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Sustainable rural economy and food security: An integrated approach to the circular agricultural model

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RESEARCH ARTICLE

Abstract

The lack of resources and increasing damage are major obstacles to sustainable economic progress. Conventional farming methods, known for their energy consumption and resulting pollution, need changes. This study focuses on agriculture, an approach inspired by natural ecological cycles that aim to promote sustainable development in rural areas through efficient resource reuse. The connection between agriculture and rural economies, along with strategies for their combined advancement, is an area that requires more exploration and thorough empirical analysis. The research involves an energy analysis methodology tailored for use in regions to assess the benefits and environmental impacts of implementing circular agriculture for sustainable rural economic growth. A multi-objective decision-making approach using TOPSIS is employed to enhance agricultural policy formulation and decision-making processes. The study concludes by developing a model that considers production, processing, recycling, and socioeconomic aspects to delve into the development of circular agriculture within rural communities and propose relevant strategies. The uniqueness of this research lies in its combination of agriculture and the coordinated advancement of rural economies, which offers a fresh viewpoint and approach to sustainable farming methods and robust rural economic development. The results contribute to the circular agriculture literature body and provide practical guidance for policymakers and farmers.

Keywords: circular agriculture; coupled development degree model; energy analysis; multi-objective decision making; rural economy; sustainable development

Introduction

The burgeoning global economy and incessant population growth have escalated resource pressures and intensified environmental concerns. Conventional agricultural economic models, typified by substantial resource consumption, inefficiency, and significant environmental degradation, no longer suffice in the quest for sustainable development (Adetama *et al.*, 2022; Alahacoon and Edirisinghe, 2022; Gao, 2022; Gusmanov *et al.*, 2023; Herrera-Franco *et al.*, 2023; Jiuhardi *et al.*, 2022; Lin and Hu, 2022; Luo, 2020; Miralles-Garcia, 2023; Sultanova *et al.*, 2023; Tarfi *et al.*, 2023; Tykykalo *et al.*, 2023; Wang, 2023; Zhao *et al.*, 2023). In this context, the circular agriculture model emerges as a beacon of sustainability. This model, which emulates the natural ecological cycle, showcases remarkable efficiency in resource utilization and plays a pivotal role in mitigating environmental stress, thereby heralding a new era in the sustainable evolution of rural economies (Gong *et al.*, 2020; Liu *et al.*, 2016; Wang *et al.*, 2016). In-depth exploration and integration of circular agriculture within rural economies hold immense practical and theoretical significance for fostering a green transition in socio-economic frameworks.

It has been observed that circular agriculture not only refines resource allocation and augments agricultural production efficiency but also enhances the quality of rural ecological environments and elevates living standards (Li *et al.*, 2022; Lu *et al.*, 2022; Wang, 2012). Despite these advancements, the challenge of accurately quantifying circular agriculture's contributions to sustainable rural economic development and achieving a balance between ecological and economic benefits in policy and practice persists (Mahroof *et al.*, 2021; Rotolo *et al.*, 2022). Additionally, analyzing the interplay and synergistic effects between circular agriculture and rural economic sustainability is imperative. Such an analysis is vital for uncovering their inherent linkages and offering robust support for informed decision-making processes (Aleisa *et al.*, 2021; Valencia *et al.*, 2022).

While foundational studies have laid a theoretical groundwork and provided empirical insights into the amalgamation of circular agriculture with sustainable rural economic development, prevailing research methodologies must be revised. These include constraints in selecting pertinent indices for EMA, the application of multi-objective decision-making methods, and the construction of comprehensive coupled development degree models (Chaudhary *et al.*, 2022; de Morias Lima *et al.*, 2021; Germer *et al.*, 2022). Such limitations could result in deficiencies in the models' practicality and accuracy, potentially hindering the complete alignment of research outcomes with the complexities inherent in actual agricultural production and rural economic development (Allam, 2022; Del Valle and Jiang, 2022; Pereira *et al.*, 2023).

When discussing the path to sustainable rural economic development based on the circular agriculture model, it is crucial to recognize the core element of quality assurance and safety of crops and food. Circular agriculture, as an agricultural system that simulates the natural ecological cycle, emphasizes the efficient use of resources and environmentally friendly production processes and focuses on the quality of crop growth and the end safety of food. This is because a sustained and stable output of high-quality crops is the foundation of agricultural sustainability, while food safety is a guarantee for the sustainable development of society. Circular agriculture improves soil fertility and crop disease resistance by reducing chemical fertilizers and pesticides and employing natural cyclic mechanisms such as organic fertilizers and biological control, ensuring crop quality. At the same time, the "farm-livestock-processing-consumption" closed-loop model in circular agriculture ensures traceability and transparency at every stage from the source to the table, providing solid systemic support for food safety.

This paper unfolds into six parts. The first chapter provides the introduction. The second chapter lists the emergy analysis indicators for circular agriculture models that are conducive to sustainable rural economic development in the region through emergy analysis, providing a scientific evaluation system for assessing the comprehensive benefits of circular agriculture. The third chapter employs the TOPSIS method to analyze the extensive benefits of the circular agriculture model under different rural economic development objectives, aiming to provide multi-dimensional decision support for policymakers. The fourth chapter constructs a coupled development model, including the production, processing, recycling, and socio-economic subsystem, to deeply analyze the internal mechanism of coordinated, sustainable development between circular agriculture and rural economy. It also provides strategic suggestions for promoting their synergistic development. Chapters five and six present the analysis of experimental results and conclusions.

This paper aims to explore and establish a set of effective evaluation indicators and decision-analysis methods for circular agriculture to guide its sustainable development in different rural economies. The necessity of this research stems from the global challenges we currently face, such as resource depletion, environmental pollution, and climate change, which pose severe tests to the sustainability of agricultural production, especially rural economies. By determining the benefits of circular agriculture through emergy analysis, optimizing the decision-making process with the TOPSIS method, and analyzing the interactions between different subsystems with the coupled development model, this study aims to provide policymakers and agricultural operators with scientific assessment tools and decision-making frameworks. This will promote the harmonious coexistence of agricultural production and environmental protection, thereby ensuring the long-term development of the rural economy and the well-being of farmers under the constantly changing economic and ecological conditions.

EMA in Circular Agricultural Model for Advancing Sustainable Rural Economies

The research roadmap, as depicted in Figure 1, delineates the methodology adopted in this study. The sustainable development of rural economies is confronted with multifaceted challenges, including the overexploitation of resources, ecological environment deterioration, and inefficiencies inherent in traditional agricultural production. In response to these challenges, this research undertakes an EMA of the circular agricultural model to enhance the sustainability of rural economies. This analysis systematically evaluates the impact of

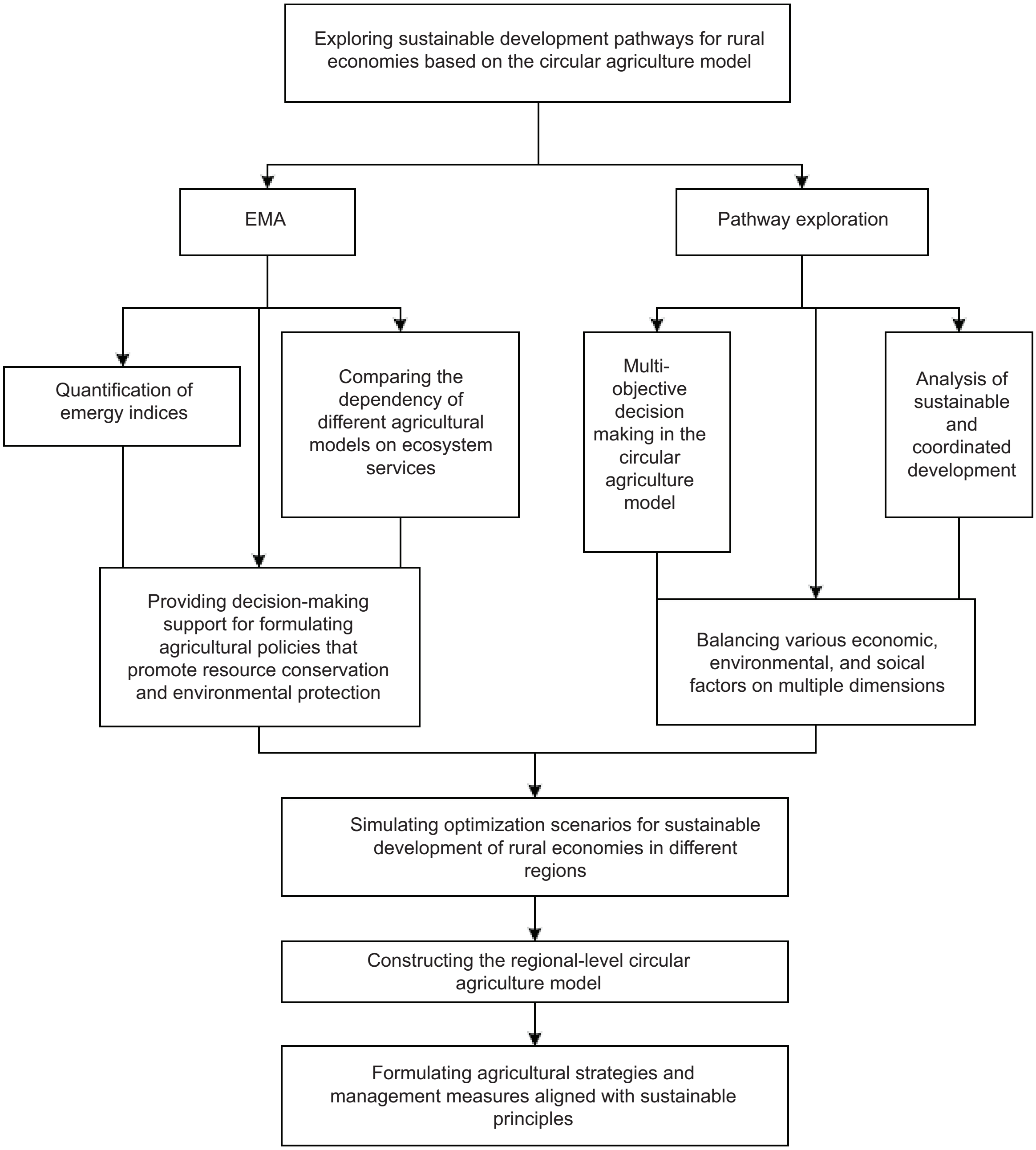

Figure 1. Research roadmap of this study.

various activities within circular agricultural practices on resources and the environment. It aims to ascertain the efficiency and sustainability of energy utilization within these systems. Central to this methodology is the quantification of energy indices, which facilitates a comparative assessment of the reliance of diverse agricultural models on ecosystem services. This comparative analysis supports decision-making for developing agricultural resource conservation and environmental protection policies. The outcomes of the EMA enable the promotion of closed-loop management in agricultural resource recycling, optimizing resource allocation in agriculture, and enhancing the recycling rate in agrarian production. Consequently, this fosters the adjustment and upgrading of the agricultural economic structure, ensuring a harmonious coexistence between farm production and the natural environment. Moreover, the secure processes of food handling and storage are also reflected in the energy value analysis, ensuring that the quality and safety of food are safeguarded throughout the entire chain, from the field to the table. Hence, energy value analysis provides a comprehensive framework to scientifically assess the overall effectiveness of quality assurance and safety of crops and food within the circular agriculture model.

True, the energy investment ratio (EIR) is a pivotal measure. Its enhancement implies reducing reliance on external energy sources, which is critical for achieving self-sufficiency and energy security in agricultural production. In rural areas where modern farming practices may be limited, energy use often needs more efficiency. A high EIR can suggest an overdependence on fossil fuels, potentially escalating costs and exacerbating environmental pollution. Therefore, an analysis of the EIR within the circular agricultural model is undertaken to explore avenues for reducing energy consumption and enhancing energy utilization efficiency.

$$\mathrm{EIR} = \frac{\text{Purchased resource emergy}}{\text{Narural resource emergy input}} \tag{1}$$

The net energy yield ratio (EYR) is intricately linked to the equilibrium between economic and ecological benefits in circular agriculture. A heightened EYR denotes generating more effective energy in the agricultural system, thereby augmenting the system's energy surplus. This elevation bolsters the economic benefits of agricultural production and mitigates environmental impact. In the current context of diminishing resources, an increase in the EYR is crucial for improving the energy efficiency of agricultural systems and fostering sustainable economic growth in rural regions.

$$\mathrm{EYR} = \frac{\text{Total output emergy}}{\text{Total input emergy}} \tag{2}$$

The energy self-sufficiency ratio (ESR) is a key objective in the circular agricultural model. It reflects the extent of a farming system's dependence on external inputs during production. Circular agriculture aims to augment the system's self-supporting capability by enhancing internal energy recycling, such as reusing crop residues and utilizing organic fertilizers. Enhancing the ESR contributes to protecting and improving rural ecological environments, facilitating a balance between economic development and environmental sustainability.

$$\mathrm{ESR} = \frac{\begin{array}{c}\text{Energy input from the}\\ \text{natural environment into the system}\end{array}}{\text{Total energy input into the system}} \tag{3}$$

Figure 2 elucidates the environmental impacts of agricultural activities, an integral measure of sustainability. A lower ecological loading ratio (ELR) indicates reduced adverse environmental effects of agricultural production, thus signifying enhanced ecological sustainability. In practical scenarios, diminishing the ELR is instrumental in alleviating the burden on ecosystem services, curtailing biodiversity loss, and combating soil degradation. These measures are imperative for preserving ecological equilibrium in rural locales.

$$\mathrm{ELR} = \frac{\begin{array}{c}\text{Total energy of non-renewable}\\ \text{energy inputs}\end{array}}{\text{Total energy of renewable energy inputs}} \tag{4}$$

The renewable resource emergy ratio is pivotal in determining an agricultural system's reliance on renewable energy sources. Sustainable rural economic development necessitates maximizing natural energy flows like solar and wind. These sources, by not exhausting non-renewable resources, mitigate environmental harm. The circular agricultural model with a heightened renewable resource energy ratio bolsters regional environmental security and economic self-reliance, particularly in areas with limited resources or ecological fragility.

$$\begin{array}{c}\text{Renewable resource}\\ \text{emergy ratio}\end{array} = \frac{\begin{array}{c}\text{Local renewable resources} +\\ \text{Purchased renewable resources}\end{array}}{\text{Total energy}} \tag{5}$$

The output energy exchange rate (EER) is a critical indicator of energy efficiency in juxtaposing output and input within agricultural systems, essential for appraising the economic feasibility of farming ventures. Addressing cost management and resource optimization in rural economic development, the augmentation of the output EER amplifies agricultural production's profitability and mirrors the efficiency of resource use and ecological advantages. Thus, optimizing the output EER is vital for realizing efficient and sustainable agricultural practices and elevating the competitiveness of the rural economy.

$$\text{Output EER} = \frac{(\$\text{income} \times (\text{sej}/\$)\text{country})}{\text{U}} \tag{6}$$

The purchased input EER indicates the relationship between externally acquired inputs and the system's total output in a circular agricultural model. In modern agriculture, minimizing reliance on external inputs like chemical fertilizers and pesticides effectively reduces production costs and environmental pollution. A lower purchased input EER within the model indicates decreased dependence on external inputs for agricultural production, which is conducive to enhancing both the environmental sustainability and the economic viability of farming practices.

$$\text{Purchased input EER} = \frac{\text{Purchased resources}}{(\$\text{income} \times (\text{sej}/\$)\text{country})} \tag{7}$$

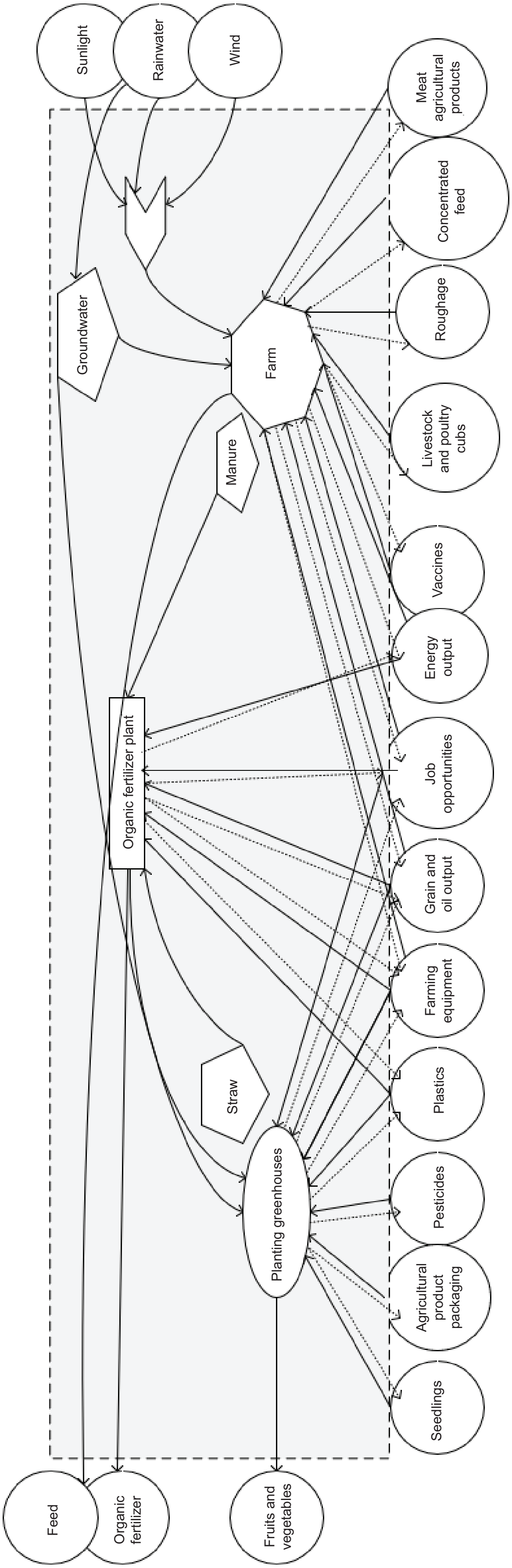

Figure 2. **Energy diagram for circular agriculture supporting sustainable rural economic development.**

The energy sustainability index (ESI) is a crucial metric that directly reflects the sustainability level of an agricultural system. A high ESI signifies a substantial reliance on renewable resources while maintaining minimal usage of non-renewable resources in the production process. This balance is essential for ensuring long-term productivity and ecological equilibrium. In rural economies, an elevation in the ESI indicates a transition towards environmentally sustainable agricultural practices. This shift is imperative for fostering the enduring prosperity of these economies.

$$\mathrm{ESI} = \frac{\text{Energy yield ratio}}{\mathrm{ELR}} \tag{8}$$

The energy index of sustainable development (EISD) analysis is conducted to systematically evaluate circular agriculture's long-term maintainability and production efficiency. This index reflects the efficiency of internal energy recycling within agricultural systems and assesses the system's ability to mitigate external environmental pressures. In the context of prevailing rural economic conditions, the EISD guides reducing reliance on non-renewable resources and enhancing self-sufficiency in agricultural production. Strategies include increasing the use of renewable energy sources and promoting the recycling of crop residues, at this moment fostering a harmonious coexistence between farm production and the natural environment.

$$\mathrm{EISD} = \frac{\text{Energy yield ratio} \times \text{Energy exchange law}}{\mathrm{ELR}} \tag{9}$$

The energy/money ratio analysis is instrumental in understanding and evaluating the interplay between agricultural production's economic benefits and environmental costs. In the circular agricultural model framework, an elevated energy/money ratio indicates a reduction in the use of external resources and ecological services in economic activities. This is pivotal for directing rural economies towards sustainable development with low costs and minimal environmental impact. Decision-makers in rural economies can leverage the energy/money ratio for strategic adjustments and optimizations of agricultural production structures, aiming to achieve economic growth and ecological preservation simultaneously.

$$\frac{\text{Energy / money ratio}}{\left(\frac{\text{sej}}{\$}\right)} = \frac{\text{Total annual energy input}}{\text{GNP}} \tag{10}$$

Return on investment (ROI) analysis is employed in agricultural production processes to assess the efficiency of resource utilization quantitatively. Given the current dynamics of rural economies, optimizing the ROI is crucial for elevating economic benefits, ensuring the rational use of resources, and maintaining ecological sustainability. Under the circular agricultural model, optimization strategies for the ROI include enhancing crop yields, improving resource management, and advancing agricultural technologies. These strategies are central to attaining heightened production efficiency and sustainability in agriculture.

$$\mathrm{ROI} = \frac{\text{Total revenue}}{\text{Total input}} \tag{11}$$

Multi-Objective Decision-Making in the Circular Agricultural Model for Sustainable Rural Economic Development

Figure 3 depicts the comprehensive schematic diagram of the circular agricultural model supporting sustainable rural economic development. In this study, multi-objective decision-making research on circular agricultural models is conducted to address the complex challenges of sustainable rural economic development. These challenges encompass the limitations of resources, the fragility of ecological environments, and the inefficiencies of traditional agricultural production methods. The aim is to identify a development pathway that ensures agricultural production efficiency and economic growth and maintains ecological balance and social welfare. The multi-objective decision analysis of the circular agriculture model provides policymakers with a basis for decision-making that considers crop quality and food assurance and safety. Crop quality and food safety are critical decision criteria when evaluating different objectives. This paper assesses the impact of various circular agricultural practices on crop production, such as crop rotation, the use of organic fertilizers, and the maintenance of biodiversity, all of which directly affect the quality and safety of the final products. In the TOPSIS model, the advantages of these practices are comprehensively considered to find the optimal balance between enhancing soil fertility, reducing chemical residues, increasing crop nutrient content, and ensuring food safety. Through this method, this paper can propose evidence-based policy recommendations that balance multiple interests, aiming to achieve the dual goals of sustainable rural economic development and food safety.

In the current research, the TOPSIS, a techno-economic preference approach, is applied for multi-objective decision-making analysis in a circular agricultural model to foster sustainable rural economic development. TOPSIS is suitable for decision-making problems involving multiple evaluation criteria. Circular agriculture encompasses multi-dimensional economic, environmental, and social indicators. TOPSIS can integrate these complex indicators to assess the overall benefit. Compared to other more complex multi-objective optimization algorithms, such as genetic algorithms or simulated annealing algorithms, TOPSIS offers higher computational efficiency and lower computational complexity. This benefits policymakers, as they can obtain results relatively quickly, facilitating decision-making.

The methodology involving TOPSIS is delineated as follows:

(a) Identification of the “search space” is initially conducted. This space encompasses potential decision-making alternatives within the circular agricultural model. These alternatives include diverse combinations of agricultural practices, each tailored to optimize specific targets such as enhancing production efficiency, diminishing environmental impact, or augmenting economic returns.

(b) The establishment of “ideal” and “non-ideal” points forms a pivotal component of this method. The ideal point symbolizes a hypothetical construct comprising the optimal values across all criteria, whereas the non-ideal point comprises the least favorable values. In the circular agricultural model context, the ideal point might signify scenarios that achieve the most efficient resource utilization, minimal environmental impact, and maximal economic returns. Conversely, the non-ideal point represents the antithesis of these criteria.

(c) Each decision option’s criteria values are transformed into dimensionless units, ensuring comparability among disparate indices. Subsequently, the Euclidean distances from both ideal and non-ideal points are computed for each option. Following this computation, the relative proximity of each option to these points is evaluated. A higher relative proximity indicates a closer alignment with the ideal solution, denoting superior performance in the multi-objective optimization scenario. The options are ranked based on relative proximity to ascertain the most optimal solution. The option with the maximal B_u value is deemed the optimal point.

$$\mathrm{RF}_{u^-} = \sqrt{\sum_{k=1}^{v}\left(d_{uk}^{NO} - d_{k}^{NA}\right)^2} \tag{12}$$

$$B_u = \frac{\mathrm{RF}_{u+}}{\mathrm{RF}_{u-} + \mathrm{RF}_{u+}} \tag{13}$$

(d) The final step involves ranking all options relative to the ideal solution. Acknowledging that different decision-making indices might exhibit diverse scales and units, such as hectares, tons, or percentages, is essential. Moreover, indices within the Pareto frontier solution set may vary significantly in magnitude.

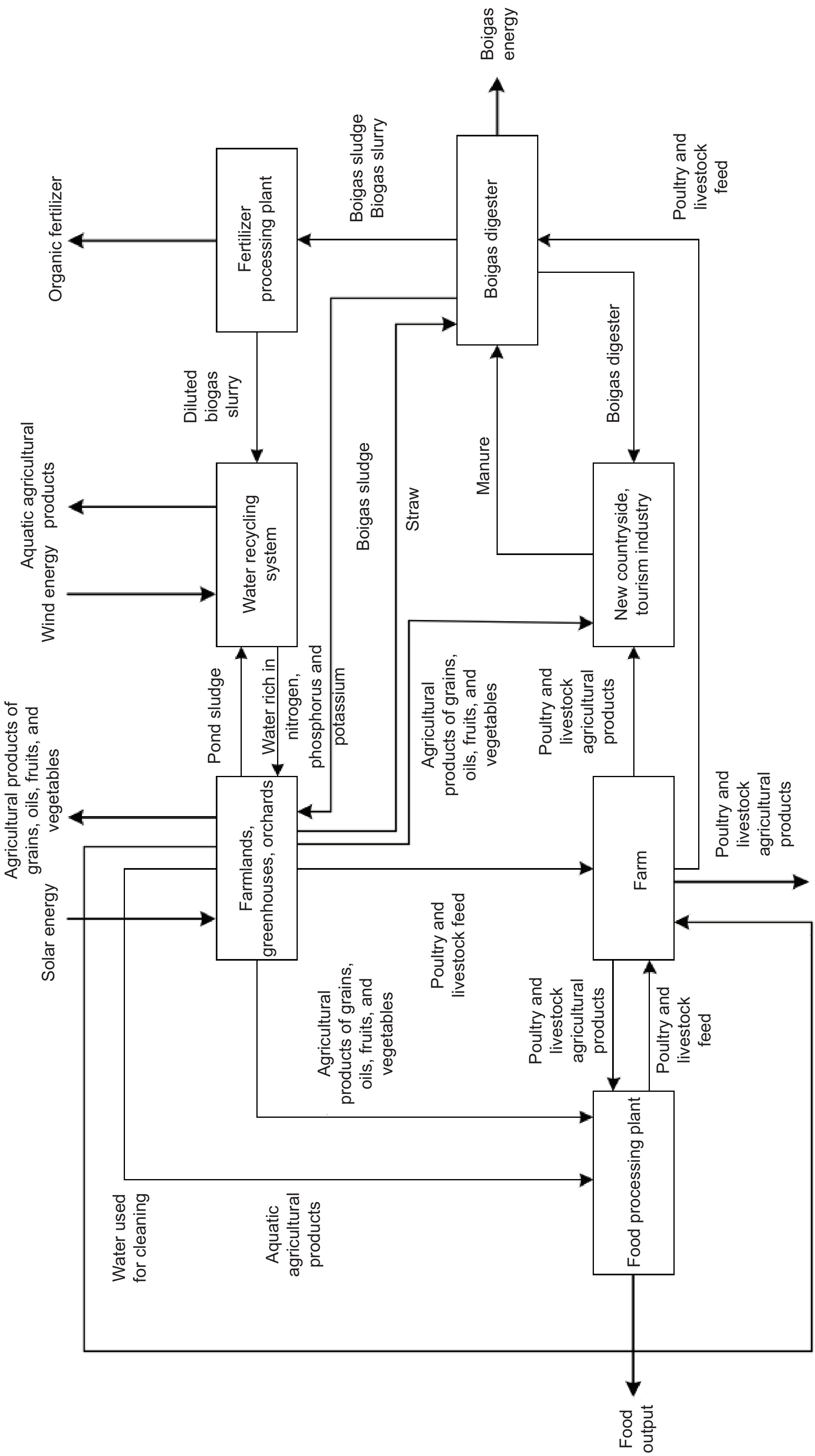

Figure 3. Schematic diagram of the circular agricultural model supporting sustainable rural economic development.

Direct comparisons without normalization could disproportionately influence outcomes. Therefore, normalization of the objective functions for minimization and maximization is conducted, as illustrated in the subsequent formulas. This step ensures that each index within the Pareto frontier is treated dimensionless, facilitating a balanced comparison and evaluation of different decision-making options.

$$d_{uk}^{NO} = \frac{d_{uk} - MAX(d_{uk})}{MAX(d_{uk}) - MIN(d_{uk})} \tag{14}$$

$$d_{uk}^{NO} = \frac{MAX(d_{uk}) - d_{uk}}{MAX(d_{uk}) - MIN(d_{uk})} \tag{15}$$

The specific formulas, assuming the deviation index of each solution from the ideal solution is represented by κ, are as follows.

$$\kappa_{+} = \sqrt{\left(\lambda_{EX} - \eta_{EX.ID}\right)^2 + \left(MZPR - MZPR_{ID}\right)^2} \tag{16}$$

$$\kappa_{-} = \sqrt{\left(\lambda_{EX} - \lambda_{EX.NA}\right)^2 + \left(MZPR - MZPR_{NA}\right)^2} \tag{17}$$

$$\kappa = \frac{\kappa_{+}}{\kappa_{+} + \kappa_{-}} \tag{18}$$

The objective functions encompass several optimization directions in the context of multi-objective decision-making for a circular agricultural model aimed at sustainable rural economic development. The initial focus is on enhancing the resource efficiency of the farm system, particularly emphasizing the maximized utilization of renewable energy in the production process by increasing the renewable resource energy ratio. Subsequently, attention is directed towards optimizing the output EER to elevate the energy efficiency of total agricultural production. Another critical aspect involves reducing the purchased input EER, diminishing reliance on external inputs, curbing production costs, and mitigating environmental impacts. Lastly, elevating the ESI ensures agricultural production's enduring sustainability and alleviates ecological pressures. These objective functions are strategically designed to achieve a harmonious balance among various directions, aiming to collectively enhance agricultural production's economic, environmental, and social benefits.

Analysis of Sustainable and Coordinated Development of Rural Economies Based on Circular Agriculture

Figure 4 shows a sustainable and recyclable agricultural development model combining various forms of agriculture. A comprehensive model is developed in the methodology for analyzing rural economies' sustainable and coordinated development based on circular agriculture, encapsulating three distinct subsystems: production, processing and recycling, and socio-economic.

In this model, food safety is considered a crucial component of the socio-economic subsystem, and its interaction with the production processing and recycling subsystem is essential. This paper analyzes how to strengthen the synergy among these subsystems through biological measures and technological innovations in circular agriculture, such as improving crop planting patterns, enhancing the cleanliness of the food processing workflow, and implementing traceability systems for agricultural product quality. This synergy can significantly enhance the sustainability of crop production, strengthen the security of the food supply chain, and promote awareness of food quality and safety in rural communities through the socio-economic subsystem.

Evaluating interconnections among these subsystems offers critical support for decision-making, enabling the development of scientifically grounded strategies and measures. To ensure the coherence and continuity between the production, processing and recycling, and socio-economic subsystems, a detailed index system has been established:

(a) Production subsystem: Indices for this subsystem are designed to assess the efficiency and sustainability of agricultural production. These include crop yield per unit area, resource utilization efficiency (e.g., water and fertilizer usage), energy consumption per unit output, biodiversity index reflecting ecological diversity in farmlands, and soil quality indicators like organic matter content and erosion rate.

(b) Processing and recycling subsystem: Focus is placed on indices relevant to waste recycling and reduction of environmental pollution. This includes the rate of waste recycling, efficiency of resource recycling, emissions of pollutants like nitrogen and phosphorus, and the rate of adoption of clean technologies, including organic farming practices and biological pesticides.

(c) Socio-economic subsystem: This subsystem's indices encompass aspects related to the quality of rural economic development and social welfare. Key indices include the average net income per farmer, the proportion of agricultural output in the gross domestic product (GDP), employment ratios in the agricultural sector, levels of social security (including healthcare, education, and pensions), and resident satisfaction with rural life quality.

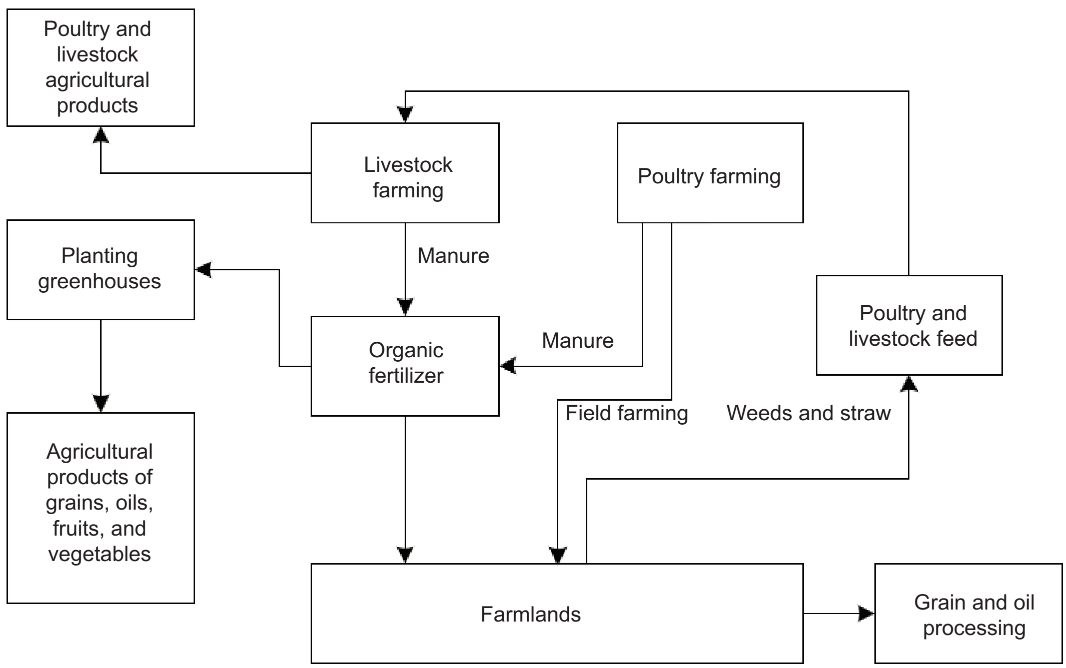

Figure 4. A sustainable and recyclable agricultural development model combining various agriculture forms.

The concept of the coupling degree, denoted as *Z*, elucidates the interdependent relationships among three critical subsystems of rural economies: production, processing and recycling, and socio-economic. The determination of the developmental levels within each subsystem, as well as their integration into a comprehensive system, poses a considerable challenge. The following formula explicates the expression of the coordinated development model tailored for sustainable rural economic development grounded in circular agriculture principles. This formulation more precisely depicts the coordinated development levels of the production, processing, recycling, and socio-economic dimensions. The model posits that the system's coordinated development degree is symbolized by *F*, while S. represents the comprehensive evaluation value. The model also incorporates undetermined weights, denoted by β, α, and ε.

$$F = \sqrt{Z \times S} \tag{19}$$

$$Z = \left[\frac{d(a) \cdot h(b) \cdot g(c)}{\left[\frac{d(a) + h(b) + g(c)}{3} \right]^3} \right]^{\frac{1}{3}} \tag{20}$$

$$S = \beta d(a) + \alpha h(b) + \varepsilon g(c) \tag{21}$$

The development levels of the three subsystems are expressed by *d(a)*, *h(b)*, and *g(c)*, with the weights of each index indicated by x_u, y_k, and z_j. The standardized data for evaluating the coordinated development degree of these subsystems are represented by a_u', b_k', and c_j', as formulated in the expression:

$$d(a) = \sum_{u=1}^{l} x_u a_u' \qquad h(b) = \sum_{k=1}^{l} y_k b_k' \qquad g(c) = \sum_{j=1}^{m} z_j c_j' \tag{22}$$

In the analysis of sustainable and coordinated development within rural economies employing circular agricultural practices, it is recognized that the dimensions, scales, and evaluation criteria for various indices can vary widely. For instance, the metric of crop yield may be quantified in terms of tons per hectare. At the same time, resource utilization efficiency might be expressed as a percentage, and the soil quality index could be represented as a dimensionless figure. The absence of a uniform standard for these diverse indices poses a challenge for direct comparison or aggregation. Standardizing these indices into a standard, comparable format is essential to address this issue. This process effectively negates the impact of differing dimensions and scales, enabling a logical and comprehensive evaluation across a consistent scale. The current study adopts the extremum method for standardizing indices a_u, b_k, and c_j.

$$a_u' = \begin{cases} \dfrac{a_u - \eta_{MIN}}{\eta_{MAX} - \eta_{MIN}} - a_u & \text{as a positive index} \\ \dfrac{\eta_{MAX} - a_u}{\eta_{MAX} - \eta_{min}} a_u & \text{as a negative index} \end{cases} \qquad (u = 1, 2, \ldots, l) \tag{23}$$

Experimental Results and Analysis

Table 1 and Figure 5 are analyzed to provide insights into the efficiencies and advantages of the circular agriculture model over other agricultural practices. The analysis is conducted on raw data and comprehensive scores of the EMA indices across five distinct agricultural models: crop cultivation, poultry farming, fruit and vegetable cultivation, livestock farming, and the circular agriculture model. The EMA methodology is applied, which assesses a system's economic and environmental performance through energy transformation and flow in ecosystems. It extends beyond solely economic benefits to emphasize ecological and environmental sustainability. The data analysis reveals that the circular agriculture model significantly outperforms the individual models in both total and net output values, indicating a considerable economic advantage and capacity to generate higher economic returns. Notably, the circular agriculture model's high EIR (0.99) reflects its reliance on substantial energy inputs. However, its EYR (8.87), the highest among the models, suggests efficient energy utilization, as each unit of energy input yields a substantially higher net output. Furthermore, its ELR of 0.52, the lowest among the models, indicates minimal environmental pressure, aligning with sustainable development goals. The circular agriculture model also excels in renewable resource energy ratio and output EER, demonstrating its efficiency in utilizing renewable resources and energy output. Its high scores in the ESI and EISD further affirm its capacity to maintain productivity while ensuring ecosystem stability and sustainability. The model also ranks highest in the energy/money ratio and ROI, reflecting superior energy economic efficiency and return on investment. Overall, the circular agriculture model achieves the highest comprehensive score (0.89), which reflects its exemplary performance in terms of economic benefits, environmental protection, and resource utilization.

This comprehensive evaluation demonstrates the circular agriculture model's significant economic benefits, resource efficiency, environmental protection, and sustainability advantages. The effective integration and evaluation of these indices underscore the importance of EMA in assessing and guiding the sustainable development of circular agriculture. EMA provides quantitative analysis results and a scientific basis for policy formulation and agricultural practices. As applied in this study, the EMA method provides a multidimensional and systematic evaluation tool with high relevance and applicational value for the circular agricultural model.

Table 2 shows the optimization results for the rural economy's sustainable and coordinated development system based on circular agriculture. This encompasses the production, processing, recycling, and socio-economic subsystems. Each subsystem underwent optimization of decision variables utilizing both the Linear Programming Techniques for Multidimensional Analysis of Preference (LINMAP) and TOPSIS decision-making methods. The data reveal that the TOPSIS method generally offers higher values for most decision variables, with pronounced improvements in variables 2, 8, and 9. This suggests the TOPSIS method's greater efficacy in

Table 1. Original data and composite scores for EMA indices of the circular agriculture model.

	Crop cultivation	Poultry farming	Fruit and vegetable cultivation	Livestock farming	Circular agriculture model
Total output value of the model (Yuan)	63254.1	2215487	421587	15685624	21455234
The net output value of the model (Yuan)	27845.6	1124562	312548	10245687	13458762
Profit of the model (Yuan)	234568.8	889562	287542	11235468	12354786
EIR	0.87	0.887	0.96	0.98	0.99
EYR	6.37	2.35	2.78	5.5	8.87
ESR	1.78	1.86	3.85	2.74	5.73
ELR	2.13	2.68	1.54	1.56	0.52
Renewable resource energy ratio	0.715	0.674	2.83	1.54	3.72
Output EER	0.82	0.831	2.79	1.84	3.89
Purchased input EER	0.83	0.9	2.98	1.92	0.15
ESI	6.3	6.1	5.2	2.7	8.5
EISD	2.3	3.1	4.2	4.7	7.5
Emergy/money ratio	0.99	0.965	3.12	1.93	4.23
ROI	0.3	0.3	0.45	0.41	0.78
Comprehensive score	0.52	0.68	0.68	0.77	0.89

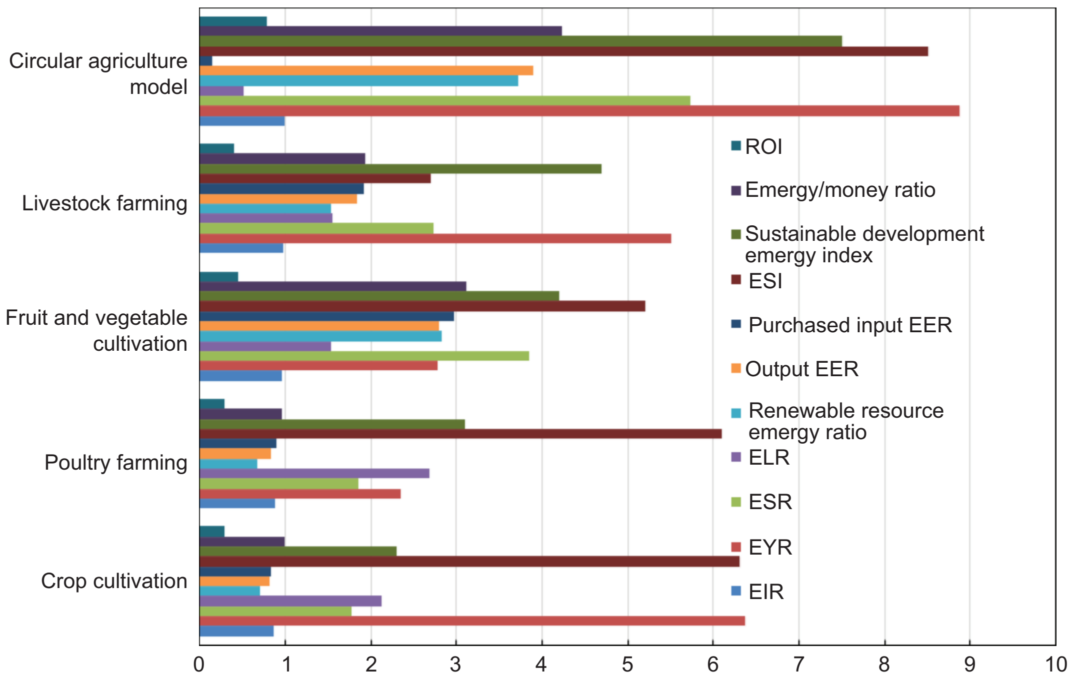

Figure 5. EMA index analysis chart for the circular agriculture model.

Table 2. Optimization results in the rural economy's sustainable and coordinated development system based on circular agriculture.

Subsystem	Decision-making method	Decision variable number										
		1	2	3	4	5	6	7	8	9	10	11
Production subsystem	LINMAP	0.97	8.07	5.22	0.86	3.62	3.76	0.85	4.7	6.9	3.57	0.68
	TOPSIS	0.99	8.82	5.71	0.53	3.78	3.88	0.15	8.6	7.5	4.23	0.78
Processing and recycling subsystem	LINMAP	0.96	8.51	5.66	0.92	3.51	3.78	0.78	5.5	6.7	3.33	0.66
	TOPSIS	0.99	8.86	5.71	0.54	3.72	3.83	0.15	8.4	7.6	4.24	0.79
Socio-economic subsystem	LINMAP	0.92	8.47	5.26	0.95	3.87	3.76	0.85	4.5	6.8	3.26	0.61
	TOPSIS	0.99	8.87	5.77	0.58	3.71	3.82	0.16	8.6	7.5	4.25	0.79

approximating the ideal solution in these subsystems, thereby enhancing rural economies' sustainable and coordinated development within circular agriculture. Upon analyzing the entire dataset, it becomes evident that the TOPSIS method consistently delivers higher values for decision variables across all subsystems. This denotes its superior optimization effects during simulations compared to the LINMAP method. The superiority of the TOPSIS method is highlighted in its ability to handle multi-objective optimization issues, which is particularly relevant in circular agriculture model studies. The TOPSIS method aptly encapsulates the relative significance of diverse objectives by attributing varied weights to each decision variable. This multidimensional approach encompasses various factors, including production efficiency, resource recycling efficiency, and socio-economic growth, offering a holistic decision-making framework for policymakers. The TOPSIS method proves instrumental in pinpointing and optimizing critical factors in the circular agriculture model. For instance, the values derived from the TOPSIS method in Table 2 could signal variables that warrant particular focus, such as enhancing resource recycling rates or amplifying production efficiency. The insights from Table 2 can guide policymakers in discerning the interplay and coherence among different subsystems. This, in turn, facilitates the formulation of more precise policies and optimization of resource distribution and fosters the sustainable advancement of rural economies.

In this research, the TOPSIS method has been effectively employed to analyze the comprehensive benefits of the circular agriculture model within a multi-objective decision-making environment. This approach has provided a robust decision support tool for policymakers, adeptly handling multidimensional data and distinctly

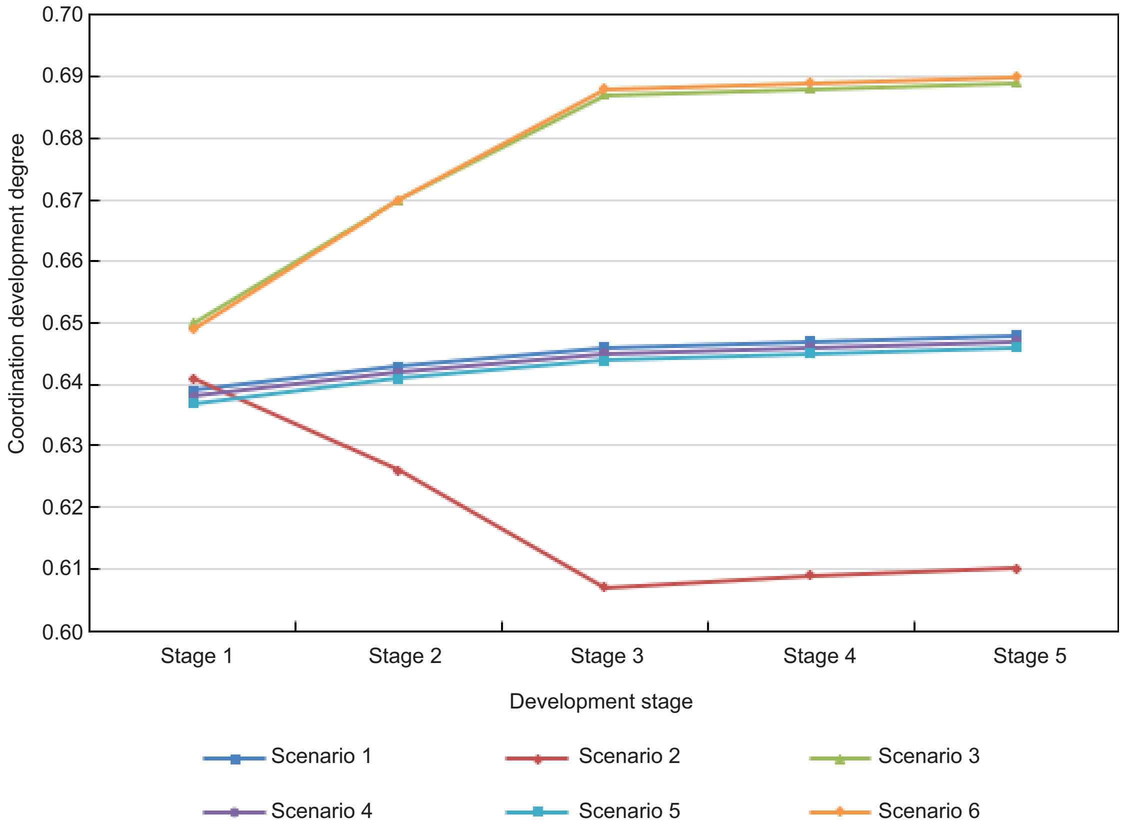

Figure 6. Coordination development degree of the sustainable and coordinated development system for rural economy under different scenarios.

outlining optimal directions for improvement. The significance of this method lies in its capacity to facilitate sustainable development in the circular agriculture model by clearly identifying areas for optimization.

This research conducted an experimental comparative study to analyze the coordinated development of rural economies' sustainable and coordinated development systems under various scenarios across three municipal-level regions. The study's design incorporated five developmental stages and six scenarios. These stages included initial development, transitional development, intermediate development, advanced development, and exemplary development. The scenarios encompass resource depletion-oriented development, circular economy advancement, technology innovation-driven, environmental policy strengthening, social-oriented growth, and comprehensive coordinated development. Figure 6 illustrates the coordination development degree values from Stage 1 to Stage 5 under seven distinct scenarios. The study involved observing the variation in coordination development degree across each stage for every scenario. This enabled a comparison of coordination development degrees across different scenarios to determine the most effective ones. Additionally, the coordination development degrees between different stages were compared to identify the progress and variations in developmental dynamics.

According to the analysis derived from Figure 6, specific scenarios (1, 4, 5, and 6) demonstrate parallel and modest growth patterns. The coordination development degrees in these scenarios show gradual increases from stage 1 to stage 5, albeit with limited magnitude. This pattern suggests that while there has been progress in the sustainable and coordinated development system for rural economies under these scenarios, significant potential for enhancement still needs to be explored. In contrast, Scenario 2 reveals a downward trend in coordination development degree from Stage 1 to Stage 3, followed by stabilization and a slight upward shift. This trend could indicate that initial policies or factors in Scenario 2 may have impeded developmental coordination, but subsequent modifications presumably led to a recovery in the degree of coordination development. Conversely, Scenarios 3 and 7 consistently exhibit a pronounced ascending trend, with steady growth across all stages. This suggests greater effectiveness of the policies or measures in these scenarios for fostering sustainable and coordinated development in rural economies.

The comparative scenario analysis elucidates that Scenarios 3 and 7 have the highest coordination development degrees, implying that the strategies and measures within these scenarios are more favorable for sustainable, coordinated development. Conversely, Scenario 2 consistently presents lower coordination development degrees, especially in Stages 2 and 3, which warrants a detailed investigation to identify underlying causes and refine strategies accordingly. A holistic stage-wise comparison indicates a progressive increase in coordination development degree from Stage 1 to Stage 5, reflecting an overall enhancement in sustainable, coordinated development from the initial to the exemplary stages.

The findings suggest that this study's coupled development degree model effectively captures dynamic shifts in rural economies' sustainable and coordinated development across various scenarios. Scenarios 3 and 7, with their higher coordination development degrees, propose potential strategies and measures that could serve as benchmarks for other scenarios. Furthermore, the model identifies challenges in scenario 2, providing policymakers with crucial insights into areas necessitating attention and improvement. Therefore, this model is instrumental in discerning subtle shifts in sustainable and coordinated development and offering a quantitative tool for policymakers to evaluate and adjust various developmental strategies, thus facilitating targeted and effective policy interventions for rural economies.

Table 3 delineates the varied impacts of distinct scenarios on the sustainable and coordinated development system's subsystems within rural economies and their overall coordination development degree. In this table, the symbols "+++" indicate an exceedingly positive influence, "++" suggests a positive influence, "+" a marginally positive influence, "-" a slightly negative impact, "--" a negative impact, and "---" an exceedingly negative impact. The table highlights that Scenario 1 exerts a profoundly positive influence on the production subsystem in Region 3. However, it adversely affects the processing, recycling, and socio-economic subsystems across all regions, with Region 3 notably impacted. The overall coordination development degree in Region 1 is marginally negative, and in Regions 2 and 3, it is negative. Scenario 2 exhibits a positive impact on the production subsystem in Region 2, with processing and recycling subsystems across all regions experiencing a very positive impact, especially in the socio-economic subsystem of Region 3. Collectively, Scenario 2 positively influences the coordination development degree in Region 3, cheerful in Region 2, and marginally positive in Region 1. Scenario 3 demonstrates positive effects on the production subsystem across all regions, but the impacts vary from marginally to highly negative on the processing, recycling, and socio-economic subsystems. Consequently, the overall coordination development degree is negative across all regions under Scenario 3. Scenario 4 positively impacts the processing and recycling subsystem but negatively impacts the production subsystem. However, Scenario 4 is favorable across all regions in the socio-economic subsystem. Under this scenario, coordination development is positive in all regions. Scenario 5 exhibits marginally positive impacts on the production and socio-economic subsystems in Regions 1 and 3, and positively in Region 2, but negatively on the processing and recycling subsystem across all regions. Overall, Scenario 5 yields a positive coordination development in all regions. Scenario 6 demonstrates positive impacts across all subsystems in all regions, indicating its efficacy in enhancing the overall coordination development degree in every region.

The experimental results reflect the interactions and trade-offs present in the complex circular agricultural system. It is observed that the interests of the production subsystem may lie in increasing output and production efficiency, which is often associated with adopting efficient agricultural technologies and methods. For instance, a scenario might promote advanced irrigation technology, significantly enhancing crop yield and

Table 3. Impact of different scenarios on the coordination development degree of the sustainable and coordinated development system for the rural economy.

Scenario type	Production subsystem			Processing and recycling subsystem			Socio-economic subsystem			Coordination development degree		
	Region 1	Region 2	Region 3	Region 1	Region 2	Region 3	Region 1	Region 2	Region 3	Region 1	Region 2	Region 3
Scenario 1	+	--	+++	--	--	---	---	---	---	-	--	--
Scenario 2	-	++	--	+++	+++	+++	++	++	+++	+	++	+++
Scenario 3	+++	+++	+++	--	+	-	---	-	--	-	-	-
Scenario 4	--	--	--	+++	+++	+++	+	+	+	+	+	+
Scenario 5	+	++	+	-	-	-	+++	++	++	+	+	+
Scenario 6	+++	+++	+	+++	+++	+++	+++	+++	+++	++	++	+++

benefiting the production subsystem. However, such technology may require more water resources or energy input, which might not be favorable for the sustainability of the processing and recycling subsystem in regions with scarce water resources or high energy costs, as it could lead to overconsumption of resources and increased environmental pressure. In comprehensively assessing the impact of different scenarios on each subsystem, it is essential to analyze the specific circumstances of each region in depth, such as resource endowment, level of economic development, and socio-cultural background, to formulate integrated strategies that consider both production efficiency and the maintenance of ecological balance and social welfare. Moreover, dynamic monitoring and flexible adjustments are needed for differentiated strategies across regions to ensure the effective implementation of policies and the sustainable development of circular agriculture.

Conclusion

This paper's principal objective has been to investigate and evaluate the impact of varying policy scenarios on rural economies' sustainable and coordinated development. Utilizing a coupled development degree model, the research scrutinized the interplay and collective progress within rural economies' production, processing, recycling, and socio-economic subsystems. A distinctive feature of this study involved the construction of a coupled development degree model aimed at comprehensively assessing the intricate interconnections of sustainable and coordinated development within rural economies. This model accounted for the interactions between various subsystems, including production, processing and recycling, and socio-economic aspects. Diverse policy scenarios were formulated to emulate various developmental strategies and interventions, influencing the rural economic subsystems. The influence of these impacts on the overall coordination development degree was further explored, encompassing a range of regions to showcase the varied responses and developmental patterns that may emerge under uniform scenarios.

The experimental findings revealed that the different scenarios influenced various regions' subsystems (production, processing, and recycling, socio-economic). Some scenarios were highly beneficial for the production subsystem yet potentially adverse for the processing and recycling subsystem. As for the overall coordination development degree, specific scenarios manifested pronounced positive effects in particular regions while concurrently exhibiting adverse effects in others. Notable regional disparities highlighted the influence of foundational conditions, resource endowments, and socio-economic structures on the effectiveness of policies.

This paper provides a comprehensive research framework for applying circular agriculture in promoting sustainable rural economic development through the construction of energy value analysis, multi-objective decision analysis, and a coupled development degree model. The significance of the research lies in the fact that it not only proposes a scientific evaluation system to measure the comprehensive benefits of the circular agriculture model but also provides multi-objective optimization-based decision support for policymakers through the TOPSIS method, thereby helping them understand how to balance different development goals. Moreover, the coupled development degree model allows the study to reveal the interactions and intrinsic connections between the production, processing, and recycling, and socio-economic subsystems, providing strategic-level guidance for achieving coordinated development. Future developments may focus on refining and tailoring these models and methods to suit the specific conditions of rural economies of different sizes and regions, including consideration of local culture, social structure, market access, and technological levels. Research might also extend to assessing and integrating new technological advancements, such as precision agriculture, biotechnology, and renewable energy, which could significantly impact the efficiency and sustainability of the circular agriculture model.

Data Availability Statement

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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