Evaluation and optimization of a circular economy model integrating planting and breeding based on the coupling of emergy analysis and life cycle assessment

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Abstract
The sustainable development of agriculture is facing problems such as high resource consumption and serious environmental pollution. The development of the circular economy model integrating planting and breeding (CEMIPB) has become an effective way to realize the sustainable development of agriculture. Due to the great difference of natural resource attributes in different regions of China, CEMIPB shows diverse characteristics on the whole. Based on this, this paper constructs a coupling model based on emergy analysis (EMA) and life cycle assessment (LCA) called EM-LCA model and conducts an empirical analysis using a typical CEMIPB in Fujian Province, China, as a case. By comparing the results of the EM-LCA and EMA models, the former effectively compensates for the deficiencies of the latter in terms of economic and environmental impact assessment, and the evaluation results can better reflect the actual situation of the system. Furthermore, sensitivity analysis is introduced to identify key processes and substances. Based on the reduce–reuse–recycle (3R) principle, several optimization suggestions, such as reducing the input of corn and veterinary drugs, are put forward. The construction of the aforementioned methodology system can provide a new perspective for research in similar fields and provide a scientific basis for local government decision making.

Keywords Planting and breeding integration · EM-LCA model · Model evaluation · Sustainable development · Sensitivity analysis · Optimization suggestions

Introduction
As the world’s population boomed, agricultural production expanded rapidly. However, such rapid development has caused problems such as resource depletion and environmental degradation (Iacovidou et al. 2021). Many countries believe that the development of the circular economy model integrating planting and breeding (CEMIPB) is an important measure to solve these problems (Chen et al. 2010). The circular economy is to change the traditional linear production model of “resources–products–discharge” into the circular production model of “resources–products–renewable resources–renewable products” by using material recycling technology (Wu et al. 2015). CEMIPB is the promotion and application of the circular economy model in the agricultural field, for example, Japan’s “resource recycling” planting model, the USA’s “precision” planting model, and the UK’s “permanent” planting model (Liu and Du 2010). As a major agricultural country, China is also facing increasingly prominent resource constraints and environmental problems (Wang et al. 2018). In order to effectively solve the aforementioned problems, the Chinese government has successively issued a number of policies and put forward the action plan for Rural Revitalization, encouraging various regions to develop CEMIPB according to local conditions, such as the “pig–methane–vegetable” model, “rice–shrimp” model, and “fruit–poultry” model (Li et al. 2019). However, due to the differences in agricultural resources in different types of regions, there is a lack of comparability between different models. Therefore, it is necessary to deeply analyze which circular model is appropriate and contributes more to the level...
of sustainable development of the local region in combination with the local resource attributes, in order to provide useful references for the local government when making decisions.

At present, a variety of evaluation methods have been applied to the study of the circular economy model, which can be mainly divided into the following three categories. The first is to find out the key factors that influence a circular economy model through the method of mathematical modeling. Škrinjarić (2020) used the gray relational analysis model to conduct an empirical analysis on the circular economy achievements of some European countries and tested the robustness of the results through a multi-standard decision model. Robaina et al. (2020) found out the driving factors influencing the sustainable development of the circular economy model in European countries through cluster analysis and vector autoregressive model. The second category is to comprehensively evaluate circular economy models by constructing evaluation indicator systems. Vardopoulos et al. (2021) used the Driver-Pressure-State-Impact-Response (DPSIR) model to build an indicator system to evaluate the feasibility of implementing circular economy management in major cities in Greece. Nowakowski and Król (2021) used the coupling method of Analytical Hierarchy Process (AHP) and Preference Ranking Organization to construct an evaluation indicator system and selected the best waste circular economy utilization mode. The third is to evaluate the sustainability of the circular economy model through system flow analysis. Foschi et al. (2021) analyzed the material flow of the recycling economy model of plastic recycling and put forward guiding suggestions for the government. Tomić and Schneider (2018) conducted an energy analysis of the biogas utilization system in Zagreb and showed that waste energy recovery is beneficial to the sustainable development of the system.

It can be seen from the earlier analysis that neither mathematical modeling, indicator system evaluation, nor flow analysis can reflect the cumulative contribution of nature and the environmental impact of pollutants. Emergy analysis (EMA) and life cycle assessment (LCA) can make up for the shortcomings of the aforementioned methods. Wu et al. (2015) evaluated a CEMIPB in northwest China by using emergy, and the results showed that the circular economy model was more conducive to improving resource utilization efficiency and reducing local environmental pressure than the traditional model. Luo et al. (2017) used emergy to analyze the CEMIPB in Changting, Fujian Province, and proposed ways to improve the CEMIPB. Zhang et al. (2015) assessed the CEMIPB with LCA and proposed corresponding energy saving and emission reduction recommendations using scenario analysis. Fan et al. (2018) used LCA to analyze the CEMIPB with different industrial chain lengths in Fujian Province and pointed out that the best ecological and economic benefits can only be achieved by a reasonable plan for the length of the integration of planting and breeding industrial chain. In summary, EMA and LCA, as mature theoretical and methodological systems, have been highly recognized by scholars in the evaluation of CEMIPB.

Both EMA and LCA focus on the assessment of system sustainability, but the former has unique advantages in the analysis of natural system investment, while the latter is more reliable in the assessment of environmental loading capacity (Wang et al. 2020). If the two methods are complementary to each other, the quantitative results may be more objective. Therefore, the two theories have the necessity of coupling development (Cano et al. 2019). Based on this, some scholars have constructed and studied the coupling model of EMA and LCA. For example, Brown et al. (2012) constructed a general decision framework for EMA by referring to the process input standard classification method widely used in LCA. The advantage of this method is that it enhances the consistency and comparability of the evaluation process, whereas the disadvantage is that environmental impacts are not considered. Wang et al. (2015) evaluated the sustainability of a large-scale pig breeding system in northern China by incorporating the emergy of ecological services needed to dilute pollutants into the emergy evaluation system. The advantage of this method is to convert the environmental impact into a unit unified with emergy, but the disadvantage is that the damaging impact of pollutants is not included in the evaluation system. In addition, some scholars proposed to integrate the damage effects of life cycle pollutant emissions into emergy assessment (Jiang et al. 2019; Reza et al. 2014). Although this method can use LCA to quantify the environmental impact of pollutants from two aspects of ecological services and emergy equivalent loss, which is a great improvement compared with the traditional EMA, it can not fully evaluate the characteristics due to the multilevel recycling of wastes in the CEMIPB.

Based on the earlier analysis, although coupling EMA and LCA can have the advantages of the two evaluation methods at the same time, the coupling methods are diverse, and different coupling methods have their own advantages and disadvantages, which should not be directly applied to CEMIPB. Therefore, on the basis of literature research, this paper constructs a complete methodology system suitable for CEMIPB.

Methodology

Firstly, based on the literature review and the characteristics of the CEMIPB, a coupling model based on EMA and LCA is constructed, which is called the EM-LCA model. Based on the traditional EMA, the LCA method was used to integrate ecological services and emergy equivalent loss into the emergy evaluation system (Reza et al. 2014). Meanwhile, according to the characteristics of multilevel utilization of waste, the comprehensive utilization efficiency (CUE) indicator is proposed.
to comprehensively evaluate the waste utilization efficiency. In addition, because the traditional emergy only considers the emery exchange ratio of the output (EERy), the impact of input–output on the economic efficiency of the system could not be measured. Therefore, the emery exchange ratio of input (EERI) (Lu et al. 2009) is introduced to improve the economic performance of the traditional emergy indicators. The previous three impact values are all converted into emergy and integrated into the comprehensive evaluation system. Secondly, this paper compares the evaluation results of the improved EM-LCA model and the EMA model to verify the robustness and reliability of the constructed model. Finally, this paper identifies the key substances that restrict the sustainability of the system through sensitivity analysis and proposes optimization measures and guidelines to improve the sustainability of the system, combined with the “reduce–reuse–recycle” (3R) principle of circular economy and the position of key substances in the system. The specific technical route is shown in Fig. 1.

Case study description and data collection

Fujian Province, located on the southeast coast of China, has rich natural resources and an excellent ecological environment, providing a good foundation for the development of modern circular agriculture. The Fujian Provincial Government attaches considerable importance to the development of high-efficiency ecological agriculture, leading in proposing the concept of ecological province construction in China. Modern integration models of planting and breeding have been practiced and explored for more than 10 years in Fujian Province, and some achievements have been made.

The paper uses a typical CEMIPB in this area as the research object and conducts empirical analysis on it. The target system is divided into farmland planting, large-scale dairy farming, and agricultural wastes comprehensive utilization subsystems with a complete production year as the boundary, as shown in Fig. 2. The total cultivated area is approximately 40 hectares, mainly planted silage corn and alfalfa. All the crops, including straw, are used as roughage for dairy cattle breeding, but some silage corn and alfalfa still need to be purchased. A total of 221 adult cows and 95 calves are at the plant, and the milk produced is sold directly to the public. In addition, a 1100-m3 biogas digester and an organic fertilizer processing plant are built in the plant area to process agricultural wastes such as manure, food residues, and crop residues. The biogas residue and biogas slurry are transported to the planting system and organic fertilizer workshop. The biogas generated is used for power generation and supply to the planting system and breeding system. The surplus power is transmitted to nearby enterprises and communities through the power grid, forming a model with multilevel utilization of materials and resource utilization of wastes.

The data sources of this paper are diverse: The input–output data is obtained by field survey; The meteorological data, such as wind speed and precipitation, are from China Meteorological Data Network CMDC (China Meteorological Data Service Center) (2020). The obtained data are analyzed and checked to ensure the reliability of the research results and reduce uncertainty.

Construction of the EM-LCA coupling indicators system

Emergy is defined as the total amount of solar energy directly or indirectly required to produce a product or service (Odum 1996). Emergy can convert different types of resources, energy, and social labor into a unified unit (sej) through unit emergy value (UEV). The calculation method is shown in Eq. (1).

\[ E_m = \sum_{i=1}^{n} f_i \times UEV_i \]  

Fig. 1 Roadmap of research methodology for CEMIPB
where \( i \) represents a specific type of material flow or energy flow in the target system. \( E_{mi} \) is the emergy value corresponding to a specific material flow or energy flow, \( f_i \) is the amount of a specific material flow or energy flow, and its unit is kilogram (kg) or currency ($). \( UEV_i \) is the unit emergy value, which represents the emergy quantity corresponding to the unit material flow or energy flow, and the unit is sej/unit (such as sej/kg; sej/$).

The emergy input or output of the system is usually divided into local renewable emergy (R), local nonrenewable emergy (N), and purchased emergy (F) depending on different sources and functions. For the purchased emergy, renewable factor (RNF) (Wilfart et al. 2013; Zhang et al. 2012a) is introduced to divide F into renewable part (FR) and nonrenewable part (FN) to accurately calculate the renewable emergy content contained in each input. \( E_{YR} \), \( E_{LR} \), \( E_{ER} \), \( E_{SI} \), and \( E_{ISD} \) are explained in Table 1.

**Impact assessment of pollutant emission**

Pollutants discharged from the system will cause irreversible damage to humans and the ecosystem through inhalable particles and eutrophication of water bodies before reaching a stable state (Zhang et al. 2014), and the damage amount can be quantified by energy equivalent loss (EL). Reliance on the ecological services provided by natural ecosystems, the concentrations of pollutants can be diluted to the acceptable concentrations specified in relevant standards, and the number of required services can be quantified by ecosystem service emergy (ES).

**Quantification of EL**

Pollutant emissions can cause damage to natural ecology, human health, and land occupation (Pittau et al. 2020; Hu 2019). Ecological loss, human health damage, and land occupation can be converted into ecological equivalent energy loss (EL\(_{EQ}\)), human health damage (EL\(_{HH}\)), and land occupation loss (EL\(_{SW}\)) by using the potential disappearance fraction (PDF), disability-adjusted life year (DALY), and land occupation coefficient (LOC), respectively, as shown in Eqs. (2)–(4).

\[
EL_{EQ} = \sum m_i \times PDF_i \times E_{bio}
\]  
(2)

In Eq. (2), PDF (%) is the percentage of species loss in a certain area at a certain time. \( m_i \) is the total emission of a pollutant. \( E_{bio} \) is the annual emergy unit allocated to natural capital in the region, and the value of \( E_{bio} \) is 5.54E+08 sej/year (Reza et al. 2014).

\[
EL_{HH} = \sum m_i \times DALY_i \times E_p
\]  
(3)

In Eq. (3), DALY represents the disability-adjusted life year (year/g) per unit of pollutant emission. \( m_i \) represents the total emissions of a pollutant. \( E_p \) represents the annual emergy of each population, and the value of \( E_p \) is 1.73E+17 sej/year/pop (Reza et al. 2014).

\[
EL_{SW} = \sum m_i \times LOC \times E_L
\]  
(4)

In Eq. (4), \( LOC \) is the land occupation coefficient (ha/t), \( m_i \) is the total amount of certain solid waste emissions (t), and \( E_L \) is the energy required per unit of land restoration (Zhang et al. 2010).

\( E_L \) is the comprehensive emergy loss caused by pollutants to natural ecology, human health, and land occupation, as shown in Eq. (5).

\[
E_L = W_{HH} \times EL_{HH} + W_{EQ} \times EL_{EQ} + W_{SW} \times EL_{SW}
\]  
(5)

In Eq. (5), \( W_{HH} \), \( W_{EQ} \), and \( W_{SW} \) represent the weight values of the three types of damage, and their values are 0.57, 0.33, and 0.10, respectively, by the analytic hierarchy process (AHP).

**Quantification of ES**

The energy required by the natural ecosystem to absorb or dilute air pollutants and water pollutants to reach an
acceptable state or concentration level is ES. Equation (6) represents the mass of air/water required to dilute a pollutant.

\[ M_{\text{air/water}} = d \times \left( \frac{W}{c} \right) \]  

Equation (6) represents the mass of air/water required to dilute a pollutant. \( d \) is the density of air or water, \( W \) is the mass (kg) of a pollutant discharged into the air or water body, and \( c \) is the specified acceptable concentration (kg/m³) of pollutants in the area (SAC (Standardization Administration of the People’s Republic of China) 2012; SAC (Standardization Administration of the People’s Republic of China) 2017).

Emergy of ecological services of air or water (ESair/water) can be obtained by multiplying the kinetic energy/chemical energy of air or water body by the corresponding energy conversion rate, as shown in Eqs. (7) and (8).

\[ ES_{\text{air}} = \frac{1}{2} \times M_{\text{air}} \times v^2 \times UEV_{\text{air}} \]  

\[ ES_{\text{water}} = M_{\text{water}} \times \rho \times UEV_{\text{water}} \]  

\( v \) is the local average wind speed, and \( \rho \) is the internal energy conversion coefficient of the water body. \( UEV_{\text{air}} \) is the emergy transformity of air (2.52 × 10³ sej/J), and \( UEV_{\text{water}} \) is the emergy transformity of water (3.05 × 10⁴ sej/J) (Odum 1996).

Equation (9) represents the total ecological service emergy (ES) required to dilute all pollutants.

\[ ES = \max(ES_{\text{air}}) + \max(ES_{\text{water}}) \]  

Max (ESair) and max (ESwater) represent the maximum values of ESair for each air pollutant and the maximum value of ESwater for each water pollutant, respectively.

**Results**

First, the emergy flow diagram of the CEMIPB is drawn based on Fig. 2, as shown in Fig. 3. Referring to the research results of Odum and Brown (2000), 15.83 × 10²⁴ sej/year is used as the emergy baseline to determine the UEV values of each substance under different baselines. According to the input–output data of the system and relevant calculation methods in “Methodology,” the system emergy analysis table is compiled (Table 2). Second, the LCA method is used

| Table 1 | EMA and EM-LCA comprehensive indicators system construction and comparative analysis |
|---------|---------------------------------------------------------------|
| EM-LCA  | EMA | Unit | Interpretation of indicators |
| R       | R   | sej  | Local renewable emergy |
| N       | N   | sej  | Local nonrenewable emergy |
| F       | F   | sej  | Purchased emergy |
| FR      | FR  | sej  | Renewable part of purchased emergy |
| FN      | FN  | sej  | Nonrenewable part of purchased emergy |
| Y       | Y   | sej  | Output emergy |
| K       | -   | sej  | The part of the emergy output that is fed back to the system |
| Ym      | -   | sej  | The part of the emergy output of the waste utilization system that flows into the market |
| ESair   | -   | sej  | Emergy of ecological services of air |
| ESwater | -   | sej  | Emergy of ecological services of water |
| ES      | -   | sej  | Emergy of ecological services |
| EL      | -   | sej  | Emergy equivalent loss |
| Em$/\text{I}$ | Em$/\text{I}$ | sej$/\text{I}$ | Emergy currency ratio, that is, the emergy value of each currency |
| Ecl     | Ecl | $    | Economic cost |
| EcY     | EcY | $    | Economic income |
| EYR = Y/(F + ES + EL) | EYR = Y/F | - | Emergy yield ratio |
| ELR = (FN + N + ESwater + EL)/(FR + R + ESair) | ELR = (FN + N)/(FR + R) | - | Emergy loading ratio |
| ERY = (EY × Em$/\text{I}$)/Y | ERY = (EY × Em$/\text{I}$)/Y | - | Output emergy exchange ratio |
| EERl = F/(Ecl × Em$/\text{I}$) | - | - | Input emergy exchange ratio |
| CUE = K/(F + K) + Ym/Y | - | - | Comprehensive utilization efficiency of wastes |
| ESI = EYR/ELR | ESI = EYR/ELR | - | Emergy sustainability index |
| EISD = EERl × ERY × EYR/ELR | EISD = EERl × ERY | - | Emergy index of sustainable development |
to evaluate the CEMIPB. Based on the EL and ES calculation method designed in “Construction of the EM-LCA coupling indicators system,” the energy analysis results of pollutants downstream of the system are obtained, as shown in Table 3. According to the data in Tables 2 and 3, the indicators reflecting the economic benefits, environmental load, and sustainability of the integrated system are calculated. The detailed results are shown in Table 4.

### Comparative analysis of EYR

EYR is an important indicator to reflect the economic output capacity of a system. The higher the EYR value, the more emergy the system outputs under a specific external emergy input. Therefore, EYR can be used to judge the industrial benefits and competitiveness of the CEMIPB. Analyzed from Table 4, the EYR of the EMA model and the EM-LCA model are 4.85 and 3.83, respectively, which are both higher than the...
| Emissions                      | Discharge area | Data (g)   | DALY/g | PDF%/g | Acceptable concentration (kg/m³) | Ecological services (sej) | Emergy equivalent loss (sej) |
|-------------------------------|----------------|------------|--------|--------|----------------------------------|---------------------------|-----------------------------|
| Carbon dioxide                | Air            | 2.85E + 08 | 2.10E−10 | -      | -                                | 5.90E + 15                | 1.42E + 16                  |
| Particulates, < 2.5 um        | Air            | 2.06E + 05 | 7.00E−07 | -      | 3.50E−08                         | 2.95E + 13                | 1.42E + 16                  |
| Ozone                         | Air            | 3.94E + 02 | -      | -      | 1.60E−07                         | 1.24E + 10                | -                           |
| Methane a                     | Air            | 2.21E + 07 | 4.40E−09 | -      | -                                | 9.58E + 15                | -                           |
| Methane b                     | Air            | 2.21E + 07 | 1.28E−11 | -      | -                                | 2.79E + 13                | -                           |
| Ammonia                       | Air            | 6.30E + 05 | 8.50E−08 | 1.56E−02 | -                                | 7.08E + 15                | -                           |
| Particulates, > 2.5 um, 10 µm | Air            | 1.12E + 05 | 3.75E−07 | -      | 7.00E−08                         | 8.03E + 12                | 4.14E + 15                  |
| Sulfur dioxide                | Air            | 9.83E + 05 | 5.46E−08 | 1.04E−03 | 6.00E−08                         | 8.22E + 13                | 5.48E + 15                  |
| Nitrogen oxides               | Air            | 8.96E + 05 | 8.87E−08 | 5.71E−03 | 5.00E−08                         | 9.00E + 13                | 8.78E + 15                  |
| Carbon monoxide               | Air            | 6.28E + 05 | -      | -      | 4.00E−09                         | 7.88E + 14                | -                           |
| Solid waste                   | Solid waste    | 2.38E + 07 | -      | -      | -                                | 8.76E + 11                | -                           |
| Cadmium                       | Water          | 4.56E + 02 | 7.12E−05 | 4.80E−01 | 5.00E−06                         | 7.52E + 16                | 3.25E + 15                  |
| Chromium                      | Water          | 2.53E + 03 | -      | -      | 5.00E−05                         | 4.16E + 16                | -                           |
| Copper                        | Water          | 1.02E + 04 | -      | -      | 1.00E−03                         | 8.42E + 15                | -                           |
| Nickel                        | Water          | 6.79E + 03 | -      | -      | 2.00E−05                         | 2.80E + 17                | -                           |
| Zinc                          | Water          | 1.98E + 04 | -      | -      | 1.00E−03                         | 1.63E + 16                | -                           |
| Lead                          | Water          | 1.13E + 03 | -      | 7.39E−03 | 1.00E−05                         | 4.61E + 11                | 1.53E + 12                  |
| COD                           | Water          | 9.59E + 05 | -      | -      | 3.00E−03                         | 2.63E + 17                | -                           |
| Cyanide                       | Water          | 6.99E + 01 | 4.60E−08 | -      | 5.00E−05                         | 1.15E + 15                | 3.17E + 11                  |
| Mercury                       | Water          | 2.21E + 01 | -      | -      | 1.00E−06                         | 1.82E + 16                | -                           |
| Aluminum                      | Water          | 3.20E + 05 | -      | -      | 2.00E−04                         | 1.32E + 18                | -                           |
| Arsenic                       | Water          | 1.05E + 03 | 6.57E−05 | 1.14E−02 | 1.00E−05                         | 4.28E + 11                | 6.80E + 15                  |

a The damage category is climate change. b The damage category is respiratory tract damage.
EYR (1.18) of China’s agricultural production system in 2015 (Liu et al. 2019). It shows that the circular model can fully develop local resources and has good industrial benefits and industry competitiveness. However, the EYR value of the EM-LCA model is significantly lower than that of EMA model, which indicates that pollutants as unexpected output have a great negative impact on the system. Therefore, since the EM-LCA model takes the output of system pollutants into consideration, it can describe the output characteristics of the system more reasonably than the EMA model.

ELR is an indicator that reflects the degree of the environmental impact of a system. The larger the value, the stronger the intensity of the use of nonrenewable emergy in the system and the higher the environmental load. According to the analysis in Table 4, the ELR indicators of the EMA model and the EM-LCA model are 4.20 and 5.51, respectively, which are higher than the research result (0.80) of Liu et al. (2018) on the “colefish” integrated planting and breeding model. According to Brown and Ulgiati (2004), as the ELR rises above 5 for a long time, a system will cause irreversible functional degradation of the environmental system due to excessive stress on the surrounding environment. It shows that the circular model is highly dependent on nonrenewable resources, and the system causes great environmental pressure on the surrounding environment. Given that the EMA model does not consider the effect of pollutants of the system on the environment, its value is 23.75% lower than that of the EM-LCA model, often leading to some cognitive misunderstandings for decision makers because the EMA model cannot actually reflect the impact of system load on the environment. The EM-LCA model only compensates for the defects of the EMA model in this respect. Consequently, from the perspective of reflecting the environmental load, the EM-LCA model has obvious advantages.

In the EMA model, the output emergy exchange ratio (EERY) is used to evaluate the emergy balance between the two parties in the transaction when the system product is sold (Odum 1996). However, a comprehensive assessment of the impact of market exchange on the system requires consideration of

![Emergy flow chart of the CEMIPB](image-url)
both emergy exchange ratios of system input and output. Therefore, in the EM-LCA model, the input emergy exchange ratio (EERI) is introduced, which is the emergy exchange rate for the purchase of production materials (Lu et al. 2009). A fair transaction should make EERI and EERY equal to 1, that is, both sides reach trade equality. Analyzed from Table 4, the EERI is 1.03, which is closer to 1 than the study result (0.62) of Wu et al. (2013). It shows that the equivalent emergy value of the currency obtained in the sale of the products is approximately equal to the actual emergy value of the products; that is, both parties in the transaction have reached trade equality, and the market price of milk represents the true value of milk. According to Table 4, the EERI indicator of the system is 0.80, which is less than 1. This finding shows that the emergy equivalent to the currency paid is higher than the actual emergy when purchasing external resources, that is, 20% of the equivalent emergy of the payment currency is lost in the process of purchasing production materials.

**Comparative utilization efficiency of wastes (CUE)**

Traditional EMA uses emergy feedback rate (EFR) to represent the waste utilization efficiency of a system. EFR refers to the proportion of waste utilization emergy fed back to a system in purchased emergy. Wu et al. (2013) estimated that the EFR of the “pig–methane–fish” integrated planting and rearing model was 0.096. However, the EFR indicator does not consider the part of waste utilization emergy that flows into the external market. Therefore, in order to make up for the shortcomings of the EFR indicator, this paper creatively proposes a CUE indicator to evaluate the system’s waste recycling capacity and incorporates it into the EM-LCA model. The indicator comprehensively evaluates the ability of waste utilization to support the operation of the system from the aspects of reducing input and increasing output. As shown in Table 4, the CUE indicator of the CEMIPB is 0.09, which shows that the sum of the proportion of reduced purchasing emergy and increased output emergy is approximately 9%. It realizes the multilevel utilization of energy and enhances the self-sufficiency of the system, which is conducive to the sustainable development of the system. From the perspective of waste utilization, this indicator can provide additional valuable information for decision makers by evaluating the self-organizing ability of circular models in different natural regions.

**Comparative analysis of ESI**

ESI is an indicator that characterizes the sustainability of the system. Generally, when the ESI is greater than 1, the production process of the system is sustainable (Odum 1996). Analyzed from Table 4, the ESI indicator of the EMA model is 1.16, which is greater than 1 and much higher than the research result (0.10) of Yang and Chen (2014). It shows that the sustainability of the circular economy model is relatively high. However, the ESI of the EM-LCA model is 0.69, which is less than 1, indicating that the sustainability of the circular economy model is low. The two models have reached opposite conclusions. The reason is that pollution emissions have a significant impact on the sustainability of the system, while the EMA model ignores the environmental impact caused by pollutants and therefore overestimates the sustainability of the system. These findings also show that the ecological services and energy damage have a considerable impact on the sustainability of the system and cannot be ignored. In addition, the ESI indicator does not reflect the contribution of the currency emergy compensation, that is, it does not consider the role of EER. Therefore, introducing the EISD indicator for further explanation is necessary.

**Comparative analysis of EISD**

EISD is a composite evaluation indicator of the sustainable development performance of the system, which considers the social and economic benefits and the pressure of the ecological environment (Yang et al. 2020). However, many emergy evaluations related to the integration of planting and breeding have not adopted this indicator (Liu et al. 2018; Luo et al. 2017). Introducing this indicator into the evaluation of the CEMIPB can more comprehensively evaluate the comprehensive sustainability of the system. Analyzed from Table 4, the EISD indicator of the EM-LCA model is 0.60, which is 49.71% lower than that of the EMA model (1.19). On the one hand, the EMA model only considers the emergy exchange ratio at the output of the system and ignores the emergy exchange ratio at the input of the system, leading to a high result (as seen in Table 4, the EERI is less than 1). On the other hand, the EMA model only considers the environmental pressure caused by resource input and ignores the ecological service benefit and equivalent loss of emergy of the system, leading to further high evaluation results. The EISD indicator of the EM-LCA model makes up for the shortcomings of the EMA model, and its evaluation results can better reflect the actual sustainable development level of the system. Therefore, the EM-LCA model has greater advantages compared with the traditional EMA model.

**Optimization discussion**

**Key emergy flow identification**

According to the aforementioned results, although the CEMIPB has realized the multilevel utilization of agricultural wastes, the sustainability of the system is low, and the potential for further optimization remains. The emergy flow input to
the upstream of the system can be divided into three types, namely, local renewable emergy flow (R), local nonrenewable emergy flow (N), and purchased emergy flow (F). By quantifying the share of the earlier three types of emergy flows in the total emergy input, the key emergy flows, i.e., those with a large proportion of weight, are identified. As analyzed in Table 2, the proportion of F in EMA and EM-LCA models is much higher than that of the remaining main emergy flows, accounting for 95.3% and 75.9%, respectively. Thus, the purchasing emergy flow is the key emergy flow that affects the level of sustainability development level of the system. To further analyze the critical substances that are the key substances affecting the sustainable development of the system in the purchasing emergy flow, sensitivity analysis is introduced for further analysis and discussion.

**Sensitivity analysis**

Sensitivity analysis is a method that reflects the change degree of relevant indicators through changes in input data. Sensitivity analysis is used to diagnose and identify critical substances in the system with reference to ISO14040 (ISO 2006) (Eq. (10)).

\[
SC = \left| \frac{(EE_2 - EE_1) / EE_1}{(C_2 - C_1) / C_1} \right|
\]  

(10)

SC is the sensitivity coefficient, \(C_1\) and \(C_2\) are the values before and after the change of main parameters, and \(EE_1\) and \(EE_2\) are the corresponding indicator values before and after the change of main parameters. The sensitivity of each key indicator is calculated according to Eq. (10), and the analysis results are shown in Table 5 and Figs. 4 and 5.

Based on the aforementioned sensitivity analysis, corn, labor force, and veterinary drugs are the key substances restricting the sustainability of the system. Combined with the “3R” principle, the following optimization scenarios are proposed to improve the sustainability of the system.

Scenario I: How can the source reduction of corn feed input be realized? One effective way is to improve the total yield of corn by optimizing the way that corn is grown. Shen et al. (2020) conducted a field experiment in Fujian Province and concluded that compared with maize monocropping, maize and soybean intercropping can increase the chlorophyll content of maize by 10.36%. Zhang et al. (2012b) suggested that maize soybean intercropping could significantly increase the content of protein, oil, and lysine in grain and improve the enzyme activity in the soil. In addition, Liu et al. (2020) concluded that grinding the harvested corn cob into corn cob powder and adding it into corn feed could effectively reduce the amount of corn input, and the crude fiber in the corn cob was conducive to the normal activity of the digestive tract function of cows. According to the case analysis in the paper, mixing corn cob meal in corn feed can reduce corn demand by 12.5%. In the EM-LCA model, the indicators EYR and EISD are increased by 4.63% and 4.49%, respectively. Therefore, the earlier measures can effectively improve crop yield and feed quality, reducing the feed input of the breeding system and improving the intensive utilization rate of local land.

Scenario II: How can the cost of labor and veterinary drugs be efficiently reduced? The application of Internet-of-Things technology to breeding subsystem can greatly reduce labor costs and improve work efficiency (Duan et al. 2018). The automatic management of dairy farming realizes the automatic feeding and milking of dairy cows, reducing the cost of labor and dairy farming, and tracing the source of each cow. In addition, the reduction of veterinary drugs can be achieved by optimizing the production mode. Qin (2019) believed that
strengthening the feeding management in the perinatal period is an important measure to improve the immunity of dairy cows and reduce the use of veterinary drugs. Such feeding management includes the selection of dairy feed, the preparation of diet, feeding methods, and daily management. Combined with the case analysis in the article, if the labor and veterinary drug costs are reduced by 10% through the previous methods, the EYR and EISD in the EM-LCA model will increase by 1.33% and 1.44%, respectively. Therefore, introducing Internet-of-Things technology and improving its feed structure can effectively reduce labor and veterinary drug costs.

Scenario III: The sensitivity of energy and fertilizers is not very high. The reason for this finding is that the feedback materials generated by the recycling of wastes replace a large proportion of energy and chemical fertilizers, resulting in low sensitivity of energy and fertilizers. Therefore, it is necessary to take corresponding measures to further enhance recycling efficiency. Many successful cases in Fujian Province show that the integration of planting and breeding with integrated waste utilization as a link promotes the development of planting and breeding industries and increases the output of agricultural products (Lin 2015). Combined with the case analysis in the article, the utilization ratio of a waste comprehensive utilization system is relatively low, and it is necessary to fully tap its utilization potential. Therefore, the waste utilization subsystem can be operated at full capacity by purchasing agricultural wastes such as straw and manure nearby, and the planting scale of alfalfa and silage corn should be expanded to fully use feedback materials. The results show that EYR in the EM-LCA model is increased by 2.66%, while ELR is reduced by 10.48%, optimizing the effect of waste recycling. Therefore, by combining the actual situation of the system and adopting the aforementioned approaches, the economy and sustainable development capability of the system will be further improved.

Based on the previous scenario analysis, the Fujian Provincial Government can adopt corresponding policies and measures to promote the optimization and promotion of CEMIPB. First of all, cooperation between production, education, and research should be strengthened to accelerate the cultivation of high-quality maize varieties and increase maize

| Item                        | EM-LCA       | EMA          |
|-----------------------------|--------------|--------------|
|                             | EYR | ELR | ESI | EISD | EYR | ELR | ESI | EISD |
| 10% increase                |     |     |     |      |     |     |     |      |
| Feed                        | 6.87%↓ | 0.32%↓ | 6.57%↓ | 7.26%↓ | 6.63%↓ | 0.72%↓ | 5.95%↓ | 5.95%↓ |
| Building materials          | 0.60%↓ | 0.51%↑ | 1.10%↓ | 0.60%↓ | 0.59%↓ | 0.52%↑ | 1.10%↓ | 1.10%↓ |
| Technology                  | 1.52%↓ | 0.54%↑ | 2.04%↓ | 1.74%↓ | 1.92%↑ | 1.02%↑ | 2.91%↓ | 2.91%↓ |
| Energy and fertilizers      | 0.42%↓ | 0.37%↑ | 0.79%↓ | 1.08%↓ | 0.35%↑ | 0.30%↑ | 0.65%↓ | 0.65%↓ |
| 10% reduction               |     |     |     |      |     |     |     |      |
| Feed                        | 7.96%↑ | 0.37%↑ | 7.56%↑ | 8.50%↑ | 7.64%↑ | 0.83%↑ | 6.75%↑ | 6.75%↑ |
| Building materials          | 0.61%↑ | 0.51%↓ | 1.12%↑ | 0.61%↑ | 0.60%↑ | 0.52%↓ | 1.12%↑ | 1.12%↑ |
| Technology                  | 1.57%↑ | 0.55%↓ | 2.13%↑ | 1.79%↑ | 2.00%↑ | 1.04%↓ | 3.07%↑ | 3.07%↑ |
| Energy and fertilizers      | 0.42%↑ | 0.37%↓ | 0.80%↑ | 0.82%↑ | 0.35%↑ | 0.30%↓ | 0.66%↑ | 0.66%↑ |

Table 5 Impact of emergy flow on key indicators after increasing and decreasing by 10%
yields to meet the needs of CEMIPB. Second, investment in research and development of agricultural machinery automation equipment should be strengthened, and subsidies for the purchase of agricultural machinery automation equipment should be increased to effectively reduce the labor cost of CEMIPB. In addition, comprehensive management actions for the abuse of veterinary drugs should be implemented, and the scientific use of veterinary drugs should be promoted to promote the healthy development of CEMIPB. Finally, the government should promote a reasonable circular economy model based on the natural and economic characteristics of different regions in Fujian Province and give full play to the potential of the comprehensive waste utilization system to promote low-carbon sustainable agricultural development in the province.

Conclusions

The main contribution of this paper is to construct a methodology system for the evaluation and optimization of CEMIPB based on the EM-LCA model and the “3R” principle. The main feature of the EM-LCA model is that it incorporates environmental impact and input-end market transactions into the indicator system and proposes a comprehensive waste utilization efficiency indicator to make the evaluation results of the indicator system more comprehensive and complete. The methodology system constructed in the thesis can provide a useful reference and reference for other scholars to study integration models of planting and breeding in different regions.

The evaluation results of the indicator system of the EM-LCA model and the EMA model show that the former model can better reflect the real situation of the sustainable development of the system. In addition, in order to further verify the stability of the model, the sensitivity coefficient is introduced for analysis. It is found that the sensitivity of the two models to parameter changes is generally similar. Because EMA is a model that has been proven to be robust, the EM-LCA model should also have good robustness. Based on the earlier analysis, the EM-LCA model constructed in this paper has good reliability and applicability. In addition, according to the “3R” principle, the paper puts forward some optimization suggestions from the “user side” and “government side,” such as corn source reduction and equipment automation, in order to provide the basis for the local government to make important decisions to improve the development level of local agricultural circular economy.

The coupling theory of emergy and life cycle assessment is in the process of continuous development. The expansion and improvement of the indicator systems still need to be improved by scholars combined with the actual situation of the system. In addition, scholars should build a list of local UVE to provide more complete and accurate basic data for the methodology system. An increasing number of experts and scholars are expected to pay more attention to this methodological system and continue to enrich and improve it.

Author contribution Qingsong Wang: investigation, conceptualization, methodology, data curation, formal analysis, writing — original draft, visualization, and writing — review and editing. Yujie Zhang: visualization and writing — review and editing. Shu Tian: conceptualization, methodology, data curation, formal analysis, and writing — review and editing. Xueliang Yuan: data curation and visualization. Qiao Ma: conceptualization and methodology. Mengyue Liu: investigation. Yue Li and Jixiang Liu: investigation.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical approval and consent to participate Not applicable.
Consent for publication  Not applicable.

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