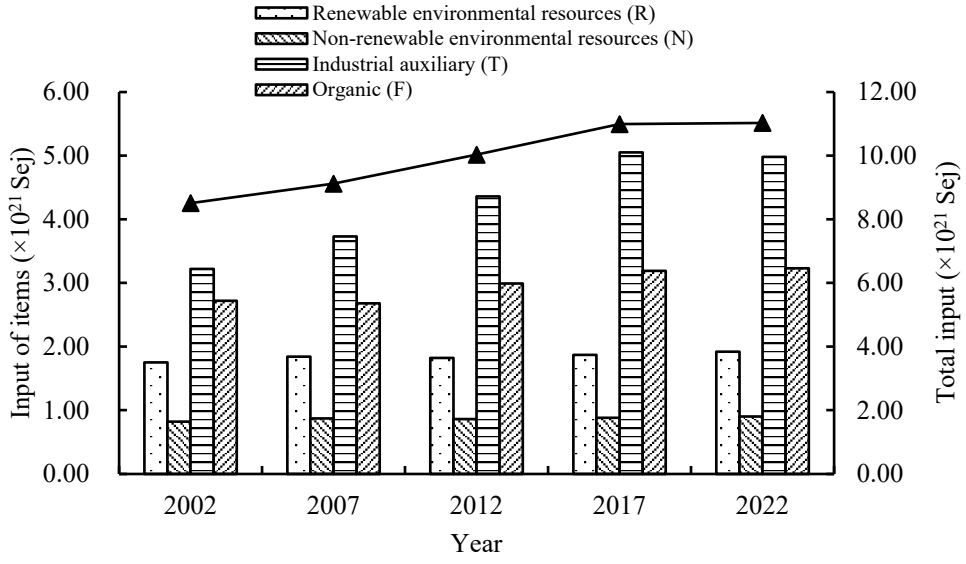


Figure 2. Changes in emergy input of agricultural ecosystem in Dazhou from 2002 to 2022.

3.2. Emergy Outputs of Agricultural Ecosystem in the Study Area

The total emergy output (EO) of AE reached its highest at 2.31×10^{22} Sej in 2007, while it was at its lowest at 1.83×10^{22} Sej in 2012. The EO of animal husbandry decreased from 1.40×10^{22} Sej to 1.21×10^{22} Sej between 2002 and 2022. The EO of crop cultivation increased from 3.81×10^{21} Sej to 6.61×10^{21} Sej. The EO of fisheries rose continuously from 6.26×10^{20} Sej to 1.78×10^{21} Sej. The EO of forestry grew from 3.26×10^{19} Sej

to 1.12×10^{20} Sej between 2002 and 2017, but then slightly decreased to 1.02×10^{20} Sej between 2017 and 2022. These data of EO of AE in the study area are listed in Table 5.

Table 5. Emergy output of agricultural ecosystem in Dazhou from 2002 to 2022.

Departments	Items (Sej)	2002	2007	2012	2017	2022
Crop farming	Paddy	1.62×10^{21}	1.55×10^{21}	1.73×10^{21}	1.77×10^{21}	1.75×10^{21}
	Wheat	3.12×10^{20}	2.58×10^{20}	1.92×10^{20}	7.91×10^{19}	3.78×10^{19}
	Corn	8.61×10^{20}	8.01×10^{20}	8.27×10^{20}	1.14×10^{21}	1.31×10^{21}
	Sorghum	6.47×10^{19}	8.77×10^{19}	7.38×10^{19}	4.52×10^{19}	4.33×10^{19}
	Oil crops	4.04×10^{20}	5.53×10^{20}	4.30×10^{20}	7.06×10^{20}	6.20×10^{20}
	Fruit	2.53×10^{19}	5.63×10^{19}	6.30×10^{19}	7.25×10^{19}	8.06×10^{19}
	Vegetable	1.08×10^{20}	1.50×10^{20}	1.78×10^{20}	2.04×10^{20}	1.92×10^{20}
	Beans	2.49×10^{20}	3.24×10^{20}	6.72×10^{20}	1.99×10^{21}	2.43×10^{21}
	Potatoes	9.09×10^{19}	9.85×10^{19}	6.51×10^{19}	8.17×10^{19}	9.38×10^{19}
	Hemp	3.90×10^{19}	7.46×10^{19}	8.59×10^{19}	3.98×10^{19}	4.11×10^{19}
	Sugar cane	7.79×10^{18}	9.77×10^{18}	7.58×10^{18}	6.17×10^{18}	7.82×10^{18}
	Tobacco leaf	3.70×10^{19}	2.66×10^{19}	3.23×10^{19}	3.97×10^{19}	1.03×10^{19}
	Cotton	3.98×10^{17}	5.82×10^{16}	4.46×10^{16}	0	0
	Subtotal	3.82×10^{21}	3.99×10^{21}	3.97×10^{21}	6.17×10^{21}	6.62×10^{21}
Forestry	Chinese herbal medicine	3.13×10^{17}	3.49×10^{19}	7.20×10^{19}	7.16×10^{19}	4.89×10^{19}
	Tea	3.08×10^{19}	3.08×10^{19}	2.19×10^{19}	2.90×10^{19}	3.84×10^{19}
	Toon	6.75×10^{16}	2.03×10^{17}	3.38×10^{17}	6.08×10^{17}	8.78×10^{17}
	Walnut	3.01×10^{17}	1.04×10^{18}	2.86×10^{18}	9.87×10^{18}	1.27×10^{19}
	Dried bamboo Shoots	1.14×10^{18}	1.14×10^{18}	1.14×10^{18}	1.14×10^{18}	1.14×10^{18}
	Subtotal	3.26×10^{19}	6.81×10^{19}	9.82×10^{19}	1.12×10^{20}	1.02×10^{20}
Animal husbandry	Silkworm cocoon	2.32×10^{18}	2.32×10^{18}	3.66×10^{18}	1.76×10^{18}	2.14×10^{18}
	Milk	6.89×10^{19}	6.89×10^{19}	6.89×10^{19}	9.52×10^{19}	8.63×10^{19}
	Honey	4.09×10^{18}	4.09×10^{18}	4.09×10^{18}	5.67×10^{18}	1.43×10^{19}
	Pork	8.99×10^{21}	1.09×10^{22}	7.12×10^{21}	7.84×10^{21}	5.50×10^{21}
	Beef	1.56×10^{21}	2.61×10^{21}	1.83×10^{21}	1.92×10^{21}	2.11×10^{21}
	Mutton	2.33×10^{20}	5.59×10^{20}	4.09×10^{20}	4.56×10^{20}	5.21×10^{20}
	Poultry	2.12×10^{21}	2.12×10^{21}	2.12×10^{21}	2.12×10^{21}	2.25×10^{21}
	Eggs	1.07×10^{21}	1.79×10^{21}	1.51×10^{21}	1.61×10^{21}	1.65×10^{21}
	Subtotal	1.40×10^{22}	1.81×10^{22}	1.31×10^{22}	1.40×10^{22}	1.21×10^{22}
Fisheries	Aquatic products	6.26×10^{20}	1.06×10^{21}	1.19×10^{21}	1.49×10^{21}	1.78×10^{21}
Total output		1.85×10^{22}	2.32×10^{22}	1.83×10^{22}	2.18×10^{22}	2.06×10^{22}

When ranked from highest to lowest, the EO of agricultural sectors is as follows: animal husbandry > crop cultivation > fisheries > forestry, as shown in Figure 3. In recent years, animal husbandry has been significantly impacted by factors such as the pandemic and unstable market demand, leading to a decline in production. Additionally, due to the lack of high-quality natural pastures, the quality of meat from sheep and cattle lacks market competitiveness, limiting its development potential. The poultry industry is mainly operated on a family scale with relatively low levels of industrialization and standardization, resulting in limited production. These are the main reasons for the decline in animal husbandry production and the decrease in the proportion of EO. The production of rice, wheat, corn, and sorghum has steadily developed. The production of beans has significantly increased, rising from 2.49×10^{20} Sej to 2.43×10^{21} Sej, indicating the successful expansion of bean cultivation. In recent years, leveraging its hilly and mountainous advantages, people have developed its forestry economy with the gradual growth of specialty industries such as Chinese herbal medicine, tea, toon leaves, walnuts, and bamboo shoots, leading to a noticeable increase in forestry EO in the research area.

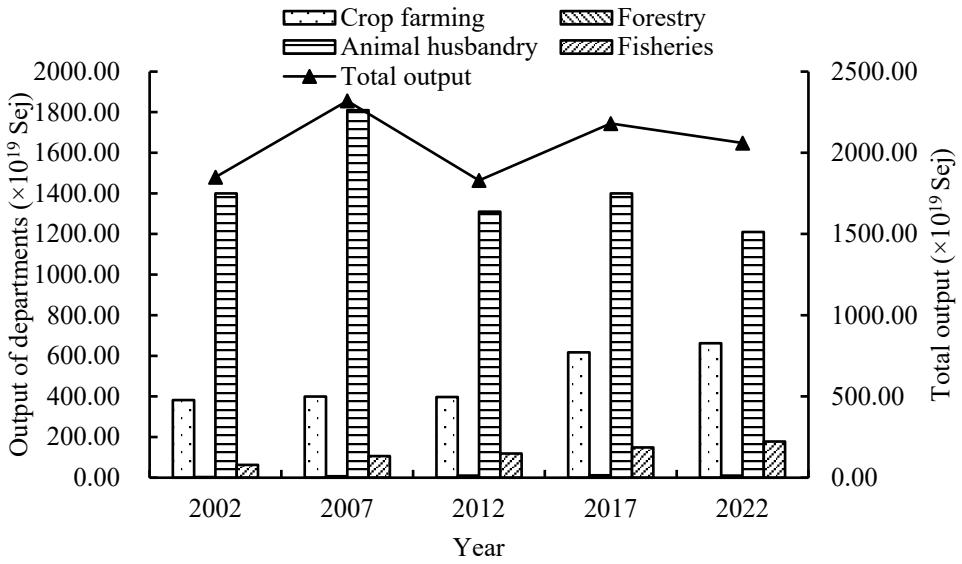


Figure 3. Changes in emergy output of agricultural ecosystem in Dazhou from 2002 to 2022.

3.3. Assessment Metrics of Agricultural Ecosystem in the Study Area

EYR fluctuated from 3.12 down to 2.51, indicating a decrease in system production efficiency between 2002 and 2022. With an average EYR of 2.88, lower than the provincial average of 3.07, the relatively low production efficiency highlights this as a disadvantageous indicator with room for improvement. Firstly, people have emphasized agricultural technology innovation and application, improving the efficiency of environmental resource utilization and making better and more rational use of natural resources such as water and heat, thereby enhancing agricultural production conditions. Secondly, economic strength has continuously improved, with significant increases in agricultural investment, a noticeable growth trend in fertilizer supply, and a further enhancement in soil fertility. Finally, the phenomenon of labor migration is prominent, with a large number of rural laborers leaving for work elsewhere, leading to a growing labor shortage issue. Additionally, the continuous rise in social wage levels has increased labor costs, requiring agricultural producers to pay more for labor. Thus, the dominant factors for the lessening of the EYR of AE are increased environmental resource utilization efficiency, higher fertilizer supply, and rising labor costs.

ESR decreased from 0.30 to 0.26, while EIR increased from 2.31 to 2.91, indicating a reduction in the system's reliance on natural environmental resources and a significant increase in agricultural economic investment between 2002 and 2022. The average ESR was 0.27, which is higher than the provincial average of 0.13, reflecting a relatively low level of reliance on natural environmental resources. The average EIR was 2.66, which is higher than the provincial average of 1.86, denoting a relatively high standard of agricultural economic investment. Dazhou's economic strength ranks sixth in Sichuan province, which is the reason why its ESR and EIR are higher than the provincial level. On the one hand, natural factors such as frequent droughts and floods, and insufficient heat, result in less favorable agricultural production conditions, significantly worse than those in regions like the Chengdu Plain and Anning River Valley, with environmental resource energy inputs below the provincial average. On the other hand, the large hilly and mountainous areas, along with soil erosion leading to lower soil quality, require more investment in fertilizers and organic manures to improve soil quality, resulting in higher T inputs and F inputs compared with the provincial average. The local government formulated policies to allocate substantial financial resources to agricultural development, which played a crucial role in ensuring the position of agriculture. Therefore, the leading causes for the diminishing ESR and increase in EIR in AE are the reduction in reliance on natural environmental resources and the increase in agricultural economic investment.

The ELR fluctuated from 3.87 to 4.75 between 2002 and 2022, and the environmental pressure brought by the system increased. The average ELR was 4.40, which is significantly

higher than the provincial average of 1.68, reflecting relatively high environmental pressure from the system. Dazhou is an industrial city, and the environmental pressure caused by agricultural development will further exacerbate ecological deterioration, which is detrimental to human life. This is one of the reasons why many people choose to move to Chengdu. A higher ELR indicates more severe ecological damage caused by the system, leading to greater environmental pressure [79]. If this pressure exceeds the ecosystem's self-recovery threshold, it could result in irreversible functional degradation or even the loss of the system's functions [80]. The government has actively promoted facility-based agriculture to improve the cultivation standards of agricultural products, which has set higher demands on agricultural production conditions. To improve agricultural production conditions, people have invested heavily in fertilizers, which may lead to issues such as soil pollution and soil quality deterioration. Therefore, the continuous increase in ELR, which is far above the provincial average, serves as a warning signal.

The ESI decreased from 0.81 to 0.53 between 2002 and 2022, indicating an overall reduction in the system's dynamic vitality. With ESI values below 1, this suggests a lack of vitality in the system and a prolonged low level of SDC. The average ESI was 0.67, which is below the provincial average of 1.17, indicating that agricultural development faces more issues that need to be addressed. Overdevelopment is the direct cause of the low capacity for sustainable agricultural development, which is different from some underdeveloped agricultural cities in the province [81]. The AE is consumption-driven, with high energy inputs from fertilizers and labor, leading to excessive environmental pressure [12,15]. The original agricultural productivity is unable to meet the demands of modern agricultural development after the ecological environment has been damaged [1,5]. The agricultural ecological environment is relatively fragile and difficult to restore once damaged [8,13]. To pursue greater economic benefits, increased economic investment has been made, which is the primary reason for the low sustainability index. Specifically, Dazhou is located in a hilly and mountainous region where natural factors such as sunlight, soil, and water resources are major constraints on agricultural development. Increased economic investment to improve agricultural production conditions has resulted in the system being sustained at a low level of SDC for a lengthy duration. The results of the assessment metrics of AE in the study area are listed in Figure 4.

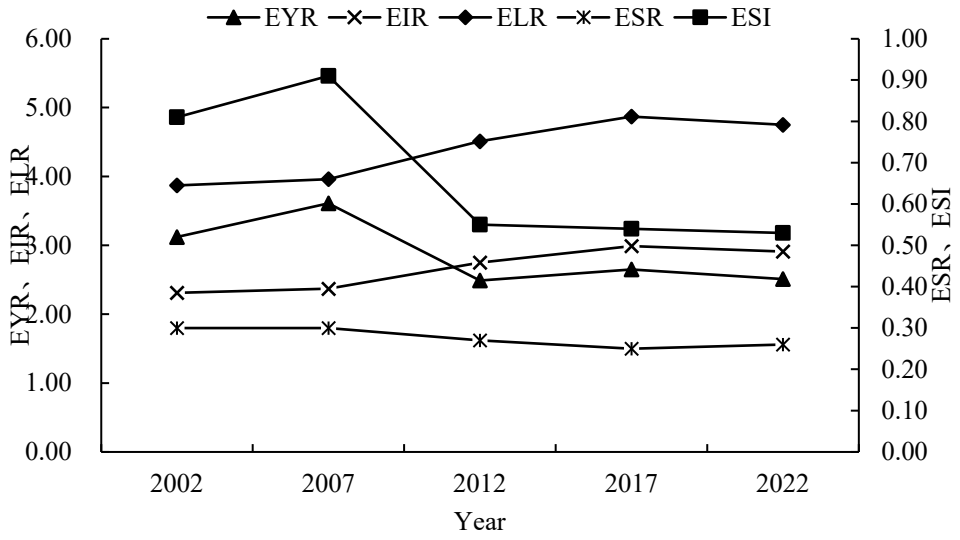


Figure 4. Results of emergy value index of agricultural ecosystem in Dazhou from 2002 to 2022.

4. Conclusions and Discussion

In the structure of EI, the ranking from highest to lowest is T > F > R > N. In the structure of EO, the ranking from highest to lowest is animal husbandry > crop cultivation > fisheries > forestry. Compared with the provincial average, AE has relatively low produc-

tion efficiency, a relatively low dependence on natural environmental resources, relatively high economic investment levels, relatively high environmental pressure, and greater unsustainability. Over time, the production efficiency of AE has declined, dependence on natural environmental resources has decreased, and agricultural economic investment has significantly increased, leading to growing environmental pressure and reduced SDC. This serves as a reminder to balance economic benefits with environmental benefits. The AE shows decreased efficiency in utilizing natural resources, increased economic investment, and is in a consumption-driven production process. The system exerts increasing pressure on the local natural environment, with SDC remaining at a low level over the long term.

If the current trend is not curbed, certain environmental and economic risks will become more pronounced. First, continuous environmental pressure will lead to land degradation, water shortages, and reduced biodiversity, which will further affect agricultural productivity and create a vicious cycle. Second, the increase in agricultural investments will fail to bring corresponding benefits, potentially resulting in resource wastage and low agricultural economic efficiency. Finally, intensified climate change will increase the frequency of extreme weather events, making agricultural production more vulnerable and further threatening regional economic stability and food security.

The AE is still in the chemical civilization stage and needs to adopt corresponding measures to enhance system sustainability and transition into the ecological civilization development stage. EYR, ELR, and ESI need to be improved to reach the provincial level.

Firstly, ecological agriculture should be promoted as a common method of agricultural production. Currently, ecological agriculture has been applied in small areas but it has not yet been implemented on a larger scale [15,16,79]. Therefore, ecological agriculture is the future direction for agricultural development [23,33,45]. Ecological agriculture adheres to ecological and economic principles, utilizing modern technology and management methods to achieve high economic, ecological, and social benefits [80]. People must reconcile the conflict between agricultural development and the environment, and aim to expand resource use while enhancing resource protection [7,23]. This will achieve the unity of economic, ecological, and social benefits and promote a positive cycle in the AE [25]. The key to ecological agriculture is to reduce the use of chemical fertilizers, which directly contributes to improving EYR, decreasing ELR, and enhancing ESI. In addition, the promotion of ecological agriculture has become possible due to policy support and the backing of farmers.

Secondly, in terms of natural environmental resource utilization, the key is to actively develop land-saving agriculture, improve the efficiency of arable land use, and implement effective administrative, economic, and legal measures to protect arable land, achieving a dynamic balance in the total amount of arable land [36]. Encouraging intercropping, relay planting, and crop rotation to fully utilize climate resources, rehabilitate abandoned land, and increase land resource utilization helps to increase EYR, reduce ELR, and enhance ESI [81].

Then, in terms of agricultural economic investment, it is important to promote the application of new agricultural resource utilization technologies, drive agricultural technological revolution, and optimize resource element allocation [18]. Developing smart agriculture by incorporating Internet of Things technology into the AE, enabling visual remote diagnosis, remote control, and disaster warnings, will significantly reduce labor demand and lower labor energy inputs, thereby increasing EYR [21]. Additionally, enhancing the resistance of high-quality seeds to pests and diseases helps reduce pesticide use and decrease environmental pressure, further reducing the ELR [26].

Finally, in agricultural output, it is important to adjust the agricultural structure based on natural resource conditions and develop specialty agriculture according to the characteristics of hilly and mountainous regions [51]. This is characterized by low environmental pressure from specialty agriculture, which maximizes the use of natural environmental resources, helping to reduce the environmental load rate and increase ESI [52].

There is some limitations in this study. One significant challenge is the availability and accuracy of data over such an extended time period. EA relies heavily on precise input and output data; however, historical records may be incomplete or of varying quality, which can lead to biased assessments of sustainability. Additionally, fluctuations in environmental conditions, policy changes, and economic activities throughout the years may further complicate data consistency and reliability. Looking ahead, future research could focus on improving data-collection methods, such as employing remote sensing technologies and big data analytics to obtain more comprehensive and accurate information.

Author Contributions: Conceptualization, Y.L.; methodology, Y.L.; software, Y.L.; validation, Y.L., J.A.B.I. and Y.S.F.; formal analysis, Y.L.; investigation, Y.L.; resources, Y.L.; data curation, Y.L.; writing—original draft preparation, Y.L.; writing—review and editing, Y.L.; visualization, Y.L.; supervision, J.A.B.I. and Y.S.F.; project administration, Y.L.; funding acquisition, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Education Innovation Project of Northwest Normal University of China, grant number 2023KYZZ-B081.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within this article.

Acknowledgments: Special thanks to the Agricultural Department of Dazhou for providing data for this research.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Kline, O.; Joshi, N.K. Mitigating the effects of habitat loss on solitary bees in agricultural ecosystems. *Agriculture* **2020**, *10*, 115. [CrossRef]
2. Cui, Y.; Zhang, Y.; Duan, C.; Wang, X.; Zhang, X.; Ju, W.; Chen, H.; Yue, S.; Wang, Y.; Li, S.; et al. Ecoenzymatic stoichiometry reveals microbial phosphorus limitation decreases the nitrogen cycling potential of soils in semi-arid agricultural ecosystems. *Soil Tillage Res.* **2020**, *197*, 104463. [CrossRef]
3. Chabert, A.; Sarthou, J.P. Conservation agriculture as a promising trade-off between conventional and organic agriculture in bundling ecosystem services. *Agric. Ecosyst. Environ.* **2020**, *292*, 106815. [CrossRef]
4. Tamburini, G.; Bommarco, R.; Wanger, T.C.; Kremen, C.; Van Der Heijden, M.G.; Liebman, M.; Hallin, S. Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* **2020**, *6*, eaba1715. [CrossRef] [PubMed]
5. Tsai, H.W.; Lee, Y.C. Will changing land use and cropping practices affect resource use efficiency and environmental sustainability of agricultural systems? A hierarchical emergy assessment approach. *Ecol. Indic.* **2024**, *160*, 111933. [CrossRef]
6. Xu, A.; Luo, X.; Song, T.; Wang, Y.; Xiang, L.; Xiong, Y.; Liu, Z.; Yang, S. Integrated life cycle assessment and emergy analysis of liquid dehumidification absorption refrigeration driven by solar energy. *Appl. Therm. Eng.* **2024**, *236*, 121540. [CrossRef]
7. Liang, J.; Geng, Y.; Su, C.; Chen, W. An emergy-based comparison between primary and secondary tungsten production in China. *Environ. Impact Assess. Rev.* **2024**, *107*, 107548. [CrossRef]
8. Li, S.; Fan, Z.; Zheng, S.; Zeng, F. Emergy analysis of three industrial reverse osmosis concentrate zero liquid discharge processes: Technical, economic and environmental comparison. *J. Clean. Prod.* **2024**, *438*, 140777. [CrossRef]
9. Cole, L.J.; Stockan, J.; Helliwell, R. Managing riparian buffer strips to optimise ecosystem services: A review. *Agric. Ecosyst. Environ.* **2020**, *296*, 106891. [CrossRef]
10. Cataldo, E.; Salvi, L.; Paoli, F.; Fucile, M.; Masciandaro, G.; Manzi, D.; Masini, C.M.; Mattii, G.B. Application of zeolites in agriculture and other potential uses: A review. *Agronomy* **2021**, *11*, 1547. [CrossRef]
11. Talukdar, G.; Bhattacharjya, R.K.; Sarma, A.K. Understanding the effect of long term and short term hydrological components on landscape ecosystem. *Ecol. Inform.* **2023**, *77*, 102267. [CrossRef]
12. Tomazelli, D.; Klauberg-Filho, O.; Mendes, S.D.C.; Baldissera, T.C.; Garagorry, F.C.; Tsai, S.M.; Pinto, C.E.; Mendes, L.W.; Goss-Souza, D. Pasture management intensification shifts the soil microbiome composition and ecosystem functions. *Agric. Ecosyst. Environ.* **2023**, *346*, 108355. [CrossRef]
13. Weiss, M.; Jacob, F.; Duveiller, G. Remote sensing for agricultural applications: A meta-review. *Remote Sens. Environ.* **2020**, *236*, 111402. [CrossRef]
14. Galychyn, O.; Fath, B.D.; Wiedenhofer, D.; Buonocore, E.; Franzese, P.P. An urban emergy footprint: Comparing supply-and use-extended input-output models for the case of Vienna, Austria. *Clean. Prod. Lett.* **2024**, *6*, 100058. [CrossRef]

15. Sabbaghi, M.A.; Soltani, M.; Fraser, R.; Dusseault, M.B. Emergy-based exergoeconomic and exergoenvironmental assessment of a novel CCHP system integrated with PEME and PEMFC for a residential building. *Energy* **2024**, *305*, 132301. [CrossRef]
16. Ding, X.; Zhou, Y.; Zheng, N.; Desideri, U.; Duan, L. Emergy analysis and comprehensive sustainability investigation of a solar-aided liquid air energy storage system based on life cycle assessment. *Appl. Energy.* **2024**, *365*, 123249. [CrossRef]
17. Jacquet, F.; Jeuffroy, M.H.; Jouan, J.; Le Cadre, E.; Litrico, I.; Malausa, T.; Reboud, X.; Huyghe, C. Pesticide-free agriculture as a new paradigm for research. *Agron. Sustain. Dev.* **2022**, *42*, 8. [CrossRef]
18. Liu, L.; Wang, B. Protection of halophytes and their uses for cultivation of saline-alkali soil in China. *Biology* **2021**, *10*, 353. [CrossRef]
19. Ouyang, X.; Xu, J.; Li, J.; Wei, X.; Li, Y. Land space optimization of urban-agriculture-ecological functions in the Changsha-Zhuzhou-Xiangtan Urban Agglomeration, China. *Land Use Policy* **2022**, *117*, 106112. [CrossRef]
20. Su, Y.; Chen, X.; Liao, J.; Zhang, H.; Wang, C.; Ye, Y.; Wang, Y. Modeling the optimal ecological security pattern for guiding the urban constructed land expansions. *Urban For. Urban Green.* **2016**, *19*, 35–46. [CrossRef]
21. Li, S.; Zhao, X.; Pu, J.; Miao, P.; Wang, Q.; Tan, K. Optimize and control territorial spatial functional areas to improve the ecological stability and total environment in karst areas of Southwest China. *Land Use Policy* **2021**, *100*, 104940. [CrossRef]
22. Yang, X.; Zhang, D.; Jia, Q.; Zhang, W.; Wang, T. Exploring the dynamic coupling relationship between agricultural economy and agro-ecological environment in semi-arid areas: A case study of Yulin, China. *Sustainability* **2019**, *11*, 2259. [CrossRef]
23. Zhang, Y.; Yang, R.; Sun, M.; Lu, Y.; Zhang, L.; Yin, Y.; Li, X. Identification of spatial protection and restoration priorities for ecological security pattern in a rapidly urbanized region: A case study in the Chengdu–Chongqing economic Circle, China. *J. Environ. Manag.* **2024**, *366*, 121789. [CrossRef] [PubMed]
24. Fu, Y.; Shi, X.; He, J.; Yuan, Y.; Qu, L. Identification and optimization strategy of county ecological security pattern: A case study in the Loess Plateau, China. *Ecol. Indic.* **2020**, *112*, 106030. [CrossRef]
25. Sun, F.; Jia, Z.; Shen, J.; Xu, C.; Huang, X.; Shang, Z.; Li, S.; Zhang, S. Research on the Accounting and Spatial Effects of Emergy Ecological Footprint and Industrial Green GDP—The Case of Yangtze River Economic Belt. *Ecol. Indic.* **2024**, *163*, 112055. [CrossRef]
26. Jing, P.; Sheng, J.; Wang, Y.; Hu, T.; Guo, L.; Zhu, R.; Dong, K.; Mahmoud, A.; Liu, Y.; Li, X. Assessing the ecological security of the Three Gorges reservoir complex ecosystem based on the improved three-dimensional emergy ecological footprint model. *Sci. Total Environ.* **2024**, *933*, 173086. [CrossRef]
27. Xiong, L.; Shah, F.; Zhao, Y.; Li, Z.; Zha, X.; Ye, M.; Wu, W. Sustainability analysis of irrigated and rainfed wheat production systems under varying levels of nitrogen fertilizer through coupling of emergy accounting and life cycle assessment. *J. Clean. Prod.* **2024**, *447*, 141423. [CrossRef]
28. Aretano, R.; Semeraro, T.; Petrosillo, I.; De Marco, A.; Pasimeni, M.R.; Zurlini, G. Mapping ecological vulnerability to fire for effective conservation management of natural protected areas. *Ecol. Modell.* **2015**, *295*, 163–175. [CrossRef]
29. Odum, H.T. *Environment, Power, and Society for the Twenty-First Century: The Hierarchy of Energy*; Columbia University Press: New York, NY, USA, 2007.
30. Odum, H.T. Self-organization, transformity, and information. *Science* **1988**, *242*, 1132–1139. [CrossRef]
31. Odum, H.T.; Odum, B. Concepts and methods of ecological engineering. *Ecol. Eng.* **2003**, *20*, 339–361. [CrossRef]
32. Odum, H.T.; Odum, E.P. The energetic basis for valuation of ecosystem services. *Ecosystems* **2000**, *3*, 21–23. [CrossRef]
33. Lu, H.F.; Cai, C.J.; Zeng, X.S.; Campbell, D.E.; Fan, S.H.; Liu, G.L. Bamboo vs. crops: An integrated emergy and economic evaluation of using bamboo to replace crops in south Sichuan Province, China. *J. Clean. Prod.* **2018**, *177*, 464–473. [CrossRef] [PubMed]
34. Lu, H.F.; Zhang, H.S.; Qin, P.; Liu, X.Z.; Campbell, D.E. Integrated emergy and economic evaluation of an ecological engineering system for the utilization of spartina alterniflora. *J. Clean. Prod.* **2020**, *247*, 119592. [CrossRef]
35. Campbell, D.E. Keeping the books for the environment and society: The unification of emergy and financial accounting methods. *J. Environ. Account. Manag.* **2013**, *1*, 25–41. [CrossRef]
36. Ghisellini, P.; Cialani, C.; Ulgiati, S. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* **2016**, *114*, 11–32. [CrossRef]
37. Chen, G.; Jiang, M.; Chen, B.; Yang, Z.; Lin, C. Emergy analysis of Chinese agriculture. *Agric. Ecosyst. Environ.* **2006**, *115*, 161–173. [CrossRef]
38. Amaral, L.P.; Martins, N.; Gouveia, J.B. A review of emergy theory, its application and latest developments. *Renew. Sustain. Energy Rev.* **2016**, *54*, 882–888. [CrossRef]
39. Lewandowska-Czarnecka, A.; Buller, L.S.; Nienartowicz, A.; Piernik, A. Energy and emergy analysis for assessing changes in Polish agriculture since the accession to the European Union. *Ecol. Modell.* **2019**, *412*, 108819. [CrossRef]
40. Ting, Y.I.; Xiang, P.A. Emergy analysis of paddy farming in Hunan Province, China: A new perspective on sustainable development of agriculture. *J. Integr. Agric.* **2016**, *15*, 2426–2436. [CrossRef]
41. Liu, G.; Meng, F.; Huang, X.; Han, Y.; Chen, Y.; Huo, Z.; Chiaka, J.C.; Yang, Q. Forecast urban ecosystem services to track climate change: Combining machine learning and emergy spatial analysis. *Urban Clim.* **2024**, *55*, 101910. [CrossRef]
42. Clasen, A.P.; Agostinho, F.; Sulis, F.; Almeida, C.M.; Giannetti, B.F. Unlocking the potential of municipal solid waste: Emergy accounting applied in a novel biorefinery. *Ecol. Model.* **2024**, *492*, 110725. [CrossRef]

43. Guan, X.; Xu, Y.; Meng, Y.; Qiu, B.; Yan, D. Emergy benefit and radiation effect of multi-dimensional service function of vegetation ecosystem. *Sci Total Environ.* **2024**, *911*, 168493. [CrossRef] [PubMed]
44. Wang, Q.; Ma, Z.; Ma, Q.; Liu, M.; Yuan, X.; Mu, R.; Zuo, J.; Zhang, J.; Wang, S. Comprehensive evaluation and optimization of agricultural system: An emergy approach. *Ecol. Indic.* **2019**, *107*, 105650. [CrossRef]
45. Wang, J.; Hou, D.; Liu, Z.; Tao, J.; Yan, B.; Liu, Z.; Yang, T.; Su, H.; Tahir, M.H.; Chen, G. Emergy analysis of agricultural waste biomass for energy-oriented utilization in China: Current situation and perspectives. *Sci. Total Environ.* **2022**, *849*, 157798. [CrossRef] [PubMed]
46. Su, Y.; He, S.; Wang, K.; Shahtahmassebi, A.R.; Zhang, L.; Zhang, J.; Gan, M. Quantifying the sustainability of three types of agricultural production in China: An emergy analysis with the integration of environmental pollution. *J. Clean. Prod.* **2020**, *252*, 119650. [CrossRef]
47. Patten, B.C. Energy, emergy and environs. *Ecol. Model.* **1992**, *62*, 29–69. [CrossRef]
48. Bastianoni, S.; Facchini, A.; Susani, L.; Tiezzi, E. Emergy as a function of exergy. *Energy* **2007**, *32*, 1158–1162. [CrossRef]
49. Nadalini, A.C.V.; Kalid, R.D.A.; Torres, E.A. Emergy as a tool to evaluate ecosystem services: A systematic review of the literature. *Sustainability* **2021**, *13*, 7102. [CrossRef]
50. Zhang, L.; Song, B.; Chen, B. Emergy-based analysis of four farming systems: Insight into agricultural diversification in rural China. *J. Clean. Prod.* **2012**, *28*, 33–44. [CrossRef]
51. Jiang, M.; Chen, B.; Zhou, J.; Tao, F.R.; Li, Z.; Yang, Z.; Chen, G. Emergy account for biomass resource exploitation by agriculture in China. *Energy Policy* **2007**, *35*, 4704–4719. [CrossRef]
52. Amiri, Z.; Asgharipour, M.R.; Campbell, D.E.; Azizi, K.; Kakolvand, E.; Moghadam, E.H. Conservation agriculture, a selective model based on emergy analysis for sustainable production of shallot as a medicinal-industrial plant. *J. Clean. Prod.* **2021**, *292*, 126000. [CrossRef]
53. Ciotola, R.J.; Lansing, S.; Martin, J.F. Emergy analysis of biogas production and electricity generation from small-scale agricultural digesters. *Ecol. Eng.* **2011**, *37*, 1681–1691. [CrossRef]
54. Hu, J.; Lyu, J.; Zhang, X. Evaluating agricultural sustainability and green GDP in China: An emergy analysis. *Int. J. Environ. Res. Public Health* **2022**, *19*, 16735. [CrossRef] [PubMed]
55. Zhang, B.; Jin, P.; Qiao, H.; Hayat, T.; Alsaedi, A.; Ahmad, B. Exergy analysis of Chinese agriculture. *Ecol. Indic.* **2019**, *105*, 279–291. [CrossRef]
56. Xie, H.; Huang, Y.; Choi, Y.; Shi, J. Evaluating the sustainable intensification of cultivated land use based on emergy analysis. *Technol. Forecast. Soc. Chang.* **2021**, *165*, 120449. [CrossRef]
57. Lu, Y.; Yan, L.; Li, J.; Liang, Y.; Yang, C.; Li, G.; Wu, J.; Xu, H. Spatiotemporal evolution of county level ecological security based on an emergy ecological footprint model: The case of Dingxi, China. *Ecol. Model.* **2024**, *490*, 110661. [CrossRef]
58. Ma, H.; Wang, Q.; Zhang, Y.; Hussain, M.B.; Xu, Y.; Tian, S.; Yuan, X.; Ma, Q.; Yuan, R.; Jia, Y. Research on sustainable development evaluation and improvement path of resource-based cities based on coupling of emergy and system dynamics. *Environ. Dev. Sustain.* **2024**, *3*, 5959–6006. [CrossRef]
59. Zou, X.; Tan, S.; Hong, J.; Du, L.; Zhao, Q.; Zuo, J. Understanding the metabolism and scaling law in construction projects: Evidence from China. *Environ. Impact Assess. Rev.* **2024**, *108*, 107572. [CrossRef]
60. Yao, X.; Chen, W.; Song, C.; Gao, S. Sustainability and efficiency of water-land-energy-food nexus based on emergy-ecological footprint and data envelopment analysis: Case of an important agriculture and ecological region in Northeast China. *J. Clean. Prod.* **2022**, *379*, 134854. [CrossRef]
61. Ferraro, D.O.; Benzi, P. A long-term sustainability assessment of an Argentinian agricultural system based on emergy synthesis. *Ecol. Modell.* **2015**, *306*, 121–129. [CrossRef]
62. Xiao, X.; Wang, Q.; Guan, Q.; Shao, W.; Luo, H.; Shan, Y.; Mi, J. Assessing the sustainability of ecosystems over fourteen years of cultivation in Longnan City of China based on emergy analysis method. *J. Environ. Manag.* **2022**, *307*, 114513. [CrossRef] [PubMed]
63. Wang, Y.; Cai, Y.; Liu, G.; Zhang, P.; Li, B.; Li, B.; Jia, Q.; Huang, Y.P.; Shu, T.C. Evaluation of sustainable crop production from an ecological perspective based emergy analysis: A case of China's provinces. *J. Clean. Prod.* **2021**, *313*, 127912. [CrossRef]
64. Wu, X.; Wu, F.; Tong, X.; Wu, J.; Sun, L.; Peng, X. Emergy and greenhouse gas assessment of a sustainable, integrated agricultural model (SIAM) for plant, animal and biogas production: Analysis of the ecological recycle of wastes. *Resour. Conserv. Recycl.* **2015**, *96*, 40–50. [CrossRef]
65. Fan, J.; McConkey, B.G.; Janzen, H.H.; Miller, P.R. Emergy and energy analysis as an integrative indicator of sustainability: A case study in semi-arid Canadian farmlands. *J. Clean. Prod.* **2018**, *172*, 428–437. [CrossRef]
66. Sun, J.; Yuan, X.; Liu, G.; Ren, R. The evaluation of wetland reconstruction with nature-based solutions for eco-economic sustainable development. *Ecol. Indic.* **2024**, *160*, 111936. [CrossRef]
67. Chandio, A.A.; Gokmenoglu, K.K.; Dash, D.P.; Khan, I.; Ahmad, F.; Jiang, Y. Exploring the energy-climate-agriculture (ECA) nexus: A roadmap toward agricultural sustainability in Asian countries. *Environ. Dev. Sustain.* **2024**, *20*, 1–27. [CrossRef]
68. Wang, Y.; Qian, Y. Driving factors to agriculture total factor productivity and its contribution to just energy transition. *Environ. Impact Assess. Rev.* **2024**, *105*, 107369. [CrossRef]
69. Ramzan, M.; Razi, U.; Usman, M.; Sarwar, S.; Talan, A.; Mundi, H.S. Role of nuclear energy, geothermal energy, agriculture, and urbanization in environmental stewardship. *Gondwana Res.* **2024**, *125*, 150–167. [CrossRef]

70. Zadgaonkar, L.A.; Darwai, V.; Mandavgane, S.A. The circular agricultural system is more sustainable: Emergy analysis. *Clean Technol. Environ. Policy* **2022**, *24*, 1301–1315. [CrossRef]
71. Lyu, Y.; Raugei, M.; Zhang, X.; Mellino, S.; Ulgiati, S. Environmental cost and impacts of chemicals used in agriculture: An integration of emergy and Life Cycle Assessment. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111604. [CrossRef]
72. Artuzo, F.D.; Allegretti, G.; Santos, O.I.B.; da Silva, L.X.; Talamini, E. Emergy unsustainability index for agricultural systems assessment: A proposal based on the laws of thermodynamics. *Sci. Total Environ.* **2021**, *759*, 143524. [CrossRef] [PubMed]
73. Yuan, Q.; Mi, S.; Meng, F.; Hou, J.; Sun, Y.; Li, H.; Shah, A.M. An emergy analysis of environmental sustainability in urban agriculture: Evidence from protected agriculture in Beijing, China. *Front. Sustain. Food Syst.* **2023**, *7*, 1288136. [CrossRef]
74. Wang, J.; Su, D.; Wu, Q.; Li, G.; Cao, Y. Study on eco-efficiency of cultivated land utilization based on the improvement of ecosystem services and emergy analysis. *Sci. Total Environ.* **2023**, *882*, 163489. [CrossRef] [PubMed]
75. Cristiano, S. Organic vegetables from community-supported agriculture in Italy: Emergy assessment and potential for sustainable, just, and resilient urban-rural local food production. *J. Clean. Prod.* **2021**, *292*, 126015. [CrossRef]
76. Moonilall, N.I.; Homenauth, O.; Lal, R. Emergy analysis for maize fields under different amendment applications in Guyana. *J. Clean. Prod.* **2020**, *258*, 120761. [CrossRef]
77. Wang, Y.; Liu, G.; Cai, Y.; Giannetti, B.F.; Agostinho, F.; Almeida, C.M.; Casazza, M. The ecological value of typical agricultural products: An emergy-based life-cycle assessment framework. *Front. Environ. Sci.* **2022**, *10*, 824275. [CrossRef]
78. Spagnolo, S.; Chinellato, G.; Cristiano, S.; Zucaro, A.; Gonella, F. Sustainability assessment of bioenergy at different scales: An emergy analysis of biogas power production. *J. Clean. Prod.* **2020**, *277*, 124038. [CrossRef]
79. Zhu, Y.; Li, M.; Lu, S.; Wang, H.; Wang, J.; Wang, W. Research on the input–output model of the rural agricultural eco-economic system based on emergy theory. *Sustainability* **2022**, *14*, 3717. [CrossRef]
80. Yang, H.; Chen, L.; Yang, B.; Shi, Z. Exploring provincial sustainable intensification of cultivated land use in China: An empirical study based on emergy analysis. *Phys. Chem. Earth.* **2022**, *128*, 103287. [CrossRef]
81. Li, Y.; Cai, G.; Tan, K.; Zeng, R.; Chen, X.; Wang, X. Emergy-based efficiency and sustainability assessments of diversified multi−cropping systems in South China. *J. Clean. Prod.* **2023**, *414*, 137660. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.