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Evaluation of the impact of the Science and Technology Backyard initiative on the rice production system in the Erhai Lake Basin based on emergy analysis

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KEYWORDS

Emergy analysis, Erhai Lake Basin, rice production, sustainability

HIGHLIGHTS

- The emergy sustainability index (ESI) of rice production in Erhai Lake Basin shows notable regional variation.
- Yield, N, P and manure fertilizer are key influencing factors of ESI.
- Large-scale application of GS technology packages can improve ESI.
- Effective strategy to improve sustainability performance is closing the yield and efficiency gap.
- Multi-stakeholder engagement is essential to promote smallholder adoption of technology.

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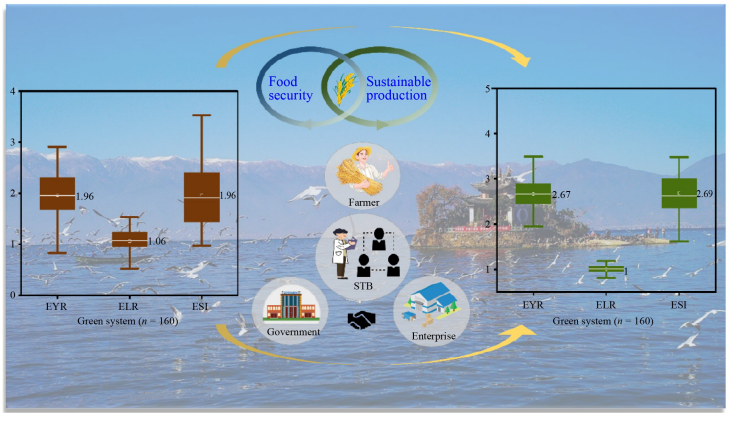
GRAPHICAL ABSTRACT



ABSTRACT

The aim of this study was to assess the current status and key constraints of rice production sustainability in the Erhai Lake Basin and to propose an effective technology package for improving sustainability performance. Emergy analysis was used to evaluate the sustainability of rice farming based on data from 171 farmer surveys and comparative experiments were conducted between the current system (CS) and a green system (GS). Unlike CS, which represents the traditional rice cultivation method in the basin, GS is a comprehensive green ecological planting model developed by the Science and Technology Backyard (STB) initiative through long-term positioning experiments. The technology package combines an optimized fertilizer application technique centered on green intelligent fertilizers with reduced mineral fertilizer and pesticide inputs, improved nutrient and water management, and better-performing rice cultivars. STB also serves as a

platform linking government agencies, scientists, smallholders and fertilizer companies. Scientists are stationed in villages to carry out on-farm trials, provide technical training and offer continuous advisory services, thereby tailoring the GS to local conditions and promoting its adoption. The results revealed clear spatial heterogeneity and general low sustainability of current rice production under CS at the town scale. Yield, N and P fertilizer inputs, and manure fertilizer input were identified as the primary factors influencing farm-level emergy-based sustainability indicators and overreliance on non-renewable inputs was a key reason for low sustainability on many farms. Compared with CS, the emergy input of GS is 34.9% lower, while its emergy output is 10.2% higher, resulting in a 33.3% higher emergy sustainability index. These findings demonstrate that the GS technology package, supported by STB-mediated social and technical services, can substantially enhance the sustainability of rice production in the Erhai Lake Basin and provide a replicable model for similar rice-producing regions.

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1 Introduction

Rice is a staple food for more than half of the global population, contributing 20% of the global dietary energy supply[1]. In 2022, the global rice harvest covered 165 million hectares, with a total production of 776 million tons. Ensuring high yields while reducing environmental impacts has therefore become a central challenge for China, especially as past yield increase have relied heavily on intensive fertilizer inputs[2–5]. However, excessive mineral fertilizer use has led to soil acidification, greenhouse gas emissions, and eutrophication, posing increasing environmental risks[6–8]. As a result, improving fertilizer and resource management is essential for achieving sustainable rice production.

The Erhai Lake Basin, the seventh-largest freshwater lake in China and the second-largest plateau lake in Yunnan Province, is often called the Mother Lake due to its vital role in supporting regional agriculture and ecological security[9,10]. However, rapid economic development, population growth, and intensified agricultural activities have increasingly threatened the basin, leading to eutrophication and ecological degradation[11]. Numerous studies have demonstrated that nitrogen and phosphorus losses from cropland are major contributors to non-point source pollution in Erhai Lake[12,13]. As a key rice-producing area in Yunnan Province, the Erhai Lake Basin is under significant environmental scrutiny. In response, the local government has enacted strict regulations prohibiting mineral N and P fertilizers and mandating organic fertilizer application, which has helped improve water quality in recent years[14]. Despite these efforts, rice production in the Erhai Lake Basin is predominantly managed by smallholders working on plots ranging from 0.1 to 0.3 ha. These farmers often heavily rely on freely available environmental resources[15]. Such practices have resulted in excessive nutrient inputs, low fertilizer use efficiency, and impaired environmental performance. Previous research has noted that inappropriate fertilizer application and manure management have become key drivers of declining agricultural sustainability and eutrophication in the basin[16–18]. Although recent studies indicate that optimizing nitrogen management can effectively reduce nutrient losses and improve N use efficiency in the region[19], existing research has largely focused on isolated agronomic components. There remains a lack of integrated assessment examining how farmer input structures, resource-use patterns, and emerging technology packages jointly influence sustainability outcomes under the unique ecological of the basin and policy constraints. Addressing these gaps requires not only technological innovation but also effective mechanisms to translate scientific knowledge into practical, farmer-adoptable solutions. Such efforts are essential for improving the sustainability of rice production in the Erhai Lake Basin.

Minimizing energy input while enhancing energy use efficiency

is important for ensuring the sustainability of rice production[20]. Reducing resource and energy inputs without compromising rice productivity can yield optimal economic and environmental benefits. Previous studies have shown that reducing fertilizer and water usage, alongside simplifying agricultural management practices, can effectively replace traditional farming methods[21,22]. However, under the unique ecological and policy constraints of the Erhai Lake Basin, particularly the prohibition of mineral N and P fertilizers, the specific pathways for reducing energy inputs without compromising yield remain insufficiently understood. A systematic assessment of energy inputs and efficiency in this region is therefore needed to identify targeted, locally appropriate management strategies that support both food production and ecological protection. Emergy analysis provides a comprehensive framework for such evaluation. By converting diverse resource flows, including sunlight, rainfall, wind, geothermal energy, and both direct and indirect human inputs, into a unified solar emergy metric[23–25], it captures the full spectrum of energy and material contributions to agricultural systems. This approach can measure the value of all energy and material flows by converting different forms of resources into solar energy. It not only considers direct energy consumption but also includes indirect energy consumption, providing a clearer reflection of the sustainability of a production system[26]. Despite its advantages, emergy analysis has rarely been applied to investigate rice production sustainability in the Erhai Lake Basin and comparisons of emergy performance across different production patterns remain limited. Addressing these gaps can provide critical evidence for designing sustainable and energy-efficient rice production strategies in the region.

The main objectives of this study are as follows: (1) to evaluate the sustainability of rice production in the Erhai Lake Basin; (2) to identify the key factors influence the sustainability of rice production and develop an ecological pattern that integrates these factors to promote environmentally sustainable practices; (3) to compare the sustainability indicators across different rice production patterns, and (4) to propose practical strategies for promoting sustainable rice agriculture in the Erhai Lake Basin. The practical significance of this study lies in providing a feasible plan for the sustainable development of rice cultivation in the Erhai Lake Basin, with the ultimate goal of enhancing farmer incomes and advancing green, high-quality agricultural development.

2 Materials and methods

2.1 Study area

The Erhai Lake Basin is situated in Yunnan Province, southwestern China, and covers an area of 2565 km^2[10]. This basin encompasses 16 townships and contains important agricultural regions, with rice being the predominant crop. The Erhai Lake Basin is situated in a low-latitude plateau characterized by a warm and humid climate, following a subtropical plateau monsoon climate pattern. It has distinct dry and wet seasons, with substantial temperature fluctuations between day and night, sufficient sunshine and relatively minor temperature variations throughout the year. The average annual temperature is 15.7 °C. The basin receives an average annual rainfall of 1000–1200 mm, with more than 85% of the total precipitation occurring between May and October.

2.2 Data sources

2.2.1 Survey questionnaire

The data for this study were collected through a household survey conducted by the research team in July 2022 across 16 townships in the Erhai Lake Basin. To ensure representativeness, the survey adopted a stratified sampling approach based on the rice-planting area of each township, ensuring proportional coverage of regions with different production scales and farming characteristics. Within each stratum, simple random sampling was used to select villages, and farmers were then randomly chosen within each selected village. This multistage sampling design minimized the risk of selection bias and ensured that the sample reflected the diversity of smallholder rice production across the basin. The survey was conducted through one-to-one interviews using a structured questionnaire in Chinese. This questionnaire gathered data on various aspects of rice farming, including fertilizer application rates, pesticide use, transplanting times, yield, labor input and machinery input. To ensure consistency in the interview process and coverage, professional training was provided to the surveyors, with assistance from local college students. Before the field survey, an initial test of the questionnaire was conducted via an online survey in June 2022. This test helped establish a reasonable range of responses and led to subsequent revisions of the questionnaire. The final face-to-face survey was conducted in July 2022 in the Erhai Lake

Basin. Of 180 questionnaires collected, 171 were deemed valid after excluding incomplete or invalid responses, resulting in an effective rate of 95%. The final sample covers farmers with varying farm sizes, management practices and geographic locations, providing a representative snapshot of smallholder rice production in the basin. Descriptive statistics of the surveyed smallholders are shown in Table S1.

2.2.2 Field experiment

The remaining data comes from a follow-up study conducted among farmers in YouSuo and ShangGuan Towns. This follow-up study includes data from 2 years, with 80 conventional pattern (CS) farmers and 80 green pattern (GS) farmers, surveyed in 2023 and 2024, respectively. The CS represents the traditional rice cultivating method used in the Erhai Lake Basin, while the GS is a new cultivation approach that has been promoted since 2023. Unlike CS, the GS uses a comprehensive green ecological rice-planting model that integrates multiple advanced technologies. These technologies were developed through positioning experiments conducted by STB at experimental sites within the Erhai Lake Basin. Among these technologies, the most significant advancement is the optimized fertilizer application technique, which centers around the use of green intelligent fertilizers.

Green intelligent fertilizer used in this study is a high-quality, data-driven fertilizer product developed collaboratively by the research team and Yunnan Yuntianhua Co., Ltd. It is produced through green manufacturing processes that allow precise nutrient formulation based on big-data-assisted optimization. The fertilizer is designed to enhance crop-soil-environment compatibility by regulating rhizosphere interactions, improving nutrient uptake efficiency and minimizing environmental losses[27,28]. A key feature of this fertilizer is the use of stratified granulation and chelation technologies that separate calcium- and magnesium-containing components from the phosphorus microdomains. This prevents the formation of insoluble precipitates that commonly reduce nutrient availability during standard compound fertilizer production. By maintaining nutrient separation within microstructures, the fertilizer exhibits a more controlled and sustained nutrient-release profile, improving efficiency while reducing losses. The final product contains a balanced nutrient formulation (N:P:K:Ca:Mg:Si=15:4.8:11.62:4:1:2) and was sealed and stored before field application.

2.3 Emergy analysis

Emergy, as defined by Odum[29], represents the total amount of available energy that is either directly or indirectly required to produce a single product or service. Emergy analysis is a method that converts diverse emergy inputs into a standardized unit called solar emjoules (sej). This approach is detailed in the works of Odum[30], Ulgiati et al.[31], and Brown et al.[23]. The unit emergy value (UEV) is fundamental in this process, as it converts all input and output emergy flows within a system into solar emergy units. UEV calculations are based on the emergy flows that drive the geobiosphere, including solar energy, tidal energy and geothermal heat, with the baseline continuously updated. This research utilizes a baseline of 1.2×10^{25} sej·yr^{-1} for the UEV, as established by Brown et al.[23]. Emergy analysis is particularly valuable as it allows for the comprehensive assessment of economic, social, and environmental factors, enabling comparisons across various production systems[32]. Consequently, this study used emergy analysis to investigate the sustainability of the rice production system in the Erhai Lake Basin.

2.3.1 System diagram

The initial phase of emergy analysis involves constructing a system diagram to delineate the principal attributes of the investigated system (Fig. 1). An emergy systems language (ESL) diagram, illustrating the symbols used in Odum's ESL[30], is used for this purpose. ESL diagrams serve to delineate the spatial and temporal limits of each agricultural production system, along with highlighting the primary energy resources, flows and their interrelationships. In this study, inputs in rice production were categorized into three types: (1) local renewable environmental inputs encompass sunlight, rain and wind; (2) local non-renewable environmental inputs consist organic matter loss; and (3) purchased inputs encompass seeds, manure, mineral fertilizers, pesticides, labor, irrigation water and fuel.

2.3.2 Emergy-based indicators

The system diagram facilitates identification of primary emergy and resource flow inputs to the entire process. Each flow was multiplied by the UEV to calculate the emergy value of each flow [33]. Relevant parameters including emergy coefficients are provided in Table S2. In this study, all emergy data were converted into values per ha per rice-growing season. Several indices and ratios have been defined based on the theory of

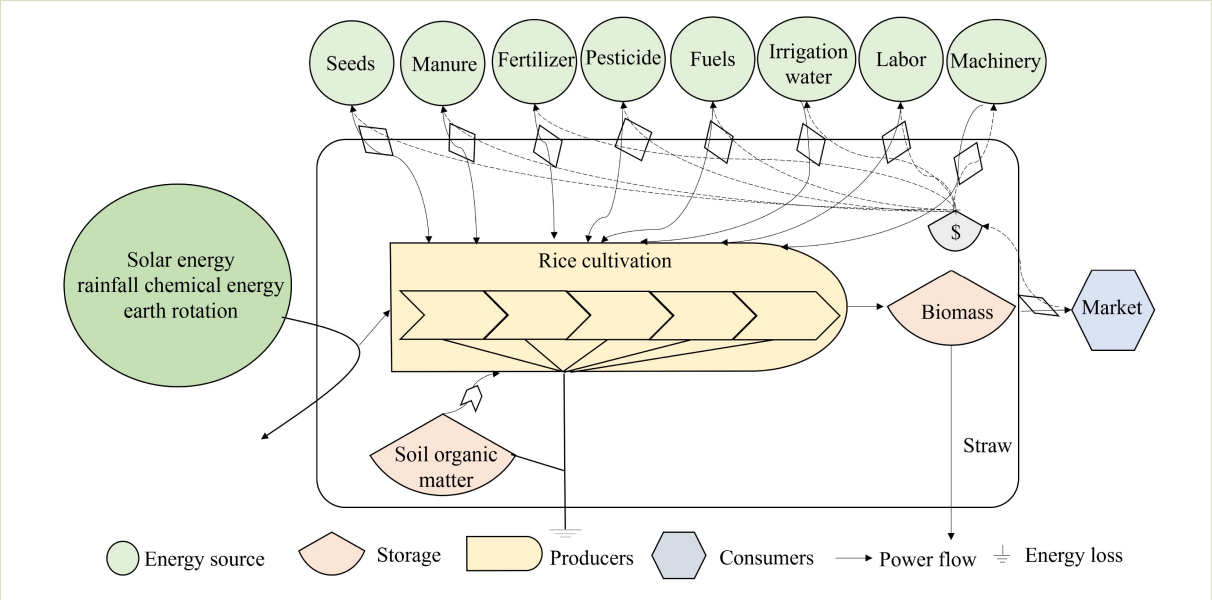

Fig. 1 Emergy system diagrams for the rice production system.

emergy as the basic unit to evaluate the investment structure and the sustainability of agricultural system. The present study used emergy-based indicators to evaluate the efficiency, environmental pressure and sustainability of rice production system in the Erhai Lake Basin. The formulation, implications and meaning of each index are listed in Table 1.

2.4 The drivers of ESI quantified by random forest model

In this study, we use the "random forest" package in R 4.2.1 software (R Core Team, Vienna, Austria) to evaluate the relative contribution rate of ESI and determine the main drivers of ESI. Random forest modeling is a machine learning algorithm, which integrates several relatively simple evaluators or decision trees. A higher value in the increase in mean squared error in random forest indicates higher relative importance.

3 Results

3.1 Emergy input-output status of rice production status in the Erhai Lake Basin

In the Erhai Lake Basin, the average emergy input for the rice production system in 2022 was around 7.24×10^{15} sej·ha^{-1}, while the corresponding emergy output was 1.08×10^{16} sej·ha^{-1} (Fig. 2(a)). Further analysis revealed that the emergy inputs were distributed as follows: renewable environmental inputs accounted for 5.1%, non-renewable environmental inputs for 3.4%, renewable purchased inputs for 53.4%, and non-renewable purchased inputs for 38.1%. As a result of the significant disparities in the latter two measures and rice yield across the different townships, there was considerable spatial variability in the total emergy input-output within the Erhai Lake Basin (Fig. 2(b)). Despite these notable variations in total emergy input among townships, the overall structure of emergy inputs for rice production across the basin was generally consistent. This indicates that while the quantity of inputs may vary, the proportional contribution of different types of emergy inputs remains relatively uniform across the region.

In summary, the average emergy evaluation ratio (EER) for rice production in the Erhai Lake Basin exceeded 1, indicating that the emergy output of the rice production system was greater than the emergy input, resulting in a net emergy gain (Fig. 2(a)). However, the EER value showed considerable spatial variability across different towns within the basin. Specifically, towns like Yousuo and Shuanglang had higher EER values, indicating more efficient emergy use and greater net gains, while Niujie and Shangguan had lower EER values,

Table 1 Emergy-based indicators used in the study

Item	Formulation	Meaning	Specification	Source
R		Renewable environmental inputs	Renewable flows from free local resources	[34]
N		Non-renewable environmental inputs	Local potentially renewable flows from free local resources that are being used in a non-renewable manner	[34]
FR		Renewable purchased inputs	Renewable flows from purchased resources	[34]
FN		Non-renewable purchased inputs	Nonrenewable flows from purchased resources	[34]
U	R+N+FR+FN	Total emergy input	Total emergy resources required to support the production system	[34]
Y		Total emergy output	Total emergy of system products	[34]
EER	Y/U	Emergy exchange ratio	The emergy exchange ratio represents a measure of the emergy content per dollar of final products	[24]
EYR	Y/FR+FN	Emergy yield ratio	EYR equals the yield output divided by the total purchased resources input. It measures the efficiency of purchased resource investment and the capacity of purchased resources to access free natural resources. The higher the ratio, the greater the yield acquired per unit of purchased input	[34]
ELR	N+ FN/FR+R	Environmental loading ratio	ELR is defined as the ratio of total nonrenewable input to the renewable input, reflecting the structure of investments and the environmental pressure on a regional eco-economic system. The higher the value, the larger the resource pressure in the region	[34]
ESI	EYR/ELR	Environmental sustainability index	ESI is defined as the ratio of EYR to ELR, measuring the coordination and sustainability of a cropping system. The higher the ESI, the higher the sustainability	[34]

Note: R, local renewable environmental inputs; N, local nonrenewable environmental inputs; FR, local renewable purchased inputs; FN, local non-renewable purchased inputs; U, total emergy input; Y, total emergy output; EER, emergy exchange ratio; EYR, emergy yield ratio; ELR, environmental loading ratio; ESI, environmental sustainability index.

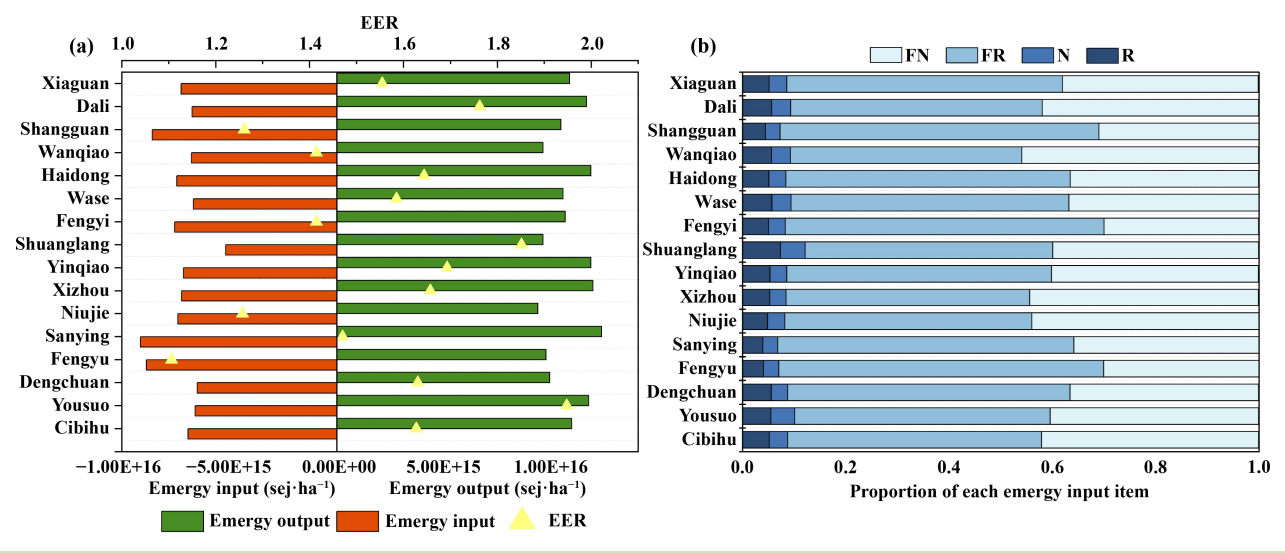

Fig. 2 Emergy distribution of rice production systems in townships across the Erhai Lake Basin (a) and proportional contributions of different emergy input categories (b). EER, emergy exchange ratio; FN, local non-renewable purchased inputs; FR, local renewable purchased inputs; N, local nonrenewable environmental inputs; R, local renewable environmental inputs.

reflecting less efficient emergy use and smaller net gains in those areas.

3.2 Emergy sustainability index of rice production status in the Erhai Lake Basin

The average emergy yield ratio (EYR) across the Erhai Lake Basin was 1.71. Yousuo and Shuanglang Towns have higher EYR values, indicating that these areas produce more rice with fewer non-renewable resources (Fig. 3). In contrast, Fengyu and Niujie Towns had lower EYR values, reflecting less efficient use of resources. Conversely, the average environmental loading ratio (ELR) for the basin was 0.81. Yousuo and Wanqiao Towns had higher ELR values, indicating greater pressure on environmental resources due to higher reliance on non-renewable inputs. Fengyu and Fengyi Towns, however, had lower ELR values, indicating a more sustainable resource use.

In terms of the emergy sustainability index (ESI), the average values for the top 25% and bottom 25% of townships were 2.59 and 2.13, respectively. The higher ESI in the top 25% is attributed to high yields and a lower proportion of non-renewable purchased inputs, while the lower ESI in the bottom 25% was associated with greater reliance on non-renewable resources and lower productivity (Fig. 3). The distribution of ESI values had significant spatial variability, with Fengyi and Shangguan Towns having higher values, indicating more sustainable practices, while Niujie and Wanqiao Towns had lower values, reflecting less sustainable practices. Detailed town-level sustainability data for the rice production system in the Erhai Lake Basin is available in the supplementary information.

3.3 Driving factors of ESI value in rice production

The relative contribution of various inputs to the ESI was analyzed based on random forest model to identify the factors driving the significant disparities in ESI values. The results showed that rice yield, N and P fertilizer inputs, and manure input were the main factors contributing to the ESI, with contribution rates of 27.5%, 23.3%, 23.2% and 16.8%, respectively (Fig. 4). Also, the contribution rates of fuels input and human labor input were also significant, accounting for 14.5% and 11.4%, respectively. Other input factors had minimal impact on the ESI. Therefore, optimizing fertilizer application and increasing yield, such as by improving fertilizer use efficiency and minimizing yield gaps, are key strategies for enhancing the sustainability of the rice production system in the Erhai Lake Basin.

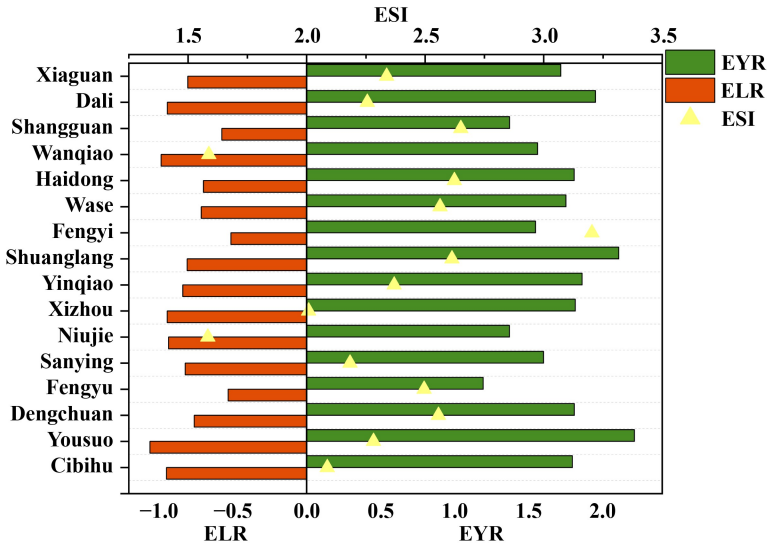

Fig. 3 Spatial distribution of the emergy sustainability index of rice production systems at the township level in the Erhai Lake Basin. EYR, emergy yield ratio; ELR, environmental loading ratio; and ESI, emergy sustainability index.

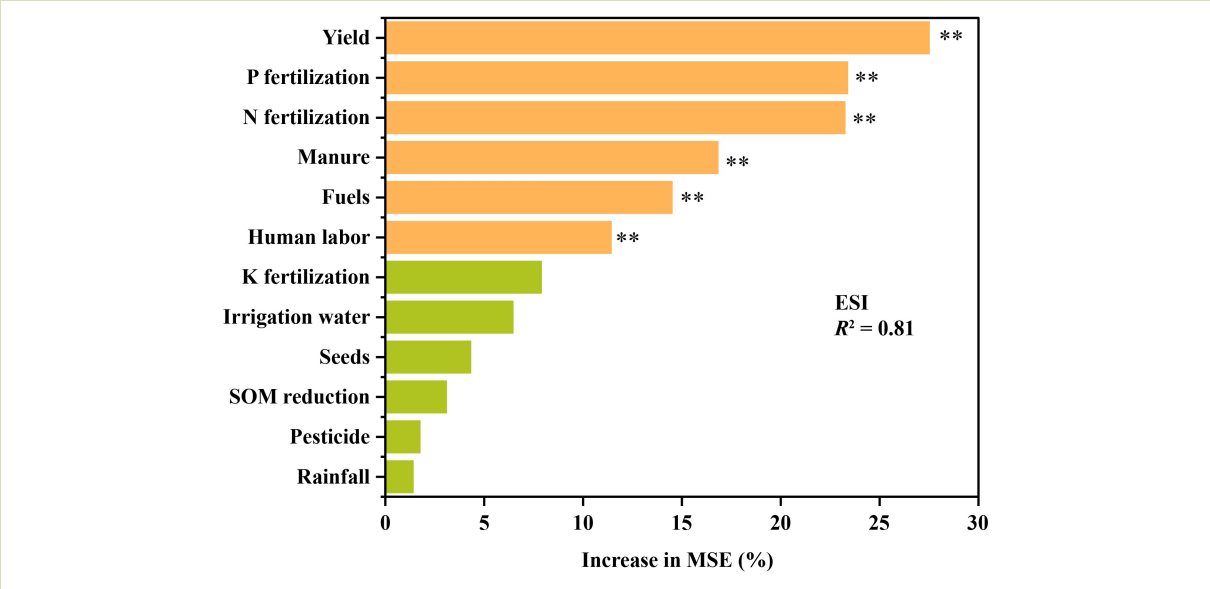

Fig. 4 Relative contribution of inputs to the emergy sustainability index (ESI) of rice production. **Statistical significance at $P < 0.01$. MSE, mean squared error.

3.4 Emergy analysis between the conventional and green patterns

The emergy input and output structures of the CS and GS rice production systems are given in Fig. 5. Obviously, the emergy from environmental inputs was similar between the two production patterns. However, the main difference in emergy input between CS and GS lies in the purchased inputs. In GS, the emergy input for N, P and K fertilizer decreased by 29%,

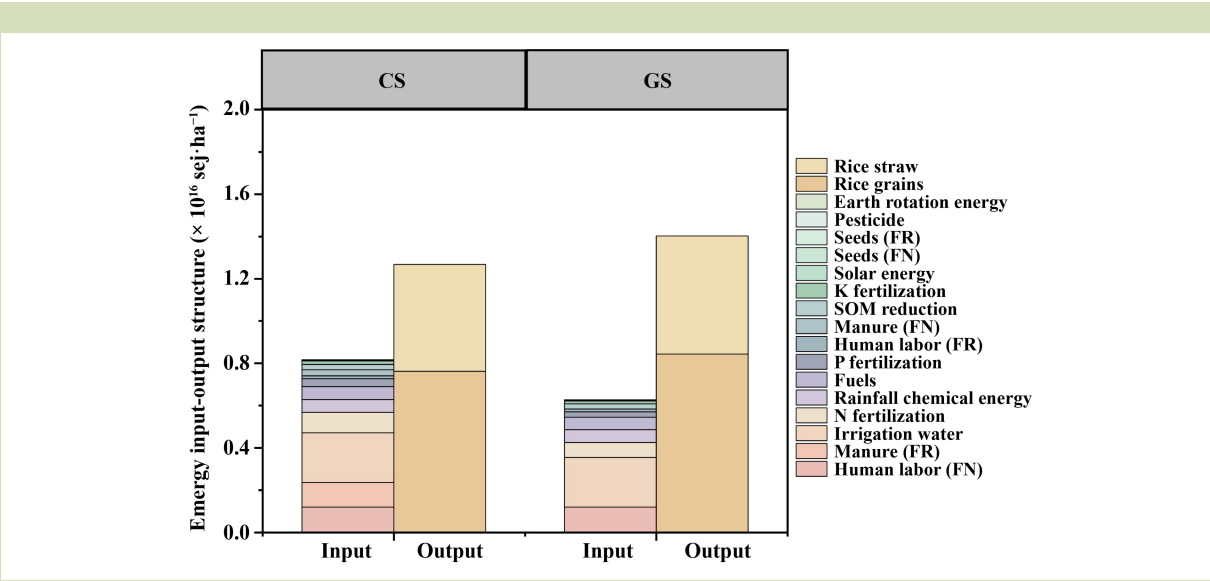

Fig. 5 Emergy input-output structure of current system and green system. CS, current system; GS, green system; FR, local renewable purchased inputs; FN, local non-renewable purchased inputs.

32%, and 20%, respectively, compared to CS. Also, CS had an extra emergy input of 1.71 × 10^{15} sej·ha^{-1} from manure fertilizer. In terms of emergy output, the GS enhanced the emergy output of rice grains and rice straw by 11% and 10%, respectively, compared to the CS.

A comparison of emergy input-output between CS and GS revealed significant differences in both input and output efficiency (Fig. 6). In terms of emergy input, GS consistently required less emergy compared to CS in both years. Specifically, the total emergy input for GS was notably lower than CS in both 2023 and 2024, with a reduction of about 34.9% in 2023 and 24.7% in 2024. For emergy output, GS outperformed CS in both years, with the total emergy output for GS being higher than that of CS by 10.2% in 2023 and 14.7% in 2024. As a result, the EER for GS was substantially higher than for CS, reflecting a more efficient exchange of emergy. Specifically, the EER for GS was about 34.9% higher than CS in 2023, and increased to 50.5% in 2024, indicating that GS achieved a more favorable balance between emergy input and output.

The EYR measures a system capacity of a system to use local inputs, while the ELR quantifies the environmental pressure exerted by the production process. A comparison of these indicators between CS and GS revealed important differences (Fig. 7). GS consistently demonstrated a higher EYR, indicating greater efficiency in using local inputs, while its ELR was consistently lower, reflecting reduced environmental stress compared to CS. Specifically, GS was 33.3% higher ESI than CS in 2023 and 37.2% higher ESI in 2024. These results indicate that GS significantly enhances the sustainability of rice production by both increasing emergy yield and decreasing environmental loading. This highlights the potential of GS to balance productivity and ecological preservation, making it a more sustainable alternative to CS.

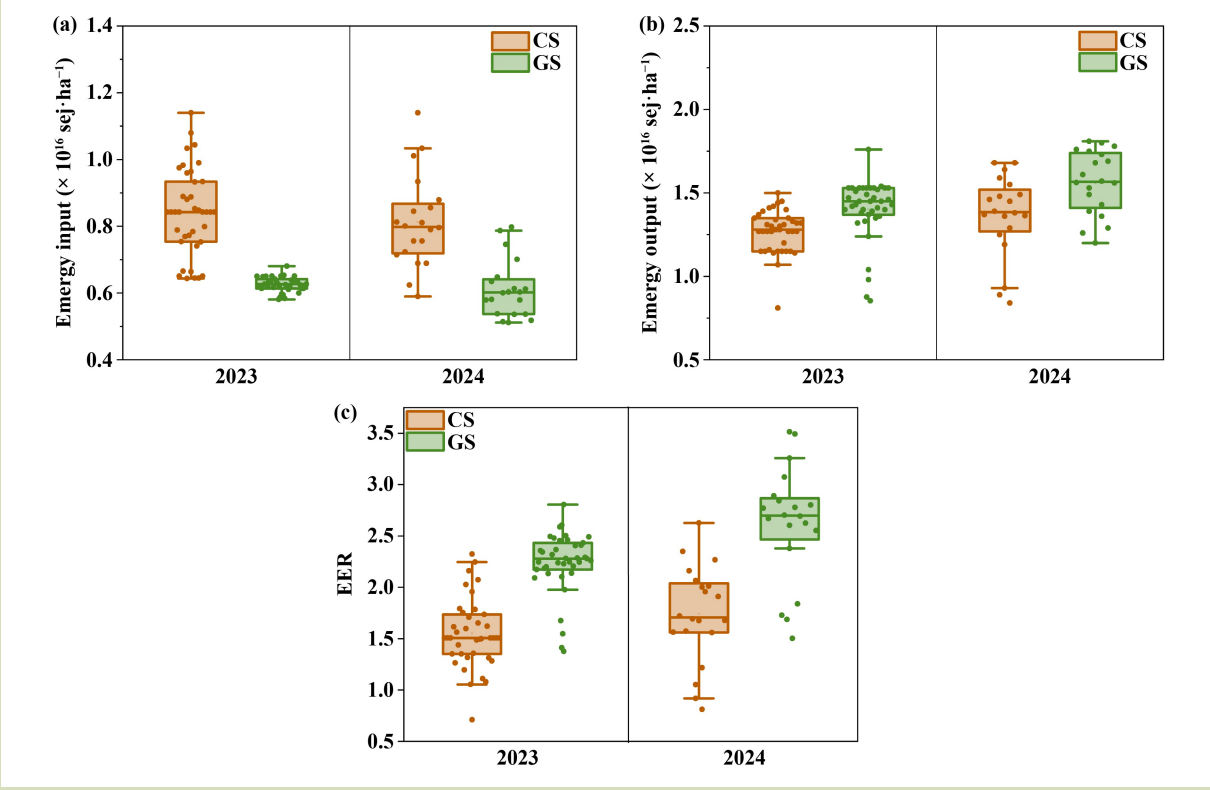

Fig. 6 Mean comparison of emergy input-output in current system and green system rice production systems. CS, current system; GS, green system; EER, emergy exchange ratio.

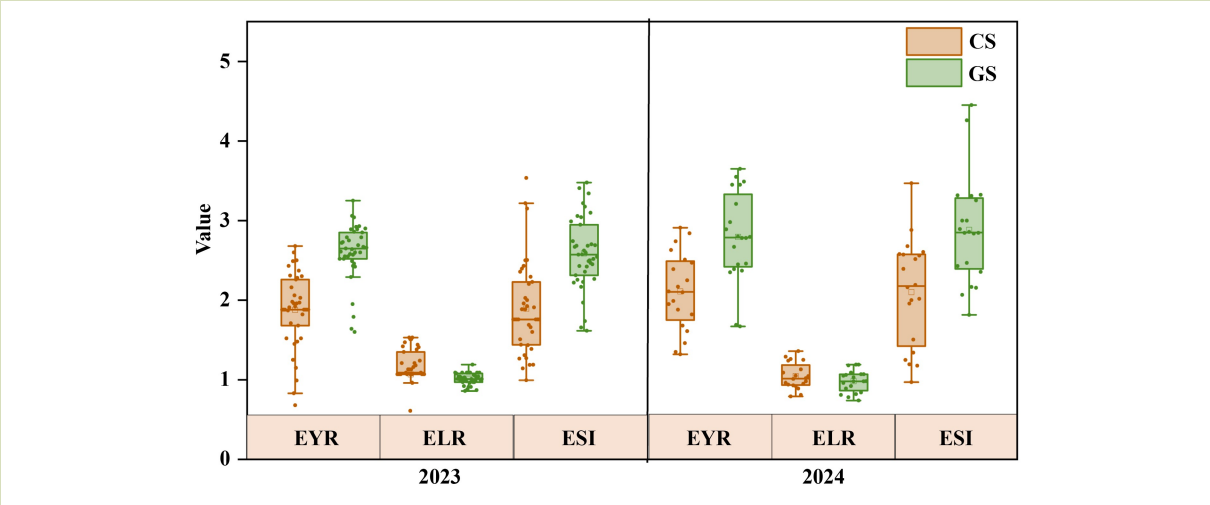

Fig. 7 Mean comparison of EYR, ELR and ESI in CS and GS rice production systems. CS, current system; GS, green system; EYR, emergy yield ratio; ELR, environmental loading ratio; ESI, environmental sustainability index.

4 Discussion

4.1 Emergy analysis of rice production status in the Erhai Lake Basin

In recent years, condition of Erhai Lake has been adversely affected by agricultural non-point source pollution, primarily driven by unsustainable farming practices. To address these issue, this study assessed the sustainability of rice production in the region, emphasizing the spatial heterogeneity in emergy input-output and sustainability across the Erhai Lake Basin. In this study, emergy analysis method was used for evaluation, which has been applied in some areas. For example, a study by Amini et al.[35] found that the sustainability of rice production in Mazandaran Province was low, largely due to the uncontrolled use of fertilizers and fuels. The study attributed these issues to limited awareness of farmers of appropriate fertilizer management and a misalignment between production practices and consumption needs. Similarly, Zhou et al.[36] applied emergy analysis to reveal that the current rice-planting system was in decline and developed an improved planting system that nearly doubled its emergy sustainability index. Survey data from this study revealed that farmer technical cognition, ecological cognition, production cognition, and policy cognition were critical factors influencing variations in fertilizer use, pesticide application and crop yield, which ultimately affected sustainability (Table S1). Previous studies[37,38] have highlighted the relationship between farmer cognition levels, resource endowments and agricultural behavior, consistent with prior findings on cognitive differences among farmers[39]. Further analysis indicated that towns such as SanYing, FengYu and ShangGuan extensive higher emergy inputs, particularly from renewable purchased inputs, due to the extensive use of farm manure. In contrast to the common understanding that organic fertilizers are generally beneficial for crop growth and environmental sustainability[18], we found that farmers in these areas often applied large amount of incompletely decomposed manure, particularly cow manure, at rates of up to 30 $t \cdot ha^{-1}$. Under flooded conditions during the rice-growing season, the application of such organic fertilizers can accelerate the breakdown of organic matter, leading to a substantial increase in CH_4 emissions and thereby posing a potential risk to global warming[40,41]. While previous studies have linked excessive fertilizer use or poor management to low sustainability, few have documented how the combination of strict fertilizer policies, smallholder production characteristics and manure-based nutrient management uniquely affects emergy performance in plateau-lake agricultural systems such as the Erhai Lake Basin. Our results provide new evidence showing that the mandated shift toward organic fertilizer application, although environmentally intended, may inadvertently increase non-renewable energy inputs when manure is applied inappropriately. To achieve sustainable agricultural development, especially in high-fertility and ecologically

sensitive regions like the Erhai Lake Basin, it is imperative to implement scientifically-based fertilizer application strategies and agronomic practices[42]. Overall, this study provides a more nuanced understanding of the sustainability challenges in the Erhai Lake Basin by revealing that spatial differences in emergy inputs are closely linked to smallholder manure-management practices, and that the shift toward organic-only fertilizer application, while policy driven, does not automatically translate into greater sustainability without accompanying improvements in technical guidance and management capacity.

4.2 Driving factors of ESI value in rice production

The random forest model was used to analyze the factors influencing the ESI, identifying rice yield, P and N fertilizer inputs, and manure fertilizer input as the primary determinants of ESI (Fig. 4). These findings align with previous studies[24,43], particularly in highlighting yield as a critical factor. For example, Piastrellini et al.[44] found that higher yields were strongly associated with improved energy use efficiency. The importance of fertilizer inputs observed in our study also aligns with extensive evidence showing that nitrogen and phosphorus management critically influence sustainability outcomes. For example, current yields for single-season and double-season rice in China are 7.4 $t \cdot ha^{-1}$ and 5.9 $t \cdot ha^{-1}$, respectively, but have the potential to increase by at least 28% and 34%[45]. However, nutrient use efficiency remains a challenge; only 25% of the nitrogen and 41% of the phosphorus fertilizers applied in China are used by crops, significantly lower than the rates in developed countries like the USA, where nitrogen use efficiency is 68%[46] and phosphorus use efficiency is 81%[47]. These gaps highlight significant opportunities for improving both yield and resource use efficiency in Chinese agriculture. The adoption of technologies such as integrated soil-crop system management[48], soil testing and fertilizer application formula optimization[49] and enhanced nitrogen management[19] has been shown to reduce energy inputs, improve resource use efficiency and increase crop yield, thereby enhancing the energy use efficiency of production systems. Narrowing yield and nutrient efficiency gaps, particularly in nitrogen fertilizer utilization, has been widely recognized as a critical strategy for ensuring food security, reducing agricultural pollution, and achieving sustainable agricultural development[46].

A notable finding of this study concerns the role of organic manure in shaping sustainability outcomes. While appropriate manure application can enhance soil quality and contribute to sustainable production[50], our results demonstrate that excessive use of partially decomposed manure in the Erhai Lake Basin has increased emergy inputs, reduced yields and ultimately lowered sustainability. This underscores that achieving sustainability is not merely a matter of reducing mineral fertilizer use but also requires guiding farmers to apply organic manure in scientifically appropriate ways. In the unique policy context of the Erhai Lake Basin, where mineral N and P fertilizers are prohibited, this insight is particularly important, as reliance on poorly managed organic fertilizer application may unintentionally undermine sustainability goals. Therefore, tailored management strategies that optimize organic manure use, enhance nutrient-use efficiency and balance yield with resource inputs are essential for advancing sustainable rice production in this ecologically sensitive region. Future research should focus on developing and validating such strategies to support long-term agricultural and environmental sustainability.

4.3 Emergy analysis between the CS and GS

In a two-year follow-up experiment, GS, which integrates multiple technological approaches, adopted a strategy of reduced fertilizer application combined with the use of green intelligent fertilizers. Unlike traditional fertilizers, green intelligent fertilizers are designed to align agricultural green development principles with the fertilizer industry practices, optimizing the interactions among plants, soil, microorganisms, nutrients and the environment. This synergy facilitates a green transformation throughout the agricultural value chain[28]. In addition to fertilizer application changes, the GS also incorporated pesticide reduction, optimized sowing schedules and seed quantity, the selection of suitable crop cultivars, and improved water management practices. The excessive reliance on labor, capital, fertilizers, diesel and pesticides often results in high environmental loads and low system sustainability[51,52]. In comparison to CS, our results show that GS not only achieved higher yields and energy outputs but also substantially reduced overall emergy inputs, indicating a more favorable balance between productivity and resource consumption. These improvements highlight that the integrated technological measures in GS effectively address the sustainability constraints commonly observed in smallholder farming systems, constraints that previous studies have shown to be linked to inefficient fertilizer use and high non-renewable

energy dependence. A key strategy for increasing resource use efficiency is to prevent the overuse of mineral fertilizers through practices such as soil testing-based, recommended and precision fertilizer application, all of which improve fertilizer absorption rates. To further reduce environmental load and improve sustainability, increasing the use of clean sources, such as solar and wind power, in the production process can replace non-renewable energy such as fossil fuels[53]. This would complement the precision strategies of GS by reducing reliance on normal energy and lowering carbon emissions. Green intelligent fertilizer can make full use of mineral resources and industrial by products, and create green fertilizer with low resource and environmental cost[28]. Also, replacing labor with increasingly advanced machinery and enhancing producer ability to apply existing technologies will contribute to improving the efficiency and sustainability of production systems[54].

STB serves as a platform connector key stakeholders, government bodies, scientists, smallholders and fertilizer companies, thereby fostering collaboration and ensuring that the strategies are aligned with China's unique national context[55]. Within this framework, scientists are stationed in rural villages to provide agricultural training, conduct field observations and engage in various activities, strengthening the relationship between researchers and farmers. This direct interaction is effective for promoting more sustainable farming practices among smallholders[45]. The successful adoption of GS across about 1300 ha in 2023 further demonstrates its practical scalability, indicating that the combination of technological innovation and STB-mediated social services can effectively catalyze the broader transition toward sustainable rice production in the Erhai Lake Basin.

4.4 Research defects and future prospects

This study evaluated the sustainability of rice production in the Erhai Lake Basin using emergy analysis. Although representative values for key parameters (e.g., solar emergy, rainfall chemical emergy and fuels) were used, regional differences may affect data accuracy[44]. In addition, emergy analysis has inherent methodological limitations. The method relies heavily on transformity coefficients and standard conversion factors, which are often derived from studies conducted in different regions or under different environmental conditions. Such values may not fully capture local biophysical processes, leading to potential uncertainties in the emergy accounting results. In addition, emergy analysis simplifies complex ecological and socioeconomic interactions into aggregated energy-based indicators, which may overlook certain spatial, temporal and management-related variations. To improve the robustness of sustainability assessments, future research should focus on enhanced field data collection and simulation to develop a model that accounts for county-level variations, providing more precise scientific methods and tools. In addition, this study did not consider the production process of green smart fertilizers. Compared to standard compound fertilizers, green intelligent fertilizers make more efficient use of waste resources such as phosphogypsum. As a result, the relevant parameters for emergy value calculation of green intelligent fertilizers may be lower than those of standard fertilizers. However, this distinction was not made in the current study. Therefore, the use of green smart fertilizers would be more beneficial for the green development of agriculture[28].

This paper has presented a case study on Erhai Lake, one of the major plateau lakes in China, and explored feasible schemes for achieving sustainable agricultural development. The current impacts on Erhai Lake, such as eutrophication and the unsustainable use of surrounding farmland, are common to many lakes worldwide[56,57]. Therefore, this paper proposes solutions for similar situations. First, through farmer surveys and emergy analysis, we identified the key factors limiting agricultural sustainability in the basin. Based on these findings, localized technology packages were proposed to enhance sustainability. To scale up these practices, we highlight the importance of integrating them into the broader agricultural system by combining regional planning, policy support, farmer training and engagement of agricultural service organizations. This coordinated approach facilitates wider adoption, adaptation to diverse farming contexts and provides practical guidance for achieving large-scale sustainable agricultural development.

5 Conclusions

Erhai Lake, with its fragile ecological environment, urgently requires a sustainable agricultural strategy. Using emergy analysis, this study evaluate the sustainability of rice production in the Erhai Lake Basin and revealed generally low sustainability and a strong dependence on external, non-renewable inputs under CS. Yield, N and P fertilizer inputs, and manure fertilizer input were identified as the main factors

influencing farm-level emergy-based sustainability, highlighting the central role of nutrient management in improving sustainability. GS technology package, developed by the STB, provides an effective pathway to address these constraints. GS adopts a green ecological rice-planting model that combines an optimized fertilizer application technique centered on green intelligent fertilizers with reduced mineral fertilizer inputs and improved nutrient and water management. At the same time, STB links government agencies, scientists, smallholders and fertilizer companies, and promotes GS adoption through on-farm trials, field demonstrations and technical training. Together, the GS technology package and STB-mediated services significantly enhance the emergy-based sustainability of rice production in the Erhai Lake Basin and offer a replicable model for green agricultural development in other plateau-lake regions.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-26689 contains supplementary materials (Tables S1–S2).

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Compliance with ethics guidelines

Liya Huang, Weizhi Li, Shuntao Zhang, and Jiuliang Xu 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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