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Sustainability Evaluation and Optimization on the Modern Agro-Pastoral Circular System Integrating Emergy Analysis and Life Cycle Assessment

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Abstract: Developing modern circular agriculture is one of the important ways to promote agricultural sustainable development, facilitating the achievement of the Sustainable Development Goals adopted by the United Nations. However, when agricultural production operators constructed particular systems, they often lacked accurate data support and parameter matching. Consequently, problems such as unknown input and output, low circulation efficiency, and lack of comprehensive evaluation occurred, increasing challenges for efficient circulation of the systems. Therefore, based on sufficient data collection and field investigation, this research integrated emergy analysis and life cycle assessment to conduct sustainability evaluation on the modern Straw–Sheep–Cropland agro-pastoral circular system. Then the system was optimized by means of coupling parameter adjustment and key technology regulation. The results showed that the whole system required lower total emergy input after optimization. And the total weighted value of potential environmental impacts of the optimized system was 47.12% of that of the original system. Meanwhile, annual environmental service emergy in air, water, and soil was reduced significantly compared with the original one. In general, the optimized system had good performance in reduction, reuse, and controllability, so its sustainability was also high. This research formed a systematic method suitable for evaluating and optimizing the modern agro-pastoral circular system, which provided accurate guidance for the scientific construction and sustainable development of circular agriculture systems.

Keywords: circular agriculture; resource input; emergy structure; potential environmental impact; environmental service emergy; system optimization; sustainable development

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1. Introduction

Circular agriculture refers to the ecological agriculture that adopts the theory of complex ecosystem and circular economy to realize the industry chains circulating. By connecting the upstream and downstream chains, it organizes the agricultural production links such as planting, breeding, and processing into an approximate closed circular system, in order to achieve the purpose of efficient utilization of resources, reduction of waste discharge, and improvement of economic benefits [1]. Different from traditional circular agriculture formed spontaneously, modern circular agriculture with a large-scale industrialized form requires precise and smooth interface of all production links, so as to accelerate the recycle of material-energy metabolites and reduce potential environmental impacts in the entire agricultural ecosystem [2]. Under the dual pressure of resource depletion and environmental degradation, developing modern circular agriculture is one of the important ways to promote agricultural sustainable development, which not only provides solid security for realizing rural revitalization in China but also facilitates the achievement of the Sustainable Development Goals adopted by the United Nations.

The unique resource endowment and development level of various regions in China gave birth to a variety of modern circular agriculture models, for instance, Mulberry–Fish, Rice–Duck, Rice–Fish, Pig–Methane–Fruit, and so on [3–6]. However, when applying them to construct particular systems, accurate data support and parameter matching were often lacking. Consequently, problems such as unknown input and output, low circulation efficiency, and lack of comprehensive evaluation occurred, increasing challenges for efficient circulation of the systems. This might lead to the imbalance between demand and supply in some links, resulting in dissipation and blockage of substances as well as inadequate circulation or probable pollution, thus affecting the sustainable development of the modern circular agriculture system [7]. In addition, as the actual operators of the systems were mostly enterprise entities, driven by the one-sided pursuit of economic benefits, they tended to ignore the efficient utilization of local agricultural waste resources and failed to achieve the initial design intention "closed cycle" of circular systems, making the application and promotion of modern circular agriculture systems face difficulties [8].

To evaluate circular agriculture systems from different perspectives, scholars adopted ecological footprint, ecological pricing, emergy analysis, life cycle assessment, material flow analysis, and other methods [9]. Thereinto, built by ecologist H. T. Odum, emergy analysis used the driving source of the Earth system, solar energy, as a basic standard reference to calculate material flows, energy flows, information flows, and value flows in both natural ecosystems and socio-economic systems through unit emergy values [10]. It showed inherent applicability to the agro-ecosystem and was increasingly implemented for the analysis of circular agriculture systems [11]. Su et al. used emergy and economic analysis to evaluate the overall performance of three agricultural production types, including traditional rice monoculture, integrated farming, and non-grain production systems [12]. Patrizi et al. studied the integration of a goose raising system with an organic grape production by means of emergy evaluation [13]. However, this method did not consider the pollution emissions caused by system operation [14]. On the other hand, as an effective tool to assess the environmental impacts of the entire chains of processing systems, the application of life cycle assessment in agriculture has been gradually expanded with the increasing pressure on agricultural resources and environment [15]. By tracking resource utilization of the full life cycle, the material and energy consumption and its impact on the ecological environment were evaluated. Fan et al. explored the environmental loads and benefits of each sub-industrial chain of circular agriculture from the environmental and economic viewpoints by life cycle assessment [16]. Dorr et al. quantified the environmental impacts of a modern circular mushroom farm, taking a life cycle assessment as a tool [17]. Nevertheless, this method ignored the input of natural resources and human services during the production process [18]. Recently, some scholars have attempted to combine emergy analysis with life cycle assessment to make up for the shortcomings of these two methods, but also pointed out that the applicability of their combination needed to be improved due to its immaturity in the research field of circular agriculture [19]. Therefore, exploring a systematic method for sustainability evaluation and optimization on the modern agro-pastoral circular system was specifically necessary to accelerate the development and promotion of the circular agriculture industry.

2. Materials and Methods

2.1. Research Object

2.1.1. Original System

The modern Straw–Sheep–Cropland agro-pastoral circular model, created by our research team, integrated and innovated the technological chains with "mechanical collection-wrapping-fermentation-processing technology for crop straw, total mixed rations formula technology for sheep, mechanical collection-composting technology for manure, and mechanical fertilizing technology for organic fertilizer" as the core [20]. Subsequently, four circular agriculture products, including ecological grain, fermented roughage, high-quality mutton, and organic fertilizer, were produced. This model was of great value to promote the coordination of grain and straw, the integration of planting and breeding, and the combination of agriculture and animal husbandry.

To realize the application of the above model, Suzhou Jincanghu Agricultural Science and Technology Co., Ltd., Suzhou, China, the main production carrier, constructed a modern Straw–Sheep–Cropland agro-pastoral circular system in the characteristic demonstration base of Donglin Village, located in the southeast of Jiangsu Province, China (Figure 1). This original system consisted of four subsystems: cereal cropping, feed producing, sheep raising, and manure composting, with their circular links shown in Figure 2. The system owned 133.33 hm^2 high-standard cropland to implement annual multiple cropping of wheat and rice. In wheat season, some cropland was fallow, while in rice season, blanket seedlings raised by greenhouse were planted mechanically after organic fertilizer was fertilized. During both seasons, tilling, planting, managing, harvesting, and other agricultural machinery for fully mechanized production were all equipped. The feed plant covered an area of 1.33 hm^2, utilizing crop straw, bean residue, molasses, and other planting and processing wastes to make roughage after fermentation with beneficial microbial agents. With an area of 3.33 hm^2, the sheep farm was designed with an annual output of 10,000 head, and the current production level was 4000 head per year. Standardized breeding and managing measures were carried out, such as feeding roughage-based total mixed ration. The fertilizer factory covered an area of 0.5 hm^2, using sheep excrement as raw material, supplemented with agricultural wastes such as fungus residue, rice bran, and crop straw, and then producing organic fertilizer after aerobic compost.

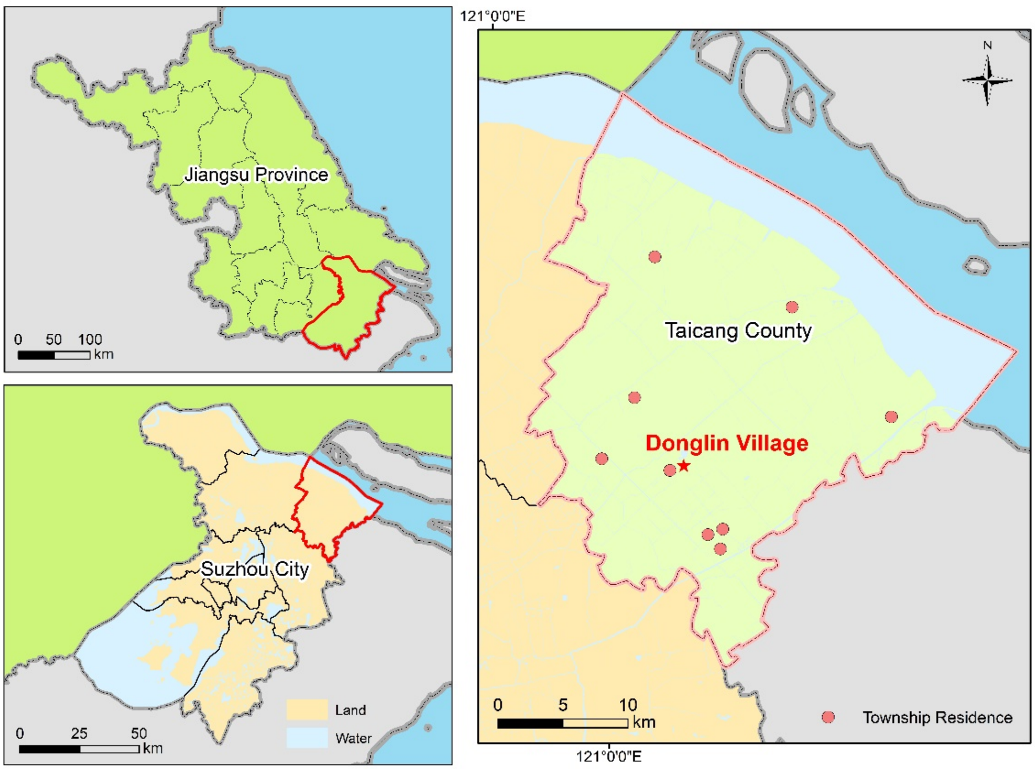

Figure 1. Geographical location of Donglin Village.

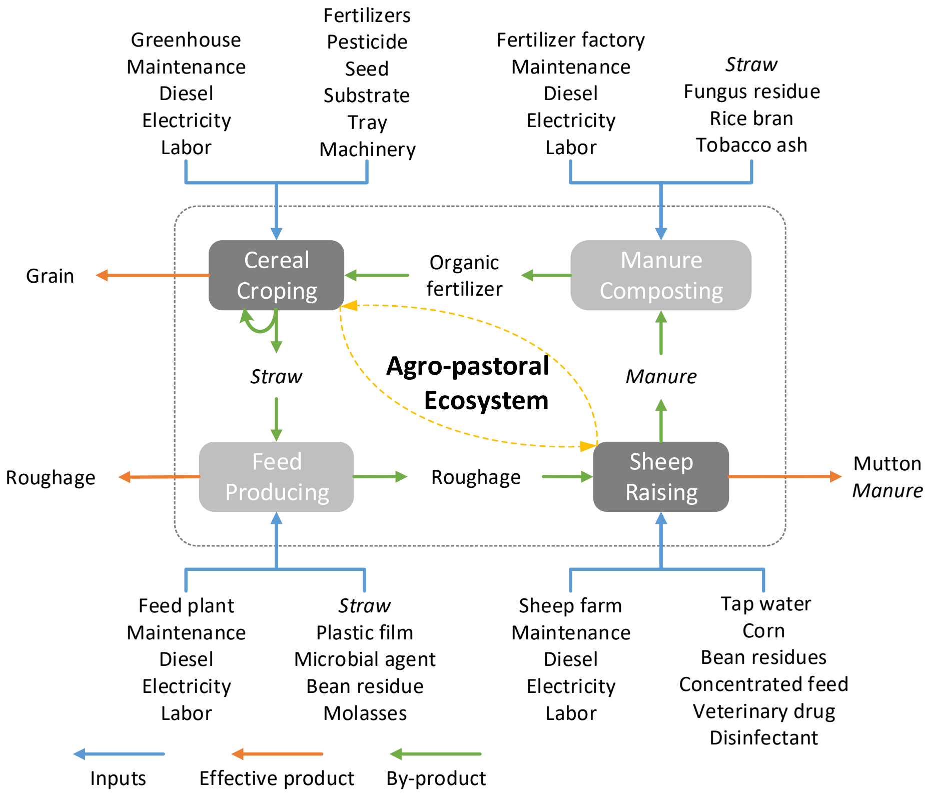

Figure 2. Structure of the modern agro-pastoral circular system in Donglin Village.

2.1.2. Optimized System

As the grey box control method was adopted in the design stage of the original system during the construction process in Donglin Village, the parameter calculation in the implementation process was imprecise. There was room for improvement in the sustainable operation efficiency of the original system. On one side, due to the tight succession time, wheat straw was not utilized in a high-value way, totally returning to the field, as well as the collection rate of rice straw that was just 80%. Hence, it required the purchase of a large amount of straw from outside for feed producing and manure composting, instead of making full use of planting waste resources within the original system. On the other side, only 1/3 of generated sheep manure was converted into organic fertilizer by manure composting, while purchased organic fertilizer was needed for supplementation in cereal cropping, resulting in the increase of breeding waste with more environmental risks in the original system. Obviously, the input–output mismatch among subsystems and the neglect of potential environmental impacts hindered the circulating efficient operation of the original one.

For the sake of enhancing the circulation efficiency of the internal system and reducing emissions' influence on the external environment, this research worked out two ways to optimize the original system. One was to coordinate the coupling parameters between the subsystems in line with the principle of matching output with an input of successive subsystems, as Equation (1). The other was to adjust the technical specification of key links by implementing the measures of source reduction, process control, and end treatment to decrease the pollution risk.

$$S_n = D_{n+i} \tag{1}$$

where S_n represents the waste supply of the nth subsystem; D_{n+i} represents the waste demand of the $(n + i)$th subsystem. In this research, crop straw and sheep manure were the main planting and breeding wastes to be focused on in the optimized system, seen in italics in Figure 2.

2.2. Data Source

2.2.1. System Boundary

A four-dimensional temporal–spatial scale was used to define the boundary of the system. The two-dimensional area was bounded by the production site of each subsystem. The height/depth space was mainly near the Earth's surface, ranging from the upper boundary of 10 m standard height of the surface wind to the lower boundary of 1 m soil depth of cereal crop roots. The fourth-dimension time was 1 natural year. Afterward, the emergy flow diagram (Figure 3) was drawn using the energy systems symbols of emergy analysis, and additionally, the environmental pollution during the operation process was also included to uniformly embody both upstream input and downstream emissions of the system.

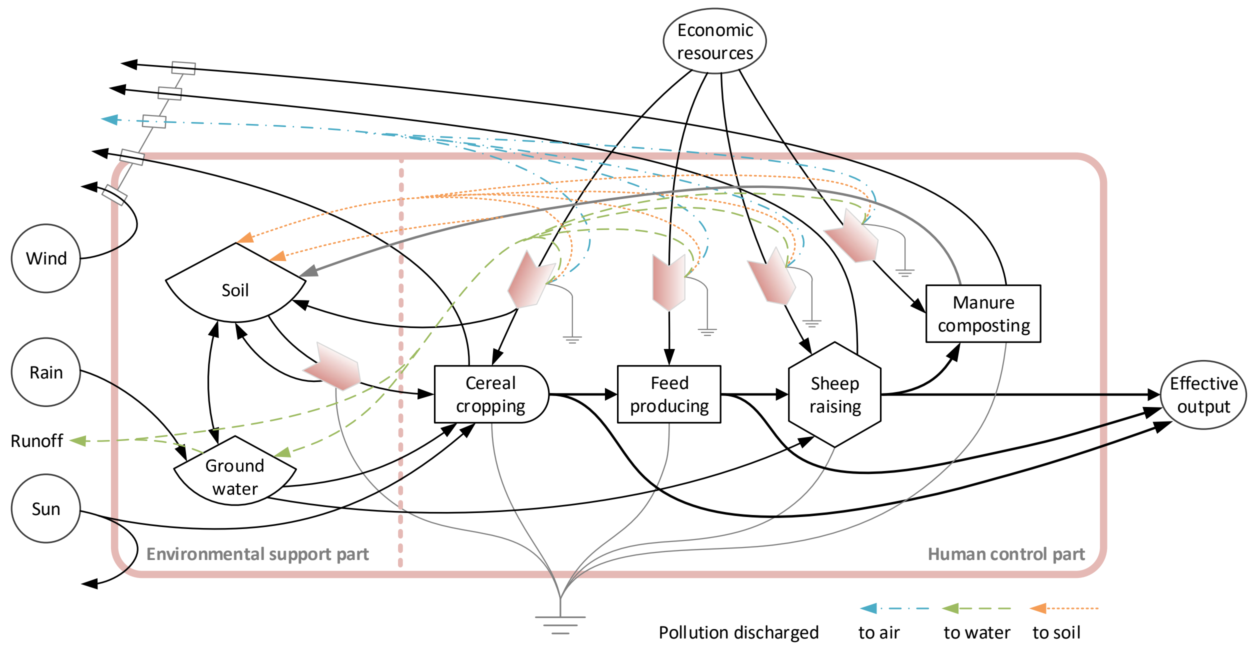

Figure 3. Emergy flow diagram of the modern agro-pastoral circular system.

The input sources of the environmental support part on the left side of the emergy flow diagram were mainly natural resources, such as solar energy, rainfall transpiration, soil organic matter, and so on, which flowed to the human control part on the right side along the energy pathways. Then the input of economic resources, such as fertilizer, pesticide, machinery, electricity, labor, and so on, went through the operation of cereal cropping, feed producing, sheep raising, and manure composting. At last, high-emergy products, generated from low-emergy materials, left the system in the form of various effective outputs, including wheat, rice, roughage, and mutton. Moreover, the emergy flow of sheep-manure organic fertilizer was recycled into production raw materials through internal feedback of the system, while some emergy flow deviated from the system in the form of dissipation. In addition, as the system operated, it also discharged pollution into the air, water, and soil with potential impacts on the environment.

2.2.2. Inventory of Input and Output

The basis for integrating emergy analysis and life cycle assessment was to obtain inventory data of input and output on account of the system boundary. Since May 2019, our research team has conducted an all-around data collection and follow-up field investigation on the original system in Donglin Village. On the one hand, the semi-structured interview was used to proceed with detailed consultation for the principals of each subsystem, in order to master the primary resource input and output of each link of the subsystems. On the other hand, input entering the system and output (including emissions) exiting the system was counted accurately by field investigating and ecological monitoring. At the same time, statistical and literature data related to the local natural environment and social economy were recorded and sorted out [21–24]. The inventory of input and output items during the whole-year operation of the original system was shown in Table A1, as was the simulated inventory data of the optimized one.

2.3. Methods

This research adopted the methodology framework of integrated emergy analysis and life cycle assessment to carry out an empirical study. At first, material and energy in the circular system were converted into comparable standard values, so that the coupling parameters of the demand and supply between each subsystem were explored. Then, the potential environmental impact on air, water, and soil during the circulating operation of the system was tracked, and the environmental service emergy for pollution degradation was also calculated. Finally, the sustainable development ability of the system was evaluated and promoted by constructing a comprehensive index system.

2.3.1. Solar Emergy

The most important content of emergy analysis was to use appropriate unit emergy values (UEV) to transform all kinds of material, energy, and service input into uniform standard solar emergy as Equation (2). According to the recommendations of the International Society for the Advancement of Emergy Research, the latest baseline of 1.20×10^{25} sej per year determined in 2016 was adopted in this research to ensure the accuracy of the analysis results [19]:

$$E_i = M_i \cdot UEV_i \tag{2}$$

where E_i represents the solar emergy value of the ith material, energy, or service; M_i represents the quantity of the ith material, energy, or service, among which the quantity of solar energy, rain (chemical potential), erosion (topsoil), etc., is calculated referring to the method provided by Odum [10]; UEV_i represents the unit emergy value of the ith material, energy, or service, with its corresponding reference source shown in Table A1.

2.3.2. Characterization

The relative potential of environmental impact was obtained based on the individual environmental threat factors, and then the characteristic values of environmental impacts were calculated as Equation (3). Picked up were six categories of potential environmental impacts, including acid potential, global warming potential, terrestrial ecotoxicity, human toxicity, freshwater aquatic ecotoxicity, and eutrophication potential, which were all closely related to agricultural production in the CML-IA Baseline Assessment Model. The characteristic values were calculated by openLCA 1.10 software [25], referring to ecoinvent database 3.7.1 [26]:

$$C_{(x)} = \sum C_{(x)j} = \sum \left[Q_{(x)j} e_{(x)j}\right] \tag{3}$$

where $C_{(x)}$ represents the characteristic value of the x environmental impact; $C_{(x)j}$ represents the characteristic value of the jth threat factor to the x environmental impact; $Q_{(x)j}$ represents the emission quantity of the jth threat factor to the x environmental impact; $e_{(x)j}$ represents the equivalent coefficient of the jth threat factor to the x environmental impact.

2.3.3. Standardization

The purpose of standardization was to eliminate the dimension and magnitude differences of characteristic values, and the selected baselines could generally be the total or average data of resource consumption or environmental emissions in the world, the country, or a certain region as Equation (4). In this research, a variety of environmental load benchmarks under the global 100-year time scale in 2000 updated by Van Oers [27], as well as the total global population of that year calculated by the United Nations Population Division [28], were taken as the baselines to standardize the characteristic results:

$$S_{(x)} = C_{(x)} / n_{(x)year} \tag{4}$$

where $S_{(x)}$ represents the standardized value of the characteristic value of the x environmental impact; $n_{(x)year}$ represents the standardization coefficients of the x environmental impact in the selected year (Table 1).

Table 1. Standardization and weight coefficients of different environmental impacts.

Environmental Impact	Unit	Standardization	Weight
Acidification potential (AP)	kg SO_2-eq	39.06	0.19
Global warming potential (GWP)	kg CO_2-eq	6908.81	0.17
Terrestrial ecotoxicity (TE)	kg 1,4-DCB-eq	178.76	0.13
Human toxicity (HT)	kg 1,4-DCB-eq	421.78	0.19
Freshwater aquatic ecotoxicity (FAE)	kg 1,4-DCB-eq	386.74	0.15
Eutrophication potential (EP)	kg PO_4-eq	25.90	0.17

2.3.4. Weighted Summation

The importance of different environmental impacts on the sustainable development of a country or a region was distinctive. Therefore, it was generally necessary to assign specific weights separately to calculate the composite pressure on various environments as Equation (5). Based on the current research progress in China, Wang et al. [29] determined the weight coefficients of different environmental impacts by an expert panel, which was further normalized to weight the standardized results in this study:

$$EI = \sum S_{(x)} w_{(x)} \tag{5}$$

where EI represents the weighted summation of environmental impacts on the system; w_x represents the weight coefficient of the x environmental impact (Table 1).

2.3.5. Pollution Degradation

The environmental service emergy required for pollution degradation of potential environmental impacts generated during system operation could be counted by the emergy input to drive the dilution process in various environments [30]. The quantity of wind, water, and soil needed to achieve the pollution degradation in air, water, and soil was calculated based on the characteristic values of environmental impacts and safe concentrations of indicator pollutants as Equation (6). Then, depending on the corresponding emergy contribution of wind, groundwater, and topsoil, the environmental service emergy required for pollution degradation was calculated as Equations (7)–(9):

$$M = C_{(x)} / t_{(x)} \tag{6}$$

where M represents the quantity of wind (M_A), water (M_W), and soil (M_S) to dilute pollutant; $t_{(x)}$ represents the threshold concentration of the corresponding pollutant in the related eco-environmental protection standard of the x environmental impact:

$$E_A = M_A \cdot DC \cdot v^2 \cdot UEV_A \tag{7}$$

$$E_W = M_W \cdot G \cdot UEV_W \tag{8}$$

$$E_S = M_S \cdot P_{OM} \cdot T \cdot UEV_S \tag{9}$$

where E_A, E_W, and E_S represent the emergy need to degrade pollution in air, water, and soil environment, respectively; DC represents the wind drag coefficient, 0.001; v represents the wind velocity; G represents Gibbs free energy, 4940 J/kg; P_{OM} represents the content of organic matter in topsoil; T represents the energy conversion coefficient of organic matter, 20,900 J/g; UEV_A, UEV_W, and UEV_S represent the unit emergy value of wind, groundwater, and topsoil, respectively.

2.3.6. Comprehensive Index System

Although modern circular agriculture kept the efficient circulation of resources as the core, it was also necessary to take the potential environmental impacts of circulating operation into consideration. Therefore, the comprehensive index system was constructed to evaluate the sustainable development ability of the modern circular agriculture system, as shown in Table 2. Specifically, the reduction indexes reflected the system's emergy demand for external resources; the reuse indexes reflected the utilization degree of renewable resources by the system; the controllability indexes reflected the emergy dependence of the system to control potential environmental impacts; and the sustainability indexes reflected the system's self-organizing ability to consistently yield effective products with less impact.

Table 2. Comprehensive index system for sustainability evaluation.

Hierarchy	Index	Expression	Explanation
Reduction	Total input demand (TID)	E_t/E_o	Emergy demand of effective output for the total input
	Economic resource demand (ERD)	F/E_o	Emergy demand of effective output for economic resources
	Purchased resource demand (PRD)	F_p/E_o	Emergy demand of effective output for purchased resources
	Fossil energy demand (FED)	F_F/E_o	Emergy demand of effective output for fossil energy
Reuse	Renewable environmental resource ratio (RERR)	R_e/E_o	Use ratio of renewable environmental resources to effective output
	Circulating material-energy ratio (CMR)	R_m/E_o	Use ratio of internal circulating material and energy to effective output
	Labor ratio (LR)	R_l/E_o	Use ratio of labor to effective output
	Unrenewable resource ratio (URR)	N/E_o	Use ratio of unrenewable resources to effective output
Controllability	Air pollution degradation index (APDI)	E_A/E_o	Emergy index of pollution degradation in air to effective output
	Water pollution degradation index (WPDI)	E_W/E_o	Emergy index of pollution degradation in water to effective output
	Soil pollution degradation index (SPDI)	E_S/E_o	Emergy index of pollution degradation in soil to effective output
	Composite environmental impact index (CEII)	EI/E_o	The composite index of potential environmental impacts for effective output
Sustainability	Emergy self-sufficiency ratio (ESR)	L/E_t	Self-organizing ability during system operation
	Emergy yield ratio (EYR)	E_y/F	Contribution of system operation to economic resources
	Environmental loading ratio (ELR)	N/R	Pressure caused by system operation on the surrounding environment
	Emergy sustainability index (ESI)	EYR/ELR	Degree of sustainable development of system operation

E_t: emergy of the total input; E_o: emergy of effective output; F: emergy of economic resources; F_p: emergy of purchased resources; F_F: emergy of fossil energy; R_e: emergy of renewable environmental resources; R_m: emergy of internal circulating material and energy; R_l: emergy of labor; N: emergy of nonrenewable resources; E_A: emergy for pollution degradation in air; E_W: emergy for pollution degradation in water; E_S: emergy for pollution degradation in soil; EI: weighted summation of environmental impacts, L: emergy of local resources; E_y: emergy of effective products; R: emergy of renewable resources.

3. Results

3.1. Emergy Structure

The annual emergy input of cereal cropping, feed producing, sheep raising, and manure composting subsystems was 5.02×10^{18}, 1.57×10^{19}, 8.59×10^{18}, and 3.26×10^{18} sej, respectively, according to emergy analysis on the circulating operation of the original system. It could be clearly seen in Figure 4 that the emergy input of the feed producing subsystem was larger than that of the other three subsystems, which was 4.8 times that of the manure composting subsystem with the least input. Correspondingly, the UEV (sej/J) of effective products from each subsystem was 1.00×10^5 for grain, 3.90×10^4 for roughage, 4.11×10^5 for mutton, and 1.20×10^5 for organic fertilizer, while the UEV (sej/J) of by-products was 1.08×10^5 for straw and 1.49×10^5 for manure. By comparison, it was found that although the feed producing subsystem required more emergy input, the UEV of its effective product roughage, was the smallest due to its huge production scale, while the UEV of effective product mutton was the biggest as its role of the consumer in the agro-pastoral ecosystem. The total annual emergy input of the original system was 2.49×10^{19} sej, which was lower than the emergy input sum of the four subsystems, 3.26×10^{19} sej. The reason was that 7.69×10^{18} sej of internal material and energy circulated within the system after these subsystems' successive operations. Therefore, the internal circulation rate of material-energy was 23.59% in the original system.

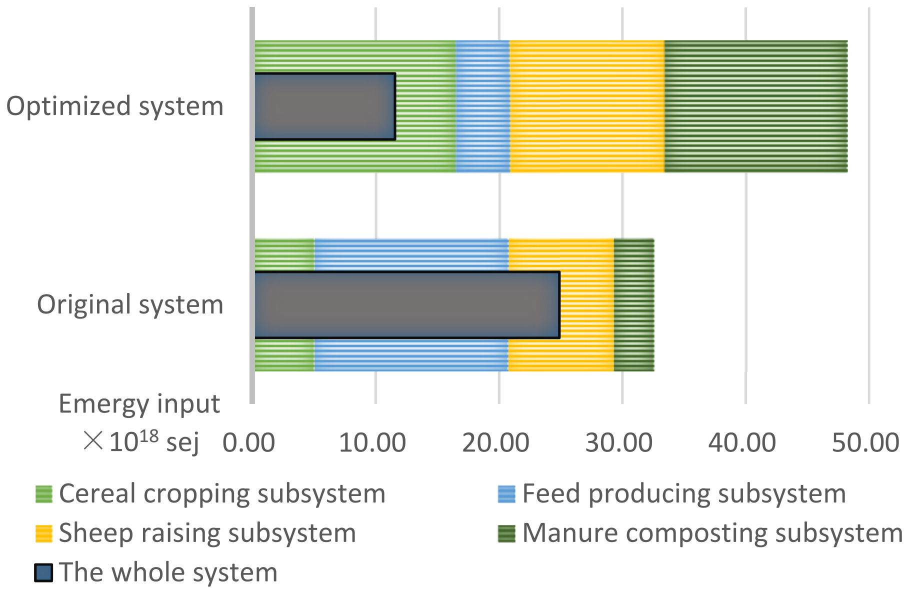

Figure 4. Comparison of emergy input of subsystems in the original and optimized systems.

Compared with the original system, the emergy input of cereal cropping, sheep raising, and manure composting subsystems of the optimized system all increased, mainly because the former two improved their input of internal circulating material and energy, while the latter enlarged its production scale. But the emergy input of the feed producing subsystem decreased due to the shrinkage of its production scale. The total annual emergy input of this system was reduced by 53.53% in comparison to the original system, primarily because the material and energy involved in the internal circulation replaced the required external input. Thus, the internal circulation rate of material-energy in the optimized system reached 76.01%. At the same time, incremental was the UEV of all the effective products and by-products of the optimized system. The major reason was that the circulating efficient operation of successive subsystems needed a large amount of material-energy flow within the system to drive, and the dynamic balance of input and output made the products yielded by subsystems at a higher emergy level.

3.2. Potential Environmental Impact

According to the characteristic results of potential environmental impacts generated by the original system and its four subsystems annually (Figure 5a), the feed producing subsystem was an important source that influenced the system's environmental performance. Especially for HT and FAE, the environmental impact from the feed producing subsystem accounted for more than 52% of the total impact of each category. Meanwhile, TE caused by the sheep raising subsystem reached 86% of its total impact. In addition, the AP, GWP, and EP of the above two subsystems were all high. However, potential environmental impacts of different categories from the cereal cropping and manure composting subsystems were all small, so the sum of these two subsystems was less than 15% of the total impacts of each category. Comparatively, the source of potential environmental impact in the optimized system was different, as shown in Figure 5b. The sheep raising subsystem accounted for the highest proportion, followed by the manure composting subsystem, and their sum exceeded 84% of the total impact of each category.

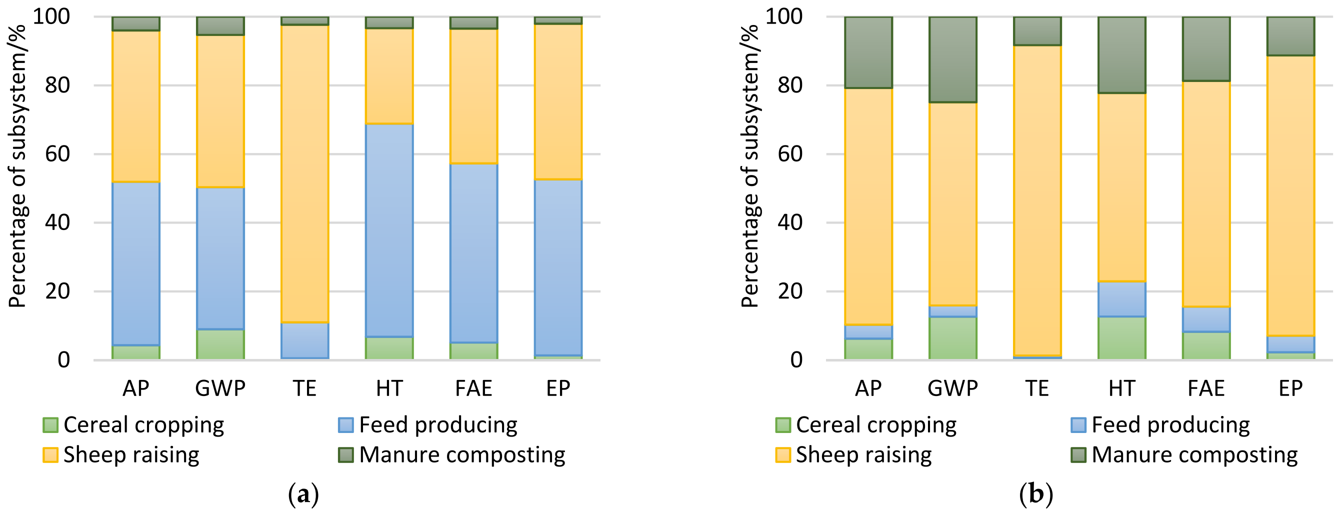

Figure 5. Proportion comparison of the characteristic value of potential environmental impacts among subsystems: (**a**) The original system. (**b**) The optimized system.

The weighted normalization results were obtained based on the standardization of characteristic values of potential environmental impacts generated during the whole year, as shown in Table 3. In either the original system or the optimized system, the HT from the cereal cropping, feed producing, and manure composting subsystems was respectively the largest among different categories, followed by the FAE, while the FAE from the sheep raising subsystem was the largest among different categories, followed by the HE. In addition, the TE from all the subsystems was the smallest. As for the total value, the potential environmental impacts from the feed producing and sheep raising subsystems were much higher than those from the cereal cropping and manure composting subsystems, and the sum of the above two was more than 92% of the total weighted summation in the original system. However, the environmental impact of sheep raising was significantly higher than the other three subsystems and exceeded 63% of the total weighted summation in the optimized system. By comparison, except for the manure composting subsystem, the values of the optimized system were lower than the corresponding values of the original one, so the total weighted summation of the former was only 47.12% of that of the latter.

3.3. Environmental Service Emergy

Integrating emergy analysis and life cycle assessment for different types of indicator pollutants with potential environmental impacts, the emergy consumed by diluting pollutants to a safe concentration was calculated by referring to the corresponding standard threshold. When the original system operated to yield various effective products throughout the year, to achieve the pollution degradation of potential environmental impacts simultaneously, the required environmental service emergy in air, water, and soil was 1.41×10^{14}, 1.43×10^{21}, and 1.49×10^{17} sej, respectively, as shown in Table 4. As mentioned previously, the FAE and HT had an important impact on the environment, so the corresponding pollution degradation called for a great deal of environmental services in water and air. Although the potential environmental impact TE was small, the required environmental service emergy in soil was also large because the pollution dilution process of arable soil was more complex with more emergy consumed.

After the simulated optimization and regulation on the modern Straw–Sheep–Cropland agro-pastoral circular system, the required environmental service emergy in air, water, and soil to realize pollution degradation was 6.76×10^{13}, 7.92×10^{20}, and 1.18×10^{17} sej, respectively. Compared with the original system, it was reduced by 52.14%, 44.44%, and 21.03%, accordingly. In the optimized one, environmental services for pollution degradation of the feed producing subsystem were significantly reduced, and those of the cereal cropping and sheep raising subsystems also decreased to a certain extent. Though those of the manure composting subsystem increased with its expansion of production scale, their contribution to the whole system remained under control. Depending on the calculation results of environmental service emergy integrating emergy analysis and life cycle assessment, it was beneficial to adopt targeted optimization measures for cutting down the environmental impact of the modern agro-pastoral circular system.

3.4. Comprehensive Evaluation

Through the quantitative evaluation by a comprehensive index system, the sustainable development ability of the original and optimized systems could be evaluated from diversified aspects (Table 5). In terms of reduction indexes, the TD, ED, PD, and FD of the optimized system were apparently lower than those of the original one, showing an obvious feature of emergy input decrement. From the point of reuse indexes, under the same regional environmental resource condition, the higher effective output emergy of the optimized system led to a lower TER. But the lifted CMR, as well as depressed LR and UR, evidently indicated that the optimized system had a low dependence on nonrenewable resources. As for the controllability indexes, with the identical scale of planting–breeding in the same production model, the optimized system could commendably lessen the environmental service emergy compared with the original one, embodying its effectiveness in controlling potential environmental impacts.

Table 3. Weighted normalization values of potential environmental impacts in the systems.

Potential Environmental Impact		AP	GWP	TE	HT	FAE	EP	Total
Original system	Cereal cropping subsystem	21.12	50.26	1.31	264.84	147.80	9.20	494.53
	Feed producing subsystem	232.37	231.61	25.61	2419.72	1509.46	349.48	4768.25
	Sheep raising subsystem	232.05	248.16	215.46	1084.32	1136.12	330.36	4415.20
	Organic composting subsystem	19.58	29.73	5.75	130.40	100.21	13.99	299.66
	The whole system	505.13	559.77	248.12	3899.27	2893.59	703.03	9977.64
Optimized system	Cereal cropping subsystem	18.76	47.36	1.22	236.66	132.85	8.24	445.10
	Feed producing subsystem	12.26	12.30	1.37	191.25	117.31	17.25	351.73
	Sheep raising subsystem	207.21	221.96	174.53	1023.67	1057.09	293.38	2977.84
	Organic composting subsystem	62.42	93.43	16.03	414.47	300.42	40.50	927.26
	The whole system	300.65	375.05	193.15	1866.05	1607.67	359.36	4701.92

Table 4. Environmental service emergy to degrade pollution from the systems.

Item		AP	GWP	TE	HT	FAE	EP
Indicator pollutant		SO_2	CO_2	1,4-DCB	1,4-DCB	1,4-DCB	PO_4
Reference standard		HJT 335—2006 [31]	HJ 568—2010 [32]	HJ 25.3—2014 [33]	GB 18468—2001 [34]	GB 8976—1996 [35]	GB 8976—1996 [35]
Threshold concentration		0.05 mg/m^3	750 mg/m^3	0.07 mg/(kg·d)	1.00 mg/m^3	0.60 mg/L	1.00 (P) mg/L
Environment to degrade pollution		Air	Air	Soil	Air	Water	Water
Original system	Cereal cropping	1.42×10^{12}	4.64×10^{10}	7.97×10^{14}	9.59×10^{12}	7.29×10^{19}	5.45×10^{16}
	Feed producing	1.56×10^{13}	2.14×10^{11}	1.56×10^{16}	8.76×10^{13}	7.44×10^{20}	2.07×10^{18}
	Sheep raising	1.44×10^{13}	2.29×10^{11}	1.29×10^{17}	3.93×10^{13}	5.60×10^{20}	1.83×10^{18}
	Manure composting	1.31×10^{12}	2.74×10^{10}	3.51×10^{15}	4.72×10^{12}	4.94×10^{19}	8.29×10^{16}
	The whole system	3.27×10^{13}	5.17×10^{11}	1.49×10^{17}	1.41×10^{14}	1.43×10^{21}	4.04×10^{18}
Optimized system	Cereal cropping	1.26×10^{12}	4.37×10^{10}	7.44×10^{14}	8.57×10^{12}	6.55×10^{19}	4.88×10^{16}
	Feed producing	8.22×10^{11}	1.13×10^{10}	8.33×10^{14}	6.93×10^{12}	5.78×10^{19}	1.02×10^{17}
	Sheep raising	1.39×10^{13}	2.05×10^{11}	1.06×10^{17}	3.71×10^{13}	5.21×10^{20}	1.74×10^{18}
	Manure composting	4.19×10^{12}	8.62×10^{10}	9.78×10^{15}	1.50×10^{13}	1.48×10^{20}	2.40×10^{17}
	The whole system	2.02×10^{13}	3.46×10^{11}	1.18×10^{17}	6.76×10^{13}	7.92×10^{20}	2.13×10^{18}

To avoid double counting, environmental service emergy for pollution degrading in the same environment was only figured up as the largest item.

Table 5. Comprehensive evaluation results integrating emergy analysis and life cycle assessment.

Hierarchy	Index	Original System	Optimized System	Change Rate
Reduction	TID	1.19	1.02	−14.27%
	ERD	1.16	1.01	−13.49%
	PRD	0.88	0.23	−74.24%
	FED	6.23×10^{-2}	1.94×10^{-2}	−68.90%
Reuse	RERR	8.17×10^{-3}	4.73×10^{-3}	−42.08%
	CMR	0.28	0.78	176.17%
	LR	6.40×10^{-2}	2.14×10^{-2}	−66.49%
	URR	0.86	0.34	−61.23%
Controllability	APDI	5.18×10^{-6}	1.44×10^{-6}	−72.28%
	WPDI	52.32	16.84	−67.82%
	SPDI	5.47×10^{-3}	2.50×10^{-3}	−54.26%
	CEII	3.22×10^{-16}	9.99×10^{-17}	−68.93%
Sustainability	ESR	9.39×10^{-3}	2.02×10^{-2}	115.18%
	EYR	0.82	0.98	19.67%
	ELR	7.65	6.57	−14.20%
	ESI	0.11	0.12	39.48%

Taken together, sustainability reflected the system's all-around sustainable development ability. The ESR of the optimized system was 2.02×10^{-2}, which was 115.18% higher than that of the original one, manifesting that the original system needed more external resources, while the optimized one has demonstrated strong self-sufficiency ability. The EYR of the optimized system was 19.67% higher than that of the original one, reflecting that the former utilized the internal environmental resources, waste resources, and renewable resources within the system and converted them into effective products, thereby providing support for the development of the external economic system. Meanwhile, the ELR of the optimized system was 14.20% lower than that of the original one, indicating that the pressure caused by the system on the surrounding environment was reduced to some degree. Overall, the ESI of the optimized system increased by 39.48% compared with the original one, revealing that the sustainable development ability of the system could be significantly improved after scientific parameter coordinating and reasonable technology regulating.

4. Discussion

To deal with the issue of poor utilization of planting and breeding waste resources in the original system, the subsystems were regulated to ensure that their output could be matched with the input of the successive subsystems in line with the proposed principles in Section 2.1.2. Thus, the whole system was simulated to be optimized, and the specific measures were as follows.

1. Cereal cropping subsystem: To ensure the implementation of steady grain production capacity, the planting area of rice and wheat throughout the year was not adjusted. In terms of material-energy circulation, the present straw collection was insufficient. Therefore, it was suggested to regulate the variety layout, stubble management, and harvest support links, and then the annual straw supply could be increased by 4.50×10^5 kg. As for environmental impact, the fertilization process was an important source. Thus, it was proposed to expand the application area of sheep manure organic fertilizer to improve the local fertilizer substitution rate on the premise of the increasing yield of sheep manure organic fertilizer.

2. Feed producing subsystem: The primary task was to absorb straw waste from the cereal cropping subsystem and then to convert it into roughage for supplying the sheep raising subsystem. The current production scale of this subsystem was too large in the whole circular system in Donglin Village, and its environmental impact was obvious. Therefore, it was suggested to decrease the daily yield to 3.15×10^3 kg, which could not only efficiently utilize straw collected from the cereal cropping subsystem but also provide roughage for the sheep raising subsystem.
3. Sheep raising subsystem: The high potential environmental impact restricted the sustainable development of the original system. Therefore, it was proposed to further refine the feed formula and improve its conversion ratio in the feeding process. Moreover, necessary pollution disposal links should be amplified to reduce the potential environmental impact.
4. Manure composting subsystem: The primary task was to absorb manure waste from the sheep raising subsystem and to convert it into organic fertilizer for supplying the cereal cropping subsystem. But at present, the sheep manure was not fully disposed, and the organic fertilizer was not adequately furnished. Hence, it was suggested to increase the daily yield to 1.50×10^4 kg, which could consume the excrement emissions of the sheep raising subsystem to offer organic fertilizer for the cereal cropping subsystem, on the basis of its indistinctive environmental impact.

In the light of the comprehensive evaluation results of this research, these above countermeasures were able to provide a guarantee for promoting the sustainability of the system throughout the whole year's operation. However, with the further improvement of mechanization level and the continuous innovation of technical means in the future, optimization measures should receive timely adjustments. In addition, according to different target needs for various circular agriculture systems in diverse regions, the regulation preference would also be changed dynamically. Although there might be differences in optimization schemes, the basic principle for improving the sustainable development ability of the systems was consistent.

Depending on the results of this study, in intensive production areas, implementing circular agriculture on a moderate scale is beneficial to improve the utilization efficiency of agricultural waste and reduce the environmental impact of agricultural production. During the construction of circular agriculture systems, planting and breeding links should be designed reasonably according to the resource endowment of the region to promote the circulation of material and energy. In the operation process of circular agriculture systems, attention should be paid to coordinating the coupling parameters among the subsystems and optimizing the technical parameters of the key links.

5. Conclusions

This research took the modern Straw–Sheep–Cropland agro-pastoral circular system in Donglin Village as an empirical object. On the four-dimensional temporal–spatial scale, the system boundary was defined by drawing the emergy flow diagram; hence, the input and output inventory of the system was amply sorted out during its whole-year operation. After parameter coordinating and technology regulating, the original system was simulated to be optimized. Integrating emergy analysis and life cycle assessment, the environmental service emergy required in different environments to dilute pollutants to a safe concentration was calculated, and the sustainable development ability of the systems was comprehensively evaluated. The results proved that optimization measures of the more coupled subsystems could significantly advance the system's sustainability. This research formed a systematic method suitable for evaluating and optimizing the modern agro-pastoral circular system, which provided accurate guidance for the scientific construction and sustainable development of circular agriculture systems.

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Appendix A

Table A1. Inventory of input and output items of the original and optimized systems annually.

Input\Output	Item/Unit	Original System	Optimized System	Source	Unit Emergy Value/(sej/Unit)
Input of cereal cropping subsystem	Rain, chemical potentiality/J	9.32×10^{12}	9.32×10^{12}	a	2.37×10^{4} [36]
	Erosion, topsoil/J	1.17×10^{11}	1.17×10^{11}	a	9.40×10^{4} [36]
	Ground water/J	3.19×10^{12}	3.19×10^{12}	a	2.06×10^{5} [36]
	Seed/J	3.95×10^{11}	3.95×10^{11}	a	2.54×10^{5} [37]
	Substrate/g	1.08×10^{8}	1.08×10^{8}	a	3.43×10^{6} [37]
	Tray/¥	3.50×10^{4}	3.50×10^{4}	a	2.74×10^{11} [24]
	Nitrogenous fertilizer/g	5.21×10^{7}	4.96×10^{7}	a	4.83×10^{9} [10]
	Phosphatic fertilizer/g	1.16×10^{7}	1.12×10^{7}	a	4.96×10^{9} [10]
	Potash fertilizer/g	1.84×10^{7}	1.77×10^{7}	a	1.40×10^{9} [10]
	Organic fertilizer (produced)/J	2.71×10^{13}	7.42×10^{13}	a	-
	Organic fertilizer (purchased)/g	9.93×10^{8}	0.00	a	3.43×10^{6} [37]
	Pesticide/¥	1.53×10^{6}	1.53×10^{6}	a	2.74×10^{11} [24]
	Electricity/J	5.54×10^{11}	4.65×10^{11}	b	2.21×10^{5} [36]
	Diesel/J	1.49×10^{12}	1.47×10^{12}	c	8.39×10^{4} [36]
	Machinery/¥	4.70×10^{5}	4.70×10^{5}	d	2.74×10^{11} [24]
	Labor/J	5.42×10^{9}	5.42×10^{9}	a	4.83×10^{5} [38]
	Greenhouse (depreciation)/¥	1.20×10^{5}	1.20×10^{5}	e	2.74×10^{11} [24]
	Maintenance/¥	8.00×10^{3}	8.00×10^{3}	f	2.74×10^{11} [24]
Input of feed producing subsystem	Solar energy/J	4.62×10^{13}	4.62×10^{12}	a	1.00 [36]
	Straw (produced)/J	1.16×10^{13}	1.08×10^{13}	a	-
	Straw (purchased)/J	2.25×10^{14}	0.00	a	4.96×10^{4} [10]
	Plastic film/¥	1.69×10^{6}	1.73×10^{5}	a	2.74×10^{11} [24]
	Microbial agent/¥	9.79×10^{4}	4.47×10^{3}	a	2.74×10^{11} [24]
	Bean residue/g	4.90×10^{9}	2.23×10^{8}	a	3.43×10^{6} [37]
	Molasses/J	5.45×10^{12}	2.49×10^{11}	a	1.08×10^{5} [37]
	Electricity/J	4.40×10^{12}	2.84×10^{11}	b	2.21×10^{5} [36]
	Diesel/J	9.14×10^{11}	3.61×10^{11}	c	8.39×10^{4} [36]
	Labor/J	5.44×10^{10}	7.33×10^{9}	a	4.83×10^{5} [38]
	Feed plant (depreciation)/¥	2.25×10^{6}	2.25×10^{5}	e	2.74×10^{11} [24]
	Maintenance/¥	4.50×10^{5}	4.50×10^{4}	f	2.74×10^{11} [24]

Table A1. *Cont.*

Input\Output	Item/Unit	Original System	Optimized System	Source	Unit Emergy Value/(sej/Unit)
Input of sheep raising subsystem	Solar energy/J	1.16×10^{14}	1.16×10^{14}	a	1.00 [36]
	Corn/J	4.16×10^{13}	4.16×10^{13}	a	1.06×10^{5} [10]
	Bean residue 1/J	2.40×10^{13}	1.92×10^{13}	a	9.17×10^{4} [11]
	Bean residue 2/g	3.19×10^{9}	3.33×10^{9}	a	3.43×10^{6} [37]
	Roughage (produced)/J	1.02×10^{13}	1.84×10^{13}	a	-
	Concentrated feed/g	3.15×10^{4}	3.15×10^{4}	a	8.64×10^{13} [39]
	Veterinary drug/¥	2.07×10^{4}	2.07×10^{4}	a	2.74×10^{11} [24]
	Disinfectant/g	1.28×10^{7}	1.28×10^{7}	a	1.27×10^{9} [11]
	Tap water/J	1.74×10^{11}	1.74×10^{11}	a	8.39×10^{5} [37]
	Electricity/J	1.29×10^{12}	1.25×10^{12}	b	2.21×10^{5} [36]
	Diesel/J	2.16×10^{11}	2.07×10^{11}	c	8.39×10^{4} [36]
	Labor/J	3.14×10^{10}	3.14×10^{10}	a	4.83×10^{5} [37]
	Sheep farm (depreciation)/¥	1.75×10^{6}	1.75×10^{6}	e	2.74×10^{11} [24]
	Maintenance/¥	3.50×10^{5}	3.50×10^{5}	f	2.74×10^{11} [24]
Input of manure composting subsystem	Solar energy/J	1.74×10^{13}	3.48×10^{13}	a	1.00 [36]
	Manure (produced)/J	1.71×10^{13}	4.67×10^{13}	a	-
	Straw (produced)/J	0.00	7.25×10^{12}	a	
	Straw (purchased)/J	2.65×10^{12}	0.00	a	4.96×10^{4} [10]
	Fungus residue/J	2.51×10^{9}	6.88×10^{9}	a	4.83×10^{5} [39]
	Rice bran/J	4.76×10^{12}	1.30×10^{13}	a	6.35×10^{4} [11]
	Tobacco ash/J	6.08×10^{9}	1.66×10^{10}	a	6.44×10^{4} [40]
	Electricity/J	8.34×10^{11}	1.66×10^{12}	b	2.21×10^{5} [25]
	Diesel/J	1.69×10^{11}	3.35×10^{11}	c	8.39×10^{4} [36]
	Labor/J	1.05×10^{10}	2.09×10^{10}	a	4.83×10^{5} [38]
	Fertilizer factory (depreciation)/¥	1.65×10^{5}	3.30×10^{5}	e	2.74×10^{11} [24]
	Maintenance/¥	3.30×10^{4}	6.60×10^{4}	f	2.74×10^{11} [24]
Output of subsystems	Grains/J	2.63×10^{13}	2.63×10^{13}	a	-
	Straw/J	1.16×10^{13}	1.80×10^{13}	a	-
	Roughage/J	4.03×10^{14}	1.84×10^{13}	a	-
	Mutton/J	3.97×10^{12}	3.97×10^{12}	a	-
	Manure/J	4.67×10^{13}	4.67×10^{13}	a	-
	Organic fertilizer/J	2.71×10^{13}	7.42×10^{13}	a	-

a was derived from semi-structured interview and field investigation; b was converted from electricity fee statistics of agricultural electricity price published by State Grid; Among c, transport distance referred to the study of Liang [41]; d referred to the calculation of mechanical input from Wang [11]; In e, the greenhouse was depreciated by the 10-year service life, while the feed plant, sheep farm, and fertilizer factory were depreciated by the 20-year service life [42]; f was converted according to the ratio of maintenance cost to investment cost of the infrastructures.

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