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An integrated framework of emergy analysis and LMDI for assessing sustainability: a case study of tobacco production system

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KEYWORDS

Sustainability, framework, emergy analysis, LMDI, tobacco

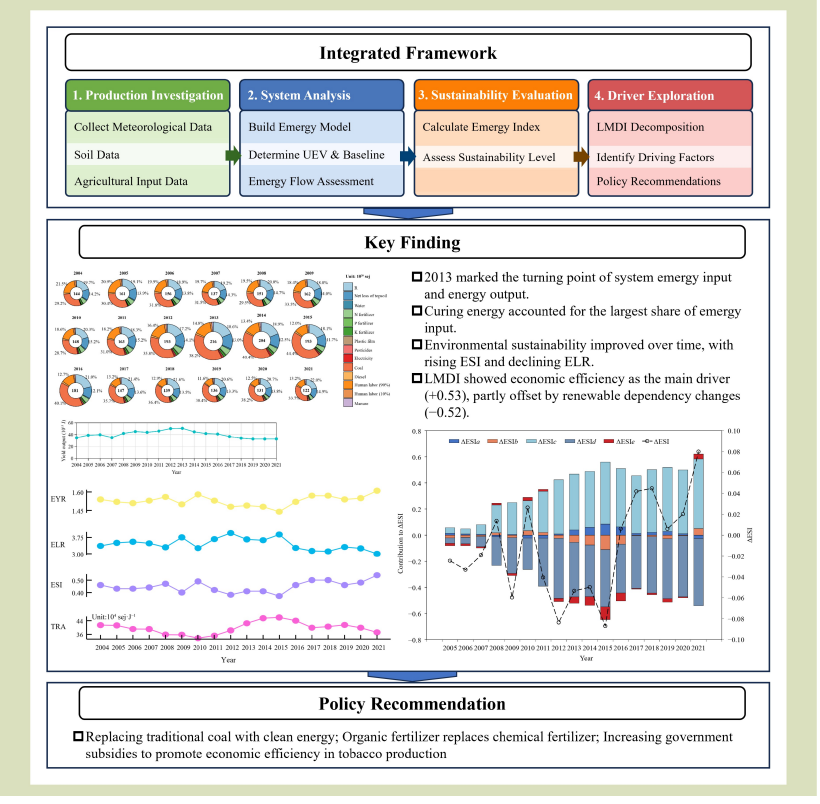
HIGHLIGHTS

- Emergy-LMDI framework assessed tobacco production sustainability in China.
- Tobacco leaf energy output and emergy input peaked in 2013.
- Environmental sustainability index (ESI) rose from 0.46 to 0.54, while ELR declined from 3.36 to 3.00.
- Economic efficiency was the main driver of sustainability improvement.

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GRAPHICAL ABSTRACT



ABSTRACT

To tackle the challenges of resource consumption and environmental pressure in agricultural production systems, quantifying sustainability performance and identifying its driving mechanisms are critical. This study introduces an integrated framework based on emergy analysis and the Logarithmic Mean Divisia Index (LMDI), covering production investigation, system analysis, sustainability evaluation, and driver exploration, and ultimately guiding targeted production recommendations. The results reveal that tobacco energy output rose from 3.5×10^{16} J in 2004 to 5.1×10^{16} J in 2013, before declining to 3.3×10^{16} J in 2021. Total emergy input exhibited a similar pattern, peaking at 2.2×10^{22} sej in 2013. From 2004 to 2021, the environmental sustainability index increased from 0.46 to 0.54, while the environmental loading ratio decreased from 3.36 to 3.00, indicating a steady improvement in sustainability. Significant spatial variability was observed across provinces. LMDI decomposition revealed that economic efficiency contributed significantly to the sustainability improvement (0.53), while changes in renewable resource dependency offset –0.52 of this gain. Based on this framework, targeted strategies are proposed to optimize curing energy utilization, refine fertilizer management, and enhance economic efficiency. These findings offer practical support for promoting the sustainable transformation of the tobacco production system.

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1 Introduction

Agriculture is fundamental to human survival and development. The Green Revolution significantly boosted agricultural productivity, but this progress has also led to severe environmental challenges, including resource depletion, environmental pollution, and climate change[1–3]. These issues highlight the urgent need for sustainable agricultural practices. In 2015, the United Nations integrated sustainable agriculture into the Sustainable Development Goals (SDGs), with SDG 2.4.1 specifying the indicator 'the proportion of agricultural area under production and sustainable agricultural practices'[4]. Consequently, properly assessing the sustainability of agricultural systems has become a critical priority. In the 1980s, systems ecologist Dr. H.T. Odum introduced emergy analysis, a concept that incorporates economic, social, and natural subsystems. By converting materials, energy, and services within a system into solar emjoules, emergy analysis enables the quantification of energy flows, environmental burdens, and sustainability[5]. This quantitative framework provides a valuable tool for evaluating agricultural sustainability.

Emergy analysis has been widely applied to assess the sustainability of agricultural production systems and offers scientific insights into the impact of various management practices on ecosystem health and production efficiency. Zhao et al.[6] and Zhai et al.[7] used emergy analysis to evaluate the environmental sustainability index (ESI) and spatial variability of wheat and maize production systems in China, respectively, providing key insights for optimizing crop structures and enhancing resource use efficiency. Zhuang et al.[8] analyzed emergy indicators and improvement potential for China's three major staple crops using survey data from 1851 counties. Their findings highlighted that increasing crop yields and improving nutrient use efficiency could significantly enhance the ESI. Guo et al.[9] evaluated the emergy flow characteristics of China's greenhouse vegetable production system, revealing a sustainability index of 0.11, which could be increased by 5.99% through comprehensive optimization measures. Jafari et al.[10] found that the ESI of the date palm system (1.30) in Iran was significantly higher than that of pistachio (0.93), suggesting a more favorable path for sustainable development. They recommended improving fertilizer efficiency and reducing topsoil loss. Similarly, Guo et al.[11] conducted an emergy analysis of winter wheat production by 210 small farmers in the North China Plain and found that the system had a higher ESI (0.45) compared to the summer maize system (0.34). This higher ESI was primarily attributed to differences in agricultural input strategies between the two systems. McDougall et al.[12] examined urban agricultural systems in Australia, noting its high productivity but also significant environmental pressures that challenge its sustainability. These studies provide valuable insights for future policy development and management practices. However, while emergy analysis effectively quantifies resource inputs and evaluates ecological sustainability, it remains primarily descriptive and does not explicitly reveal how changes in input structure, resource dependency, and economic performance contribute to variations in sustainability indicators.

To address this limitation, a quantitative decomposition approach is necessary to untangle the structural drivers underlying changes in sustainability. Therefore, this study integrates emergy-based sustainability assessment with the Logarithmic Mean Divisia Index (LMDI) method[13] to link sustainability performance with its economic and resource-use determinants. The LMDI method enables complete decomposition without residuals and allows precise attribution of changes to individual driving factors. This integrated framework shifts the analysis from a descriptive evaluation to a mechanism-oriented approach.

Tobacco production is a globally significant cash crop and supports a major agricultural sector in numerous countries. However, it is characterized by high resource intensity, relying not only on key climatic factors such as temperature, light, and water but also on substantial inputs of chemicals and energy. Globally, approximately 32.4 million tons of fresh tobacco leaves are produced annually to manufacture around six trillion cigarettes. This process involves 27.2 million tons of material inputs, over 62 million GJ of energy consumption, and 22 billion tons of water usage[14]. The intensive resource use in tobacco production results in a considerable environmental burden. Recent studies from Brazil[15,16], Pakistan[17], Iran[18], and China[19,20] have assessed the environmental impacts of tobacco production using life cycle assessment (LCA) methods. While these studies provide detailed life-cycle inventories and impact quantifications, they primarily focus on environmental emissions and impact categories, offering limited insights into the structure and contribution of natural resource inputs and their role in shaping overall sustainability performance and driving mechanisms. To fill this gap, this study developed an integrated framework combining production investigation, system analysis, sustainability evaluation, and driver exploration. This framework was empirically validated using the tobacco production system as a case study, leading to the formulation of targeted production strategies. The framework aims to: (1) assess the spatiotemporal dynamics of emergy input-output and sustainability levels of tobacco production in China from 2004 to 2021; and (2) explore the driving factors of sustainability and provide policy recommendations to enhance the sustainability of the tobacco production system.

2 Material and methods

This study was conducted within an integrated framework comprising four key components: production investigation, system analysis, sustainability evaluation, and driver exploration (Fig. 1). (1) Production investigation involved the collection of meteorological data, soil characteristics, and agricultural input information for tobacco production. (2) System analysis included constructing an emergy framework for the Chinese tobacco production system based on Odum's emergy theory, determining unit emergy values (UEVs) and the latest geobiosphere emergy baseline, and analyzing emergy flow characteristics from temporal and spatial perspectives. (3) Sustainability evaluation utilized multiple emergy-based indicators to assess the sustainability level of the tobacco production system. (4) Driver exploration employed the LMDI method to identify key driving factors and provide recommendations for the sustainable development of the tobacco production system. This systematic framework supports evidence-based decision-making for the green transformation of China's tobacco industry and can be adapted to assess sustainable crop production in other regions.

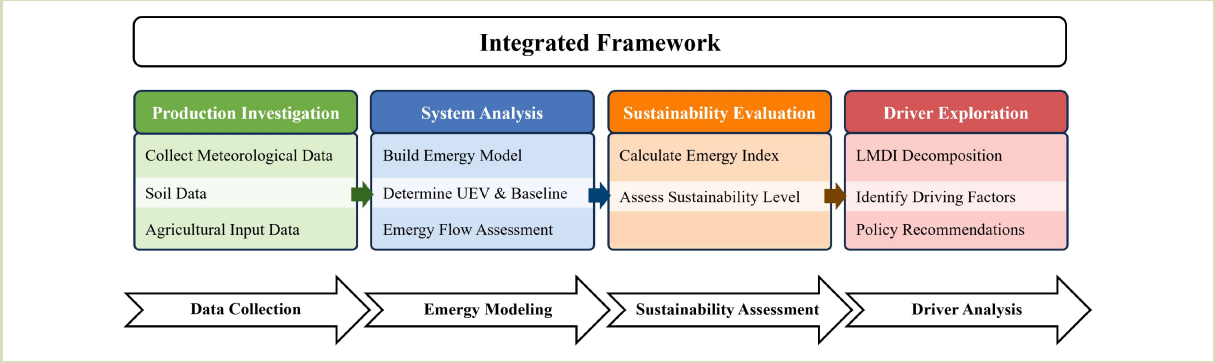


Fig. 1 Comprehensive flowchart of emergy analysis for the tobacco production system.

2.1 System boundary

Based on Odum's theory[21], this study used China's tobacco production system as the research subject to define the system boundaries and construct an energy flow diagram (Fig. 2). The system required various resource inputs, including local renewable resources (R), local non-renewable resources (N), purchased renewable resources (FR), and purchased non-renewable resources (FN). The emergy output considered only the dry tobacco leaf product, excluding by-products. The geobiosphere emergy baseline was updated to 12.0×10^{24} sej[22], and all UEVs were calibrated. The specific calculation methods and data sources are detailed in Table S1. To further evaluate the economic, social, and environmental conditions of the tobacco production system, several emergy indicators were employed, with symbols and meanings presented in Table 1. ESR and R% represent the proportion of non-renewable and renewable resources in the system, respectively. EIR and EYR indicate the system's dependence on purchased resources and local resources, respectively. ELR denotes the system's environmental loading ratio, ESI reflects the system's sustainable development level, and TRA signifies production efficiency within the system.

Sensitivity analysis was performed to further explore the internal factors influencing the ESI in tobacco production systems. Sensitivity analysis, a standard technique for uncertainty assessment, is primarily used to examine how changes in parameters affect model outcomes[25]. To advance the sustainable development of China's tobacco production, sensitivity analysis was performed on emergy input using average data from 2004 to 2021. Since higher emergy flows have a substantial impact on the results[25], the primary contributors to total emergy input were selected for the sensitivity analysis. Based on the emergy input data (Fig. 3), coal, human labor (90%), and nitrogen fertilizer were chosen from the purchased non-renewable resources for sensitivity analysis. Adjustments of ± 20% were applied to these resources to calculate the system's ESI, consistent with previous sensitivity analysis studies in emergy-based and environmental systems assessments[26].

2.2 Data sources

Due to limitations in data availability and completeness, this study focused on 17 regions in China (Gansu, Jilin, Guangxi, Anhui, Jiangxi, Guangdong, Heilongjiang, Chongqing,

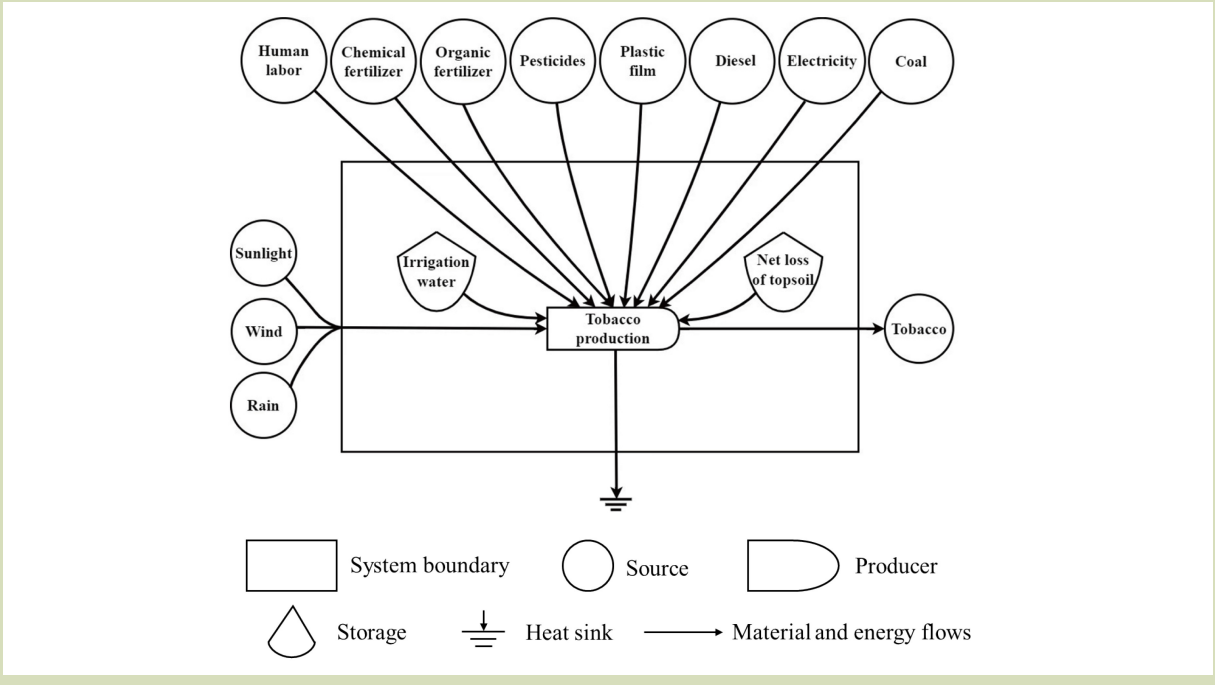


Fig. 2 Emergy system graph of the tobacco production system.

Table 1 Variables used to evaluate the emergy of the tobacco production system and their significance

Index	Symbol	Formulation	Implication	Reference
Total emergy input	U	U = R + N + FR + FN	Total emergy flows needed to support a production system	[21]
Total energy output	G		The physical energy output of the tobacco production system	[23]
Emergy self-support ratio	ESR	ESR = (N + R) /U	Percentage of the entire local resources emergy flows used by the production system. A higher ESR value indicates a greater proportion of local resources in the system	[21,23]
Emergy investment ratio	EIR	EIR = (FN + FR) / (N + R)	The ratio of the entire purchased resources emergy flows to the entire local resources emergy flows. This indicator reflects dependence on purchased resources; the higher the EIR value, the greater the dependence on purchased resources in the system	[21,23]
Emergy renewability	R%	R% = (FR + R) /U	Percentage of the entire renewable resources used by the production system	[21,23]
Emergy yield ratio	EYR	EYR = (U) / (FN + FR)	This indicator reflects the dependence on local resources, that is, the ability to enhance the significance of internal resources through investment in external resources	[21,24]
Environmental loading ratio	ELR	ELR = (N + FN) / (R + FR)	A measure represents the potential stress that the production system imposes on the local environment	[21,24]
Environmental sustainability index	ESI	ESI = EYR/ELR	A measure represents the sustainability of the production system, reflecting the trade-off process between the emergy advantage of the system and the environmental pressure	[21,24]
Transformity	TRA	TRA = U/G	A measure represents emergy using efficiency of the given system. A lower TRA value indicates higher energy efficiency per unit yield	[21,23]

Shaanxi, Hubei, Shandong, Fujian, Sichuan, Henan, Hunan, Guizhou, and Yunnan). These provinces together represent over 98% of the total flue-cured tobacco planting area in China during the study period, ensuring their strong national representativeness. Data on chemical fertilizers, organic fertilizers, pesticides, plastic film, irrigation electricity consumption, diesel, coal, labor, and tobacco production costs were sourced from the National Agricultural Production Cost-Benefit Compilation[27], published by the Price Department of the National Development and Reform Commission of China. Tobacco planting area and yield data were obtained from the China Statistical Yearbook[28], published by the National Bureau of Statistics of China. Solar radiation data were provided by Feng and Wang[29], wind speed data from the National Oceanic and Atmospheric Administration (NOAA)[30], rainfall data from Peng et al.[31], and soil data from the Soil Testing and Fertilizer Recommendation Base Nutrient Dataset[32]. Meteorological and soil attributes for each province were calculated by averaging values from their respective prefecture-level cities.

2.3 Logarithmic Mean Divisia Index (LMDI) decomposition analysis

The decomposition analysis was conducted using the LMDI method, as proposed by Ang[13]. This method is widely used in environmental and resource studies due to its complete decomposition property and zero-residual characteristic, which ensures consistent and additive results when quantifying changes in composite sustainability indicators. LMDI has been extensively applied to identify structural driving forces in carbon emission analysis[33], water resource assessment[34,35], energy consumption studies[36,37], and ecosystem service evaluation[38,39], demonstrating its robustness in analyzing complex socio-ecological systems. Within the integrated evaluation–decomposition framework developed in this study, the LMDI method was employed to decompose changes in the Emergy-based Sustainability Index (ESI) of China's tobacco production system. Drawing from previous agricultural sustainability research, five driving factors were identified: (1) agricultural development level, (2) purchased resource pressure, (3) economic efficiency, (4) renewable resource dependency, and (5) non-renewable resource intensity. The changes in ESI are described by the following equation:

$$\begin{aligned} \mathrm{ESI} &= \frac{\mathrm{EYR}}{\mathrm{ELR}} = \frac{\mathrm{U}\times(\mathrm{FR}+\mathrm{R})}{(\mathrm{FN}+\mathrm{FR})\times(\mathrm{FN}+\mathrm{N})} \\ &= \frac{\mathrm{U}}{\mathrm{A}}\times\frac{\mathrm{A}}{\mathrm{FN}+\mathrm{FR}}\times\frac{\mathrm{GDP}}{\mathrm{A}}\times\frac{\mathrm{FR}+\mathrm{R}}{\mathrm{GDP}}\times\frac{\mathrm{A}}{\mathrm{FN}+\mathrm{N}} \end{aligned} \quad (1)$$

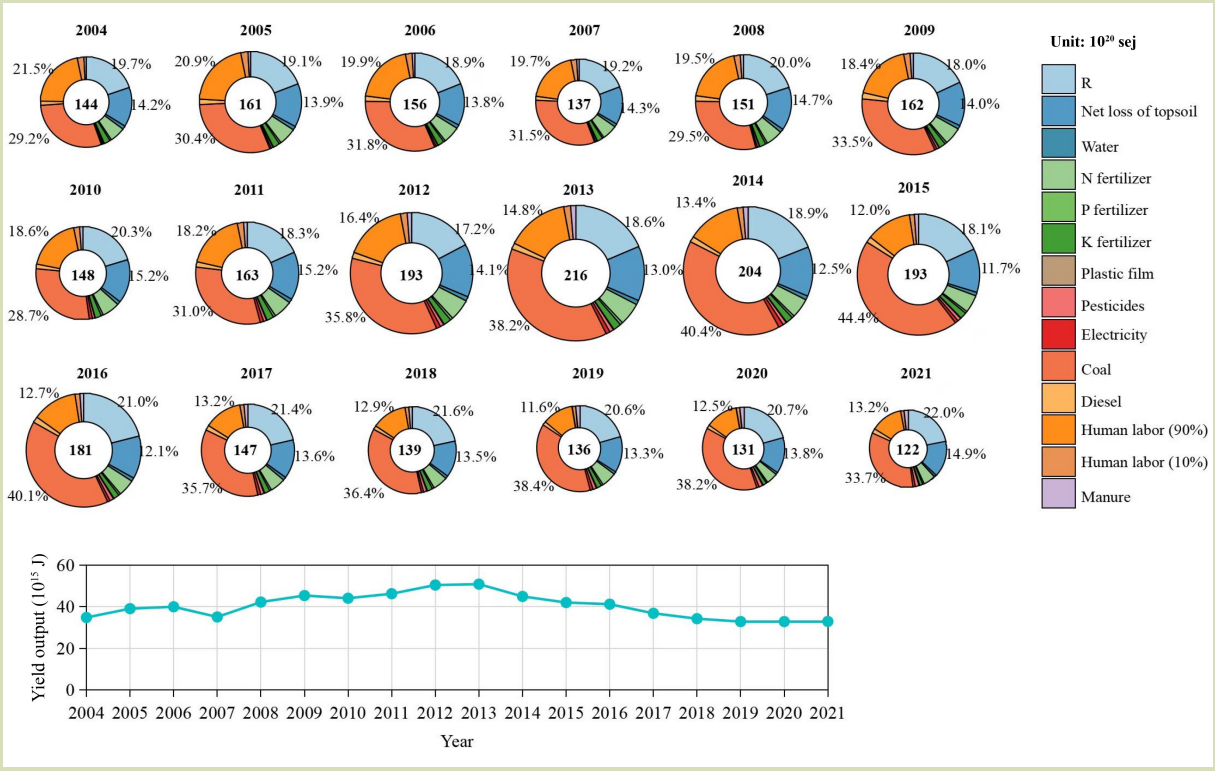


Fig. 3 Emergy input and energy output in tobacco production systems from 2004 to 2021.

$$\mathrm{ESI} = \mathrm{ESI}a \times \mathrm{ESI}b \times \mathrm{ESI}c \times \mathrm{ESI}d \times \mathrm{ESI}e \quad (2)$$

Where U refers to the tobacco emergy flows in tobacco production; A represents the total tobacco area; FN + FR denotes the total emergy flows from purchased resources (sej); GDP is the total tobacco revenue (yuan); FR + R represents the total emergy flows from renewable resources (sej); and FN + N denotes the total emergy flows from non-renewable resources (sej). The ratio $\frac{\mathrm{U}}{\mathrm{A}}$ serves as an intensity factor (ESIa), representing the development level of tobacco production system based on solar emergy (sej·m^{-2}). The ratio $\frac{\mathrm{A}}{\mathrm{FN+FR}}$ denotes the reciprocal of external pressure on the tobacco system from purchased resources (ESIb), measured in m^2·sej^{-1}. The ratio $\frac{\mathrm{GDP}}{\mathrm{A}}$ reflects the economic efficiency of the tobacco system (ESIc), where higher values indicate greater support for economic development (yuan·m^{-2}). The ratio $\frac{\mathrm{FR+R}}{\mathrm{GDP}}$ refers to the proportion of renewable resources to tobacco production revenue (ESId), indicating the system's dependence on renewable resources (sej·yuan^{-1}). Finally, the ratio $\frac{\mathrm{A}}{\mathrm{FN+N}}$ indicates the intensity of the non-renewable resource factor (ESIe), representing the reciprocal of non-renewable resource use per unit area within the tobacco production system (m^2·sej^{-1}).

$$\Delta\mathrm{ESI} = \mathrm{ESI}_t - \mathrm{ESI}_0 = \Delta\mathrm{ESI}a + \Delta\mathrm{ESI}b + \Delta\mathrm{ESI}c + \Delta\mathrm{ESI}d + \Delta\mathrm{ESI}e \quad (3)$$

$$\Delta\mathrm{ESI}a = \sum \frac{\mathrm{ESI}_t - \mathrm{ESI}_0}{\ln\mathrm{ESI}_t - \ln\mathrm{ESI}_0} \ln\left(\frac{\mathrm{ESI}a_t}{\mathrm{ESI}a_0}\right) \quad (4)$$

$$\Delta\mathrm{ESI}b = \sum \frac{\mathrm{ESI}_t - \mathrm{ESI}_0}{\ln\mathrm{ESI}_t - \ln\mathrm{ESI}_0} \ln\left(\frac{\mathrm{ESI}b_t}{\mathrm{ESI}b_0}\right) \quad (5)$$

$$\Delta\mathrm{ESI}c = \sum \frac{\mathrm{ESI}_t - \mathrm{ESI}_0}{\ln\mathrm{ESI}_t - \ln\mathrm{ESI}_0} \ln\left(\frac{\mathrm{ESI}c_t}{\mathrm{ESI}c_0}\right) \quad (6)$$

$$\Delta\mathrm{ESI}d = \sum \frac{\mathrm{ESI}_t - \mathrm{ESI}_0}{\ln\mathrm{ESI}_t - \ln\mathrm{ESI}_0} \ln\left(\frac{\mathrm{ESI}d_t}{\mathrm{ESI}d_0}\right) \quad (7)$$

$$\Delta\mathrm{ESI}e = \sum \frac{\mathrm{ESI}_t - \mathrm{ESI}_0}{\ln\mathrm{ESI}_t - \ln\mathrm{ESI}_0} \ln\left(\frac{\mathrm{ESI}e_t}{\mathrm{ESI}e_0}\right) \quad (8)$$

The change in ESI from the base period to the target period is denoted by ΔESI. The subscripts 0 and t denote the base period and the target period, respectively. The above calculations were performed using Microsoft Excel.

3 Results

3.1 Emergy input and energy output of the tobacco production system in China

The energy output, which represents crop yield based on energy value, initially increased before decreasing in China's tobacco production system (Fig. 3). In 2004, total energy output was 3.5×10^{16} J, rising to 5.1×10^{16} J in 2013 with an average annual growth rate of 5.1%. After 2013, energy output steadily declined, reaching 3.3×10^{16} J in 2021, slightly below the 2004 level. Similarly, total emergy input followed a parallel trend, increasing from 1.4×10^{22} sej in 2004 to 2.2×10^{22} sej in 2013, reflecting a 49.9% increase, and then decreasing to 1.2×10^{22} sej in 2021, again slightly below the 2004 level. Among total emergy inputs, purchased non-renewable resources made up the largest proportion (approximately 62.5%), followed by local renewable resources (19.6%), local non-renewable resources (14.9%), and purchased renewable resources (2.9%).

Further analysis of purchased non-renewable resources revealed an initial increase followed by a decline from 2004 to 2021 (Fig. 3). In 2004, purchased non-renewable resources amounted to 8.9×10^{21} sej and, despite fluctuations, increased by 56.6% between 2004 and 2013. After 2013, the emergy input from purchased non-renewable resources decreased annually, reaching 7.2×10^{21} sej in 2021. Coal, labor (90%), and nitrogen fertilizer were the primary contributors to purchased non-renewable resources, accounting for 55.7%, 25.8%, and 8.6%, respectively.

3.2 Evaluation of temporal changes in tobacco emergy indicators

All emergy indicators showed positive trends in China's tobacco production system (Fig. 4). The emergy self-support ratio (ESR) increased from 0.35 in 2004 to 0.38 in 2021. The emergy investment ratio (EIR) decreased from 1.85 in 2004 to 1.63 in 2021. The emergy renewability (R%) rose from 0.23 in 2004 to 0.25 in 2021. The emergy yield ratio (EYR) fluctuated, increasing from 1.54 in 2004 to 1.61 in 2021. The environmental loading ratio (ELR) decreased from 3.36 in 2004 to 3.00 in 2021. The emergy sustainability index (ESI) increased from 0.46 in 2004 to 0.54 in 2021, while the emergy transformity (TRA) decreased from 4.1×10^5 sej·J^{-1} in 2004 to 3.7×10^5 sej·J^{-1} in 2021.

3.3 Sensitivity analysis on ESI

Sensitivity analysis is a valuable tool for identifying the key internal factors influencing the ESI of tobacco production systems (Fig. 5). Using the average resource input levels from 2004 to 2021 as a baseline, this study selected coal, labor, and nitrogen fertilizer, which accounted for the largest share of purchased non-renewable resources, for sensitivity analysis. The results showed that a 20% increase or decrease in coal, labor, and nitrogen fertilizer led to changes in ESI ranging from −11.4% to 14.5%, −5.5% to 6.1%, and −1.9% to 2.0%, respectively. This analysis highlights that curing energy (coal) is the most sensitive factor affecting the sustainable development of the tobacco production system.

3.4 Evaluation of spatial changes in tobacco emergy indicators

The emergy indicators revealed significant spatial heterogeneity across provinces (Fig. 6), reflecting variations in resource endowment and production intensity. Heilongjiang, Fujian, and Jilin exhibited the highest EYR of 2.21, 1.76, and 1.74, likely due to more efficient utilization of local natural resources. In contrast, Chongqing, Jiangxi, and Hubei displayed the lowest EYR values, indicating greater reliance on purchased inputs. ELR was highest in Chongqing, Guizhou, and Jiangxi (6.94, 5.44, and 4.95), suggesting a stronger dependency on non-renewable and external resources, while Heilongjiang, Fujian, and Guangdong recorded the lowest ELR, indicating relatively lower environmental pressure. The ESI ranked highest in Heilongjiang, Fujian, and Guangdong (1.30, 0.93, and 0.81), while Chongqing, Guizhou, and Jiangxi had the lowest ESI, signaling weaker sustainability performance under input-intensive production systems. Major tobacco-producing provinces such as Yunnan, Guizhou, Hunan, Hubei, and Henan generally demonstrated relatively low ESI values. R% was highest in Heilongjiang and Fujian (0.36 and 0.34), signifying a larger contribution from renewable resources, while Chongqing and Guizhou had the lowest values. Regarding TRA, Henan and Gansu recorded the lowest values (3.0×10^5 and 3.1×10^5 sej·J^{-1}), possibly reflecting higher emergy conversion efficiency in large-scale production systems, whereas Fujian and Guangxi exhibited the highest TRA, likely linked to a greater reliance on renewable ecological inputs. Provinces with lower U values, such as Chongqing and Guizhou, showed higher dependence on non-renewable resources, while Shandong and Fujian showed stronger overall emergy utilization capacity.

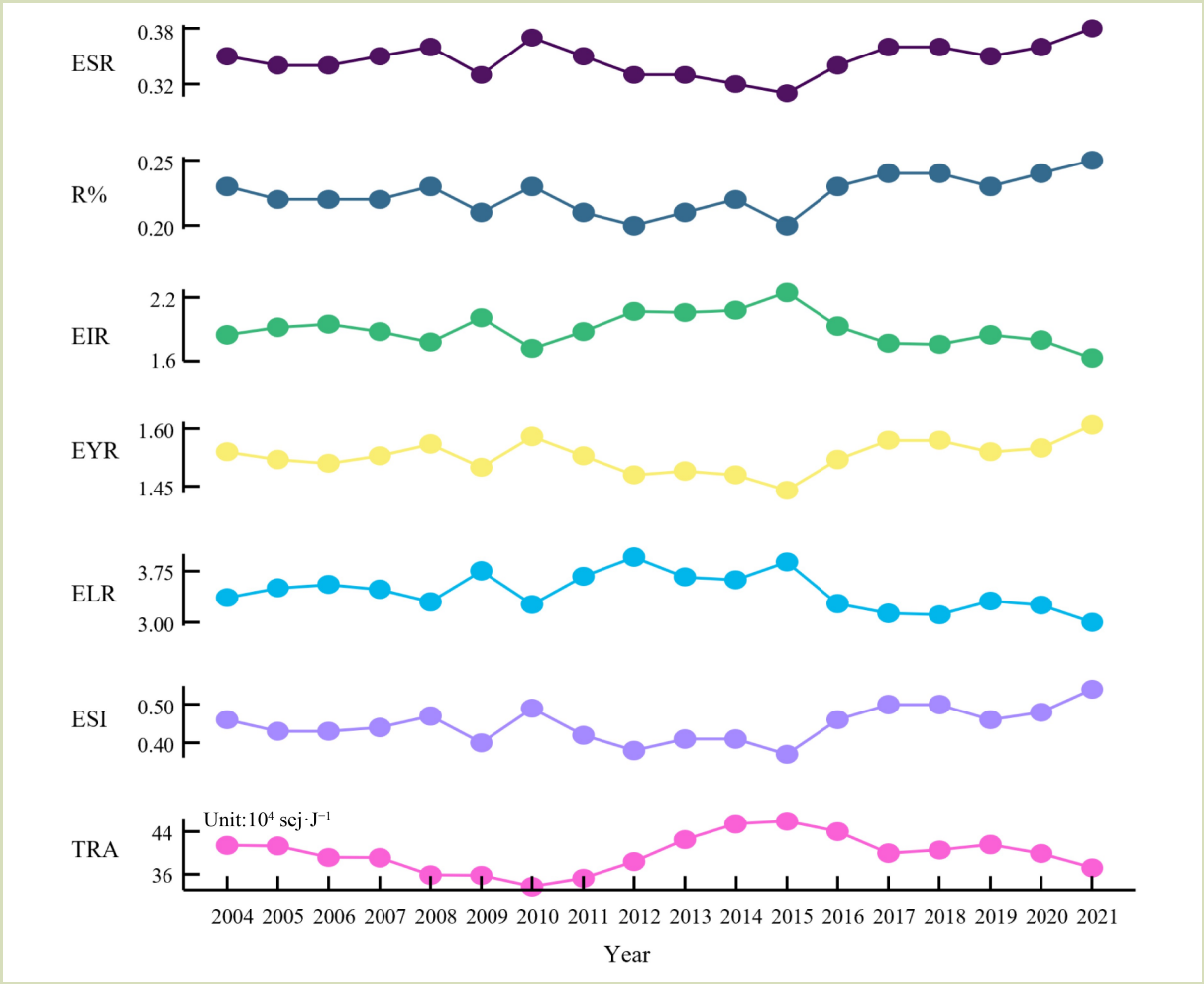


Fig. 4 Temporal changes in tobacco emergy indicators from 2004 to 2021.

3.5 Decomposition of tobacco production system's ESI

To enhance the sustainability of the tobacco system, key driving factors were analyzed. Based on the results of the LMDI decomposition (Fig. 7), the overall effect of the driving factors was positive, indicating a trend toward more sustainable development in the tobacco production system.

From 2004 to 2021, economic efficiency (ΔESI*c*) had the most significant positive impact on the system's ESI, contributing a 0.53 increase. The second largest contributor was the external pressure from purchased resources (ΔESI*b*), adding 0.05 to the ESI, followed by the intensity of non-renewable resource use (ΔESI*e*), which contributed 0.04. Conversely, the dependency on renewable resources (ΔESI*d*) was the most significant factor reducing ESI, with a decrease of 0.52. Additionally, the development level of the tobacco system (ΔESI*a*) contributed to a 0.02 decrease in ESI.

4 Discussion

4.1 Framework construction and cross-regional applicability

This study developed a comprehensive framework comprising four key components: production investigation, system analysis, sustainability evaluation, and driver exploration. The production investigation phase integrated data on statistics, meteorological conditions, soil attributes, and agricultural

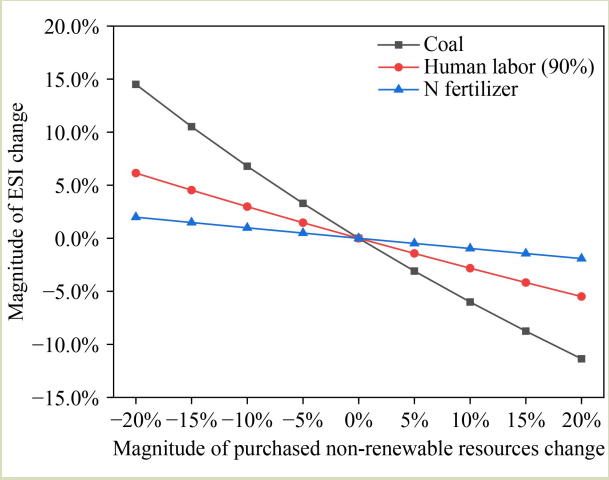


Fig. 5 Sensitivity analysis of ESI.

inputs to assess regional resource endowments and production patterns. In the system analysis phase, emergy analysis quantified resource inputs, with particular emphasis on the purchased non-renewable resources, reflecting the system's dependence on external resources. The sustainability evaluation phase utilized the ESI as the core indicator, providing both temporal and spatial insights into sustainability trends and regional disparities. The driver exploration phase employed the LMDI method to decompose the impacts of macroeconomic variables, such as production scale and economic efficiency, on sustainability, identifying both enabling and constraining factors. Based on the findings from the preceding phases, targeted strategies were developed to address resource use, sustainability challenges, and inhibiting factors.

This framework establishes a closed-loop process from data collection to actionable production recommendations, offering valuable insights for tobacco production practices and providing transferable knowledge for sustainable agriculture research. Although focused on tobacco, the framework's reliance on readily available data and universally applicable methods ensures its versatility and adaptability across different crops and regions, with the flexibility to address sustainability concerns specific to the subject of study.

4.2 Comparison of emergy indicators between tobacco and other crop production systems

ESR and EIR are key indicators for assessing the environmental load and economic development level of tobacco production systems. In this study, the average ESR and EIR of China's tobacco production system were 0.34 and 1.97, respectively. These values were compared with those of other global crops, as summarized in Table S2. The ESR of tobacco exceeded that of cucumber[23] and tea systems in China[40], but was lower than that of rice[41]. Conversely, the tobacco system's EIR was lower than those of vegetables[23,42], wheat[6], tea[40], corn[43], potatoes[44], and coffee[45], but higher than that of rice[46]. These comparisons suggest that, although the tobacco system relies on purchased inputs, it maintains a relatively balanced relationship between resource use and economic output compared with more input-intensive systems such as tea and vegetable production. Overall, tobacco production shows moderate dependence on external inputs relative to other crop systems.

The R% and ELR reflect the environmental pressure from non-renewable resources, with values of 0.22 and 3.40, respectively, for the tobacco system. The ELR is lower than that of coffee[45], tea[40], and several fruit[47,48] and vegetable systems[23,42], suggesting relatively lower environmental pressure. However, it is higher than that of the ecological bean system[49] and the average level of Chinese agriculture[50,51], indicating that environmental stress persists and warrants attention. While the ELR remains below the critical threshold of 10, proactive measures are necessary to mitigate potential future risks. These comparisons place tobacco production in an intermediate position regarding environmental loading.

The ESI reflects the overall sustainability of the system, with tobacco recording a value of 0.45. This is higher than that of more intensive systems, owing to a relatively favorable EYR and moderate environmental loading. However, it remains below 1 and lower than the average for Chinese agriculture[50,51], suggesting that while the tobacco system is more sustainable than highly resource-intensive crops, it still lacks sufficient resilience and requires improvements in environmental performance. In conclusion, the cross-crop comparison positions tobacco production between highly intensive cash crops and more ecologically oriented systems.

4.3 Spatiotemporal differences in tobacco emergy indicators

Temporally, the total emergy input and energy output of China's tobacco production reached their peak in 2013, when

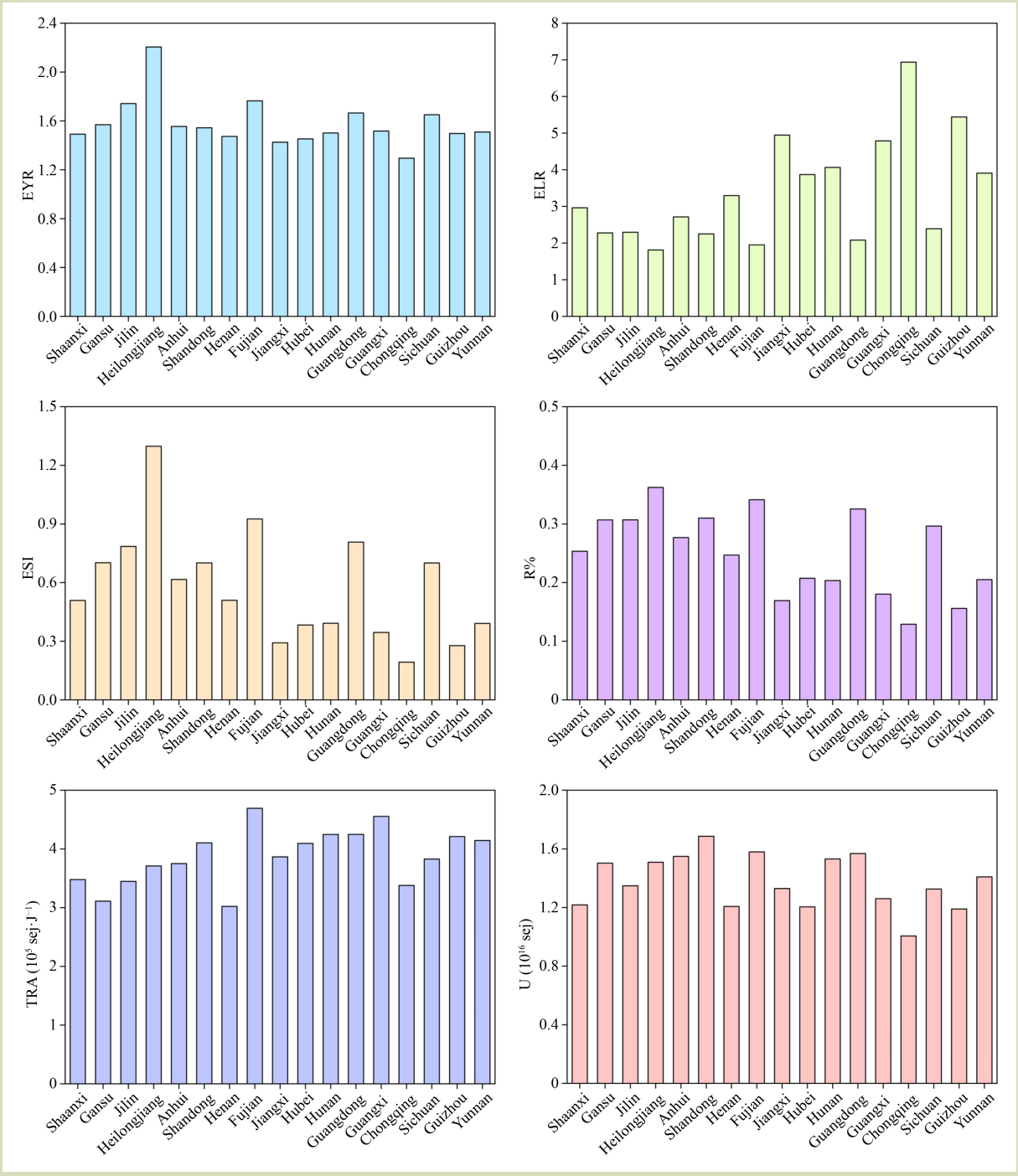


Fig. 6 Spatial variations in tobacco emergy indicators.

the planting area was 1508 thousand hectares. A structural shift occurred in 2015, marked by improvements in per-unit emergy input and related indicators. This change coincided with the national initiatives under the Thirteenth Five-Year Plan, which emphasized carbon emission control, optimized fossil energy usage, and the implementation of the "dual reduction" strategy

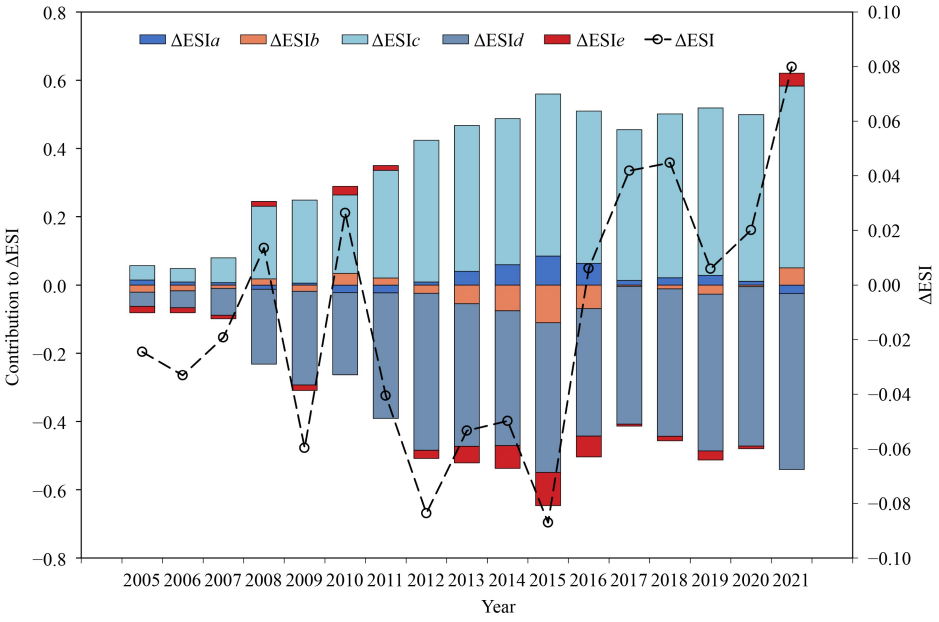


Fig. 7 Contribution of driving factors to the ESI of tobacco production from 2004 to 2021.

to lower pesticide and fertilizer consumption. These measures were part of broader efforts aimed at advancing green agricultural development and supply-side reforms, which focused on enhancing input efficiency and reducing environmental pressure. The observed decline in input intensity and the ELR after 2015 reflects, to some extent, the positive impact of these policy shifts in promoting more resource-efficient tobacco production.

Spatially, significant heterogeneity was observed across regions, reflecting differences in natural resource endowments. Heilongjiang and Jilin, endowed with abundant wind energy and fertile black soils[32], recorded higher ESI values, likely associated with their efficient utilization of local resources. This pattern may also be related to regional characteristics such as large-scale land management and higher levels of mechanization, which are generally linked to improved resource-use efficiency and reduced reliance on purchased inputs. In contrast, Chongqing, Guizhou, and Jiangxi showed higher ELR and lower ESI, indicating greater dependence on purchased inputs. The mountainous terrain and fragmented landholdings in these regions increase production costs and external input reliance, thereby raising environmental loading. Hunan and Guangxi displayed relatively high EYR, but this was accompanied by higher ELR, suggesting a structural trade-off between emergy return and environmental pressure. Fujian, however, combined high EYR with low ELR, indicating effective use of internal resources without significantly increasing environmental stress. Its relatively high TRA suggests a larger share of renewable inputs, in line with its favorable ecological endowment and stronger environmental focus. While this structure may limit short-term expansion, it fosters long-term ecological resilience by mitigating resource depletion and pollution risks[7,8]. For regions with low TRA and ESI, Fujian's strategy serves as a valuable reference. Henan, with the lowest TRA, likely reflects its more intensive production model and greater dependence on purchased non-renewable inputs.

Overall, the spatiotemporal variation in emergy indicators highlights the trade-offs between economic development and ecological conservation. Emergy performance is closely linked to policy orientation, resource endowment, and regional development strategies, suggesting that sustainability improvements should be tailored to local conditions while aligning with broader macro-level goals.

4.4 Driving factors and policy implications for sustainable tobacco production

The decomposition analysis revealed that the ESI is influenced by multiple factors, including external pressure from purchased resources, dependency on renewable resources, intensity of non-renewable resource use, economic efficiency, and the system development level.

Between 2004 and 2021, the reliance on purchased resources (ΔESI*b*) decreased by 18.9%, while the production area shrank by 14.2%, leading to a 5.8% increase in the ESI. This indicates that improved management of purchased inputs—such as optimized fertilization[52–54], pest and disease control[55], and enhanced curing energy efficiency[56]—can significantly reduce environmental burdens. Similar studies from the United States[57,58], Brazil[59], and Africa[60] emphasize the need to improve curing energy efficiency and explore alternative clean energy sources, particularly biomass-based energy for curing, to replace fossil fuels and reduce non-renewable emergy inputs.

The intensity of non-renewable resource use (ΔESI*e*) contributed 0.04 to the ESI, highlighting the importance of reducing reliance on non-renewable inputs to enhance sustainability. Practices like mulching[61] and optimized irrigation technologies, including drip[62], deficit[63], and negative pressure irrigation[64,65], are recommended to minimize non-renewable resource dependence. Conversely, the dependency on renewable resources (ΔESI*d*) had the most significant negative impact, contributing –0.52. Although renewable resource use can help offset non-renewable consumption, its share remains limited. Encouraging tobacco production in regions with abundant natural resources and promoting the use of organic fertilizers[66] and biomass energy[67,68] could mitigate environmental stress and improve sustainability.

Economic efficiency (ΔESI*c*) emerged as the most important driver, aligning with previous findings[38,69]. During the study period, economic efficiency increased from 19,000 yuan·ha^{-1} to 64,000 yuan·ha^{-1}, reflecting its significant contribution to sustainable development. Policies such as subsidies[70,71] can further enhance efficiency, increase farmers' incomes, and promote sustainability. Specifically, subsidies for biomass curing facilities and organic input substitution can reduce non-renewable emergy inputs.

The system development level (ΔESI*a*) had a relatively minor impact. From 2004 to 2021, the tobacco production area declined by 14.2%, and total emergy input decreased by 15.1%, resulting in a 1.0% reduction in ΔESI*a*. This change was mainly driven by government policies, including area control since 2013, the "dual reduction" strategy in 2015, and improvements in mechanization and labor efficiency. While these measures reduced production scale, their effect on sustainability was limited. Relying solely on downsizing without incorporating sustainability principles could even lower resource-use efficiency (Fig. S1). Thus, integrating sustainable technologies, such as innovative production practices and biomass-based curing energy, is critical.

However, high costs often impede the adoption of such technologies. Tobacco companies could mitigate this barrier by providing targeted subsidies for fertilizers and clean energy. Furthermore, the "Science and Technology Backyard" model[72,73], which fosters collaboration between universities, local governments, enterprises, and farmer organizations, offers an effective platform for technology transfer. Strengthening technical extension services and socialized agricultural services would also facilitate the sustainable transition of tobacco farmers.

4.5 Limitation and uncertainty

This study primarily focused on emergy calculations influenced by varying resource inputs and corresponding UEVs. Local resources were sourced from peer-reviewed references and datasets, while purchased resources were obtained from official and verified statistical data. Potential errors and deviations in statistical compilation were considered and controlled within an acceptable range, ensuring that the resource input data met the required quality standards. Due to the absence of international standards for selecting UEVs, the study relied on the work of recognized experts in the field, such as Odum[21] and Brown and Ulgiati[22], to ensure high reliability and minimize uncertainty.

While the study addressed the sustainable development and energy utilization efficiency of tobacco production systems from an energy flow perspective, it did not consider other critical factors, such as water consumption, greenhouse gas emissions, reactive nitrogen loss, and land degradation, all of which can significantly impact sustainability. Therefore, future research should integrate additional methodologies, such as

water footprint assessments and LCA, into the emergy framework to provide a more comprehensive evaluation of sustainability in tobacco production.

5 Conclusions

This study developed an integrated framework that combines production investigation, system analysis, sustainability evaluation, and driver decomposition, applying it to China's tobacco production system. The findings reveal that curing energy consumption is the largest emergy input and the primary constraint on system sustainability. From 2004 to 2021, the tobacco production system showed gradual improvements in sustainability performance, marked by increased renewability and reduced environmental loading, though notable spatial heterogeneity persisted across provinces. Regions with higher renewable resource contributions and lower environmental pressures demonstrated relatively stronger sustainability performance. The LMDI decomposition further highlighted that economic efficiency improvements were the main driver of sustainability enhancement, while continued reliance on non-renewable inputs partially offset these gains. Overall, sustainability performance is primarily influenced by curing energy consumption and economic efficiency. Future strategies should prioritize reducing coal dependence in tobacco curing processes through improvements in curing energy efficiency and the promotion of cleaner alternative energy sources. In addition, more sustainable fertilizer-management practices, including precise fertilization and partial organic substitution, should be encouraged to further reduce environmental pressure and enhance resource-use efficiency. Technological innovation and improvements in economic efficiency may also contribute to long-term sustainability enhancement. The proposed framework offers a transferable analytical tool for evaluating and improving sustainability in other agricultural production systems.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2027733 contains supplementary materials (Tables S1–S2; Fig. S1).

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Compliance with ethics guidelines

Yiming Li, Lan Yao, Jing Long, Chenchen Chen, Hang Yang, Zhengxiong Zhao, Tianshu Chu, and Chaochun Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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