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Analysis of economic benefits and energy value of intercropping *Stropharia rugosoannulata* under rubber forests in Hainan Province of China

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Abstract

To stabilize China's rubber planting area and maintain the security of China's natural latex supply as a strategic material, developing the cultivation of edible fungi under rubber forests is considered an effective solution. However, the proportion of suitable substrate for cultivating edible fungi under forests has not been clearly defined. The lack of clarity in economic and energy utilization efficiency hinders the promotion and development of the under-forest cultivation mode of edible fungi. In this study, we investigated the yield performance of *Stropharia rugosoannulata* cultivated under the forest using 9 different cultivation proportions. Additionally, we examined the economic and energy efficiency by calculating the input and output of each cultivation proportion, with *S. rugosoannulata* as the target. The results showed that proportion F (rubber sawdust: rice straw: rice chaff = 3:3:2) made full use of local agroforestry wastes. This proportion not only achieved the highest yield (8.51 kg m^{-2}) but also had the highest economic value, reaching 21.57 CNY m^{-2}. Therefore, it is the most suitable for widespread cultivation under the forest. This study provides reliable theoretical support for the rubber-fungus model while enhancing the rubber forest economy.

Keywords

benefit analysis; under-forest economy; rubber; *Stropharia rugosoannulata*; intercropping

Introduction

Natural rubber (*Hevea brasiliensis*) is a perennial crop, with its current planting area in Hainan Province estimated at approximately 585300 ha. Within this area, the production zone spans 389300 ha, yielding around 391200 tons (1). However, since 2013, the price of latex has been declining, discouraging farmers from production. Consequently, the phenomenon of abandoned rubber trees management has emerged in Hainan Province (2, 3). Consequently, increasing the financial gains from rubber plantations has become a pressing issue that demands attention. In recent years, numerous studies have demonstrated that utilizing the additional space beneath the rubber forest to develop intercropping crops could be a promising strategy for boosting the revenue of rubber plantations (4, 5). Among these strategies, combining rubber with edible fungus is thought to be one approach that functions effectively.

Stropharia rugosoannulata, commonly known as the wine cap *Stropharia*, belongs to the genus *Stropharia*. It contains various nutrients such as vitamins, proteins, minerals and polysaccharides. Therefore, *S. rugosoannulata* is a mushroom recommended for cultivation in developing countries by the Food and Agriculture Organization of the United Nations (FAO) (6). In recent years, there has been a growing awareness of the importance of food health care and an increasing demand for green natural products. Consequently, *S. rugosoannulata* has become increasingly popular among consumers. Previous studies have demonstrated that the reduced light levels and suitable humidity levels in the rubber forest are ideal for the growth of *S. rugosoannulata*, which improves land utilization efficiency (7). Additionally, the residue after the production of *S. rugosoannulata* can be utilized as a bio-organic fertilizer to enhance the soil's nutrient content in rubber forests (8). In summary, the rubber-fungus system can enhance the productivity of rubber plantations and improve the efficiency of resource utilization, resulting in significant economic and ecological benefits.

Economic analysis has been utilized as an important method to investigate and quantify the productivity of agricultural production systems, serving as a key indicators of the quality of cropping pattern (9). In addition to assisting farmers in determining crop efficiency, economic analysis enables them to select more economically advantageous farming practices and modify the organization of agricultural production. Furthermore, it can identify issues with resource utilization and make improvements (10). Therefore, clarifying the economic benefits and performance of the rubber-fungus system is of great significance for the popularization and application of this pattern.

On the other hand, energy input in agricultural ecosystems aims to increase production efficiency and ensure that the system can consistently produce at a high level. Between 1991 and 2012, energy consumption in agricultural production in China increased at an annual rate of 3.11 %, from 24.7 to 47.1 GJ ha^{-1} (11). Although the productivity of agricultural systems has increased due to the large -scale input of natural and manufactured resources (e.g., spawn substrates, irrigation water, fertilizers, pesticides etc.), this has also led to rising costs and a wide range of environmental issues (12, 13). The rubber-fungus system demonstrates significant ecological complementarity, as mentioned earlier. Determining the energy input characteristics and utilization efficiency of the rubber-fungus pattern is crucial for ensuring the system's sustainable development and optimizing its management.

The current lack of research on energy utilization efficiency and economic performance hinders the progress of under-forest cultivation of *S. rugosoannulata*. The present study established 9 different compost substrate proportions using local agroforestry waste materials, including rubber wood shavings, rice straw and cereal hulls, for the purpose of cultivating *S. rugosoannulata* under forest conditions. The primary objectives of this study are to (i) clarify the financial advantages and energy efficiency of cultivating *S. rugosoannulata* under forest cover using different compost substrates and (ii) identify suitable base material compositions for under-forest cultivation. This research is expected to provide the theoretical basis for optimizing and promoting the cultivation technology of the rubber-fungus pattern.

Materials and Methods

Overview of the test site

The experimental site is located in Dacheng Town, Danzhou City, Hainan Province, with a geographical location of 19°11′ N, 108°56′ E. Dacheng Town has a tropical monsoon climate with an average annual temperature of 23.5 ^{0}C and the coldest month generally stays above 16 ^{0}C. The dry and rainy seasons are distinct, with an average annual rainfall of 1815 mm. Due to the influence of the monsoon, rainfall distribution throughout the year is highly uneven. May to October constitutes the rainy season, accounting for 84 % of the annual rainfall, while November to April of the following year is the dry season, accounting for 16 % of the annual rainfall. The average annual light hours exceed 2000 h, with an average radiation of 5000 MJ m^{-2}.

Test design

The compost substrate for *S. rugosoannulata* is based on rice straw, rubber sawdust and rice chaff as the major compost substrates for cultivation, supplemented with rice bran, soybean meal, urea, lime and phosphate as minor compost substrates. Nine different compost substrate proportions were established in the present study, as detailed in Table 1, where the letters A-I represents the different compost substrates proportions. The compost substrates in this experiment were divided into 2 main groups: one based on rubber sawdust and rice straw (2MCS) and the other based on rubber sawdust, rice straw and rice chaff (3MCS). A randomized block design with 4 replicates was adopted, with each plot having an area of 3 m^2 and containing 60 kg compost substrate. The experiment was conducted from November 2022 to April 2023, with management practices based on conventional mushroom cultivation techniques (Table 1).

Determination method

Economic analysis

S. rugosoannulata yield, gross return, net return, benefit-to-cost ratio and other economic indicators were calculated as below (14-16).

Yield (kg m^{-2}) = Fresh weight per treatment (kg)/Treatment area (m^2)

Gross return (CNY m^{-2}) = Yield (kg m^{-2}) ×Price (CNY kg^{-1})

Net return (CNY m^{-2}) = Gross return (CNY m^{-2})-Total production cost (CNY m^{-2})

Benefit-to-cost ratio = Gross return (CNY m^{-2})/Total production cost (CNY m^{-2})

Basic information on energy and cost inputs was entered into Excel 2016's spreadsheet and simulated using SPSS 26.0 software (Table 2).

Table 1. The detail proportion of different compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests.

Group	Proportion	Major compost substrates	Minor compost substrates
2 MCS	A	Rubber sawdust: Rice straw =0: 1	Rice bran 5 %, Soybean meal 1 %, Urea 0.5 %, P_2O_5 0.5 %, Lime 0.5 %
	B	Rubber sawdust: Rice straw =1: 3	
	C	Rubber sawdust: Rice straw =1: 1	
	D	Rubber sawdust: Rice straw =3: 1	
	E	Rubber sawdust: Rice straw =1: 0	
3 MCS	F	Rubber sawdust: Rice straw: Rice chaff =3: 3: 2	
	G	Rubber sawdust: Rice straw: Rice chaff =1: 1: 2	
	H	Rubber sawdust: Rice straw: Rice chaff =1: 1: 6	
	I	Rubber sawdust: Rice straw: Rice chaff =0: 0: 1	

2MCS: proportions based on 2 major compost substrates (rubber sawdust and rice straw), **3MCS**: proportions based on 3 major compost substrates (rubber sawdust, rice straw and rice chaff). The letters **A-I** stand for the different compost substrates proportions. The major compost substrates for A, B, C, D, E, F, G, H, I are Rubber sawdust: Rice straw or Rubber sawdust: Rice straw: Rice chaff, the proportions of the major compost substrates for A, B, C, D, E, F, G, H, I are 0:1, 1:3, 1:1, 3:1, 1:0, 3:3:2, 1:1:2, 1:1:6, 0:0:1 respectively. The minor compost substrates are the same for all proportions.

Table 2. Energy equivalent and prices of inputs and outputs in the rubber tree-fungus inter cropping system.

Particulars	Unit	Energy equivalent (MJ/unit)	Price (CNY/ unit)	Reference
A. In puts				
1. Labor	h	1.96	12.5	(30)
2. Machinery	h	62.70		(31-33)
3. Diesel	l	56.31	8.13	(34)
4. Spawn substrate	PCS	24.26	2.50	
5. Fertilizer				
Phosphorus(P_2O_5)	kg	12.44	5.80	(35)
Urea	kg	57.20	5.30	(36)
Lime	kg	2.89	1.67	(37)
6. Compost substrate				
Rubber sawdust	kg	16.50	0.20	(38)
Rice straw	kg	14.09	1.25	(5)
Rice chaff	kg	14.84	1.10	(39)
Rice bran	kg	15.50	2.50	(40)
Soybean meal	kg	19.50	5.60	(41)
7. Pesticide				
Herbicide	kg	238	152.3	(17)
Insecticide	kg	101.2	166.0	(42)
Fungicide	kg	216	22	(17)
8.Irrigation				
Water	m^3	1.02	2.80	(43)
9. Electricity	kWh	11.93	0.90	(44)
B. Outputs				
Stropharia rugosoannulata	kg	13.9	*	(45)

***** Frist-class 23.8 CNY·kg^{-1}, Second-class 15.4 CNY·kg^{-1}, Third-class 8 CNY·kg^{-1}, Out of class 6 CNY·kg^{-1}.

Energy analysis

Energy inputs for *S. rugosoannulata* intercropping under rubber forest production include irrigation water, machinery, diesel, electricity, labor, spawn substrate, fertilizer, compost substrate and pesticide. Energy outputs include the fresh weight of *S. rugosoannulata*. The energy contained in the inputs and outputs was calculated by multiplying the statistical quantities of the inputs and outputs by the corresponding energy equivalents. The total energy input is the sum of all input energy and the total energy output is the sum of all output energy. The energy equivalent values of inputs and outputs are shown in Table 2 (17).

Energy use efficiency (EUE) = Energy output (E_o, MJ m^{-2})/ Energy input (E_i, MJ m^{-2})

Energy productivity（EP, kg MJ^{-1}）= Yield of the *S. rugosoannulata* (Y, kg m^{-2})/Energy input (E_i, MJ m^{-2})

Human energy profitability (HEPF) = Energy output (E_o, MJ m^{-2})/Human energy input (E_h, MJ m^{-2})

Statistical analysis

All data were organized using Excel 2016 (Microsoft Office, WA, USA). Analysis of variance was performed on the data using IBM SPSS Statistics 26 (IBM, NY, USA) and multiple comparisons were conducted at the 0.05 level using the least significant difference (LSD) method to determine the statistical significance of different treatments. Origin 2022 (Mapping Software, MA, USA) was used for drawing.

Results

Stropharia rugosoannulata Production under different proportions of compost substrates for intercropping *S. rugosoannulata* under rubber forests

The effect of different compost substrate proportions on the yield of *S. rugosoannulata* varied significantly (Fig. 1). Among them, proportion F had the highest yield, which was significantly higher than the other proportions. The yield of *S. rugosoannulata* in proportion F reached 8.51 kg m^{-2}, which was 155.3 times higher than that of proportion I (0.05 kg m^{-2}), the proportion with the lowest yield. As shown in Fig. 1, the yield of different proportions follows this order: F > D > H > C > G > E > A > B > I.

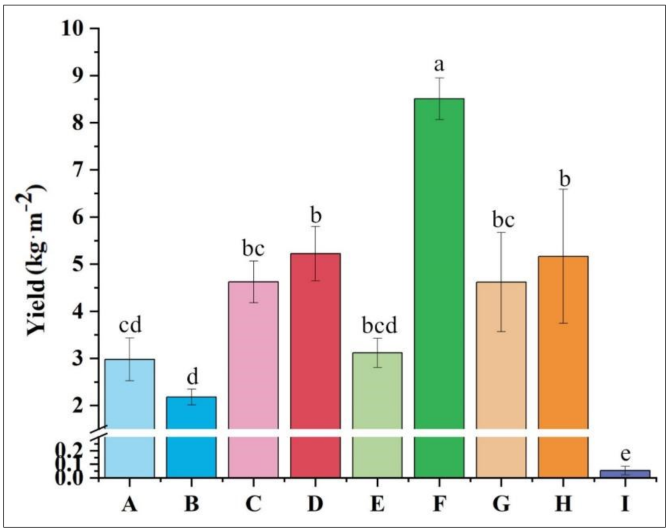

Fig. 1. *Stropharia rugosoannulata* yield under different proportion of compost substrates under rubber forests. Vertical bars represent ± SE of the mean. Means followed by different lowercase letters are significantly different according to the least significant difference (LSD) test at a significance level of 0.05. The letters **A-I** stand for the different compost substrates proportions.

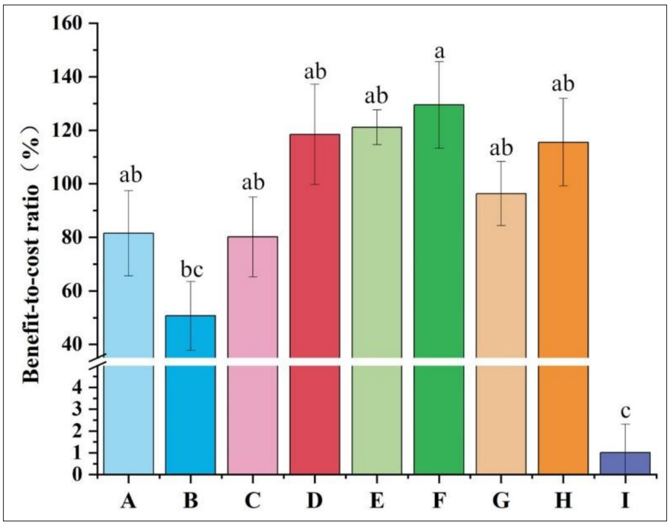

Fig. 2. Benefit cost ratio under different proportions of compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests. Vertical bars represent ± SE of the mean. Means followed by different lowercase letters are significantly different according to the least significant difference (LSD) test at a significance level of 0.05. The letters **A-I** stand for the different compost substrates proportions.

Impact of different proportions of compost substrates on economic efficiency

Benefit-to-cost ratio for different proportions of compost substrates

For sustainable production of *S. rugosoannulata*, minimizing resource consumption and achieving a high benefit-to-cost ratio are essential. Proportion F had the highest benefit-to-cost ratio of 129.26 %, followed by proportion E with a ratio of 121.14 %, proportion D with a ratio of 118.29 % and proportion G with a ratio of 115.94 %. Except for proportions F, D, E and H, the rest of the proportions (A, B, C, G, I) had a benefit-to-cost ratio of less than 100 % (Fig. 2). The order of the benefit-to-cost ratio, from highest to lowest, in all proportions was F > E > D > H > G > A > C > B > I (Fig. 2).

Total production cost, gross return and net return of different proportions of compost substrate

The total production cost, gross return and net return of *S. rugosoannulata* are shown in Table 3. Regarding total production cost, proportion A had the highest production cost among the 2MCS, totaling 73.65 CNY m^{-2}. Compared to proportions B, D and E, this cost was 9.39 %, 8.63 %, 15.37 % and 26.35 % higher respectively. The calculation of production costs revealed a gradual increase with the addition of more rice straw in 2MCS. The highest cost among the 3MCS proportions was found in proportion F, at 75.55 CNY m^{-2}. Compared to proportions G, H and I, this cost was 6.75 %, 4.01 % and 12.83 % higher respectively. Due to the high yield of proportion F, it requires high economic inputs for manual harvesting. Regarding total gross return, proportion D recorded the highest gross return in 2MCS at 73.73 CNY m^{-2}. This amount was 19.14 % higher than proportion A, 54.92 % higher than proportion B, 27.15 % higher than proportion C and 10.63 % higher than proportion E. Proportion F had the highest gross return among the 3MCS, with a value of 97.12 CNY m^{-2}. This value was 30.03 %, 14.35 % and 99.11 % higher than proportions G, H and I respectively. Among all the proportions, proportion F had a significantly higher gross return than proportions B and I, but no significant difference compared to other proportions. In terms of net return, the proportions that achieved positive returns were D, E, F and H, with 11.40, 11.65, 21.57 and 10.66 CNY m^{-2} respectively (Table 3). The rest of the proportions had negative returns. The net return of proportion F was significantly higher than that of proportions D, E and H (89.2 %, 85.2 % and 102.3 % higher respectively).

Table 3. Gross return, total production cost and net return under different proportions of compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests.

Proportion	Total production cost (CNY·m^{-2})	Gross return (CNY·m^{-2})	Net return (CNY·m^{-2})
A	73.65	59.62ab	-14.03 c
B	66.74	33.24bc	-33.50c
C	67.30	53.72ab	-13.58 c
D	62.33	73.73ab	11.40 b
E	54.25	65.89ab	11.65 b
F	75.55	97.12 a	21.57 a
G	70.46	67.95ab	-2.50 b
H	72.53	83.19ab	10.66 b
I	65.86	0.87c	-64.99 d

Means followed by different lowercase letters are significantly different according to the least significant difference (LSD) test at a significance level of 0.05. The letters **A-I** stand for the different compost substrates proportions.

Effect of different proportions of compost substrate on energy efficiency

Energy input and output of different proportions of compost substrate

Proportion E had the highest energy input of 477.58 MJ m^{-2} primarily because it was exclusively treated with rubber sawdust. The energy per unit weight of rubber sawdust was higher than that of other compost substrates, such as rice straw. Following this, proportion D had an input energy value of 459.49 MJ m^{-2} (Fig. 3). The gradual increase in energy input for proportions A-D is due to the increasing proportion of rubber sawdust in the compost substrates. The energy inputs of proportions F-I were as follows, 445.20 MJ m^{-2}, 442.59 MJ m^{-2}, 444.47 MJ m^{-2} and 440.88 MJ m^{-2} respectively (Fig. 3).

substrate and pesticide. The proportion of indirect energy to total energy inputs (94.16-96.23 %) was higher than that of direct energy inputs (3.77-5.84 %) (Fig. 4b). Direct energy inputs were ranked as H > F > G > D > C > E > A > B > I, while indirect energy inputs were ranked as E > D > I > H > G > F > C > B > A (Fig. 4b). Energy inputs mainly include machinery, diesel, irrigation water, labor, fertilizer, compost

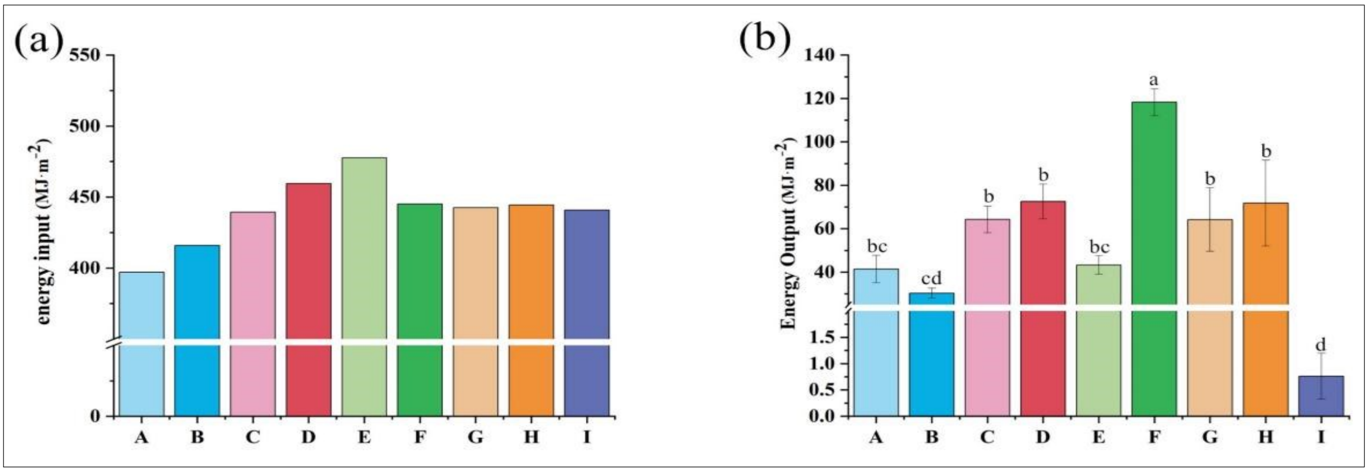

Fig. 3. Total energy input (a) and output (b) under different proportions of compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests. Vertical bars represent ± SE of the mean. Means followed by different lowercase letters are significantly different according to the least significant difference (LSD) test at a significance level of 0.05.

Non-renewable energy sources include energy from diesel, machinery, fertilizer and pesticides, whereas renewable energy sources include energy from labor, spawn substrate, compost substrates and irrigation water (Fig. 4a). The proportion of renewable energy in total energy inputs ranged from 96.77 % to 97.32 %, which was higher than the proportion of non-renewable energy inputs, ranging from 2.79 % to 3.23 % (Fig. 4a). Direct energy inputs comprises diesel fuel, irrigation water and labor used in the production process, while indirect energy inputs include machinery, spawn substrate, fertilizer, compost substrate, pesticide and spawn substrate. In terms of energy inputs, spawn substrate and compost substrate accounted for more than 90 % of the total energy inputs (Fig. 4c). The energy input from the compost substrate was the largest source of energy consumption among the proportions (331.6-251.6 MJ m^{-2}), accounting for more than 63 -69 % of the total energy input (Fig. 4c). The energy inputs of different agricultural production methods were, in descending order, compost substrate > spawn substrate > electricity > labor > irrigation water > machinery > pesticide > fertilizer > diesel (Fig. 4c).

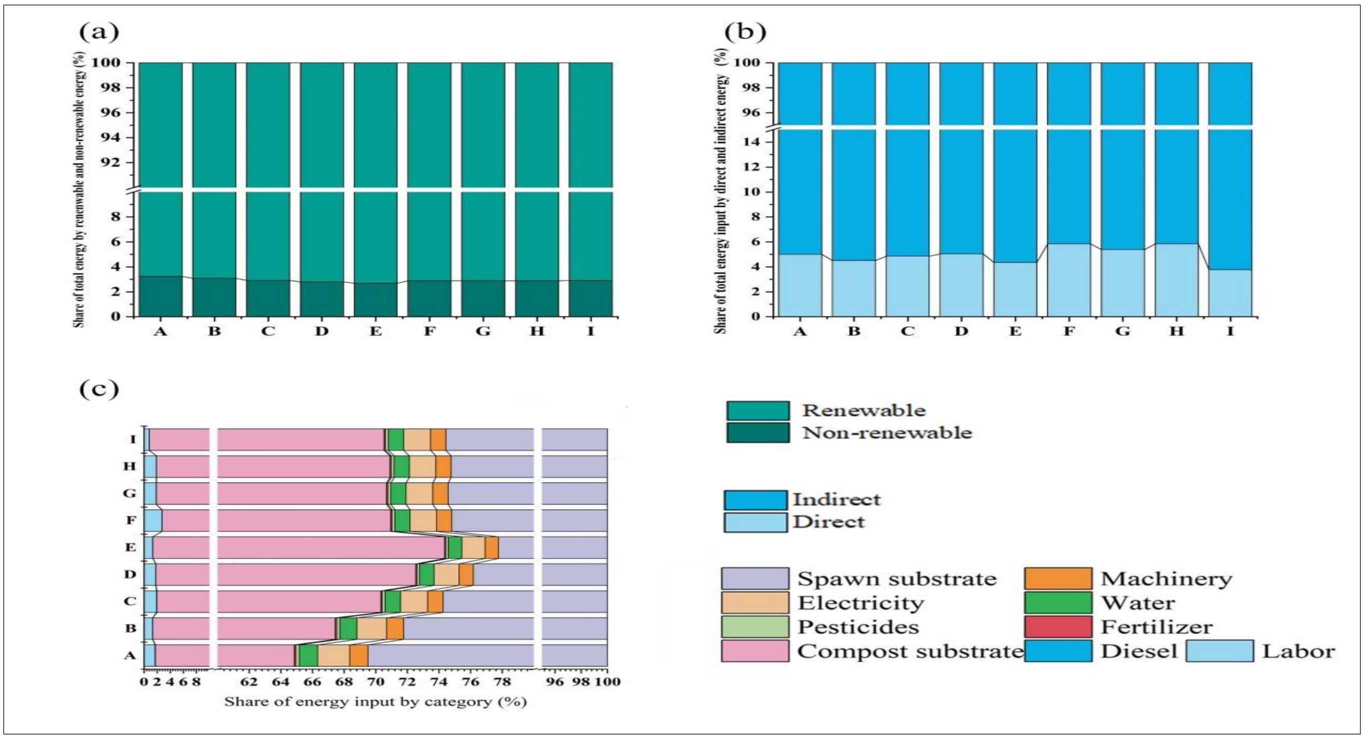

Fig. 4. Percentage of total energy input by renewable and non-renewable (**a**), direct and indirect (**b**), and different sources (**c**) (machinery, human labor, diesel, fertilizer, compost substrate, irrigation water, biocide and spawn substrate) under different proportions of compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests.

Energy use efficiency, energy productivity and human energy profitability of different proportions of compost substrates

The EUE, EP and HEPF of intercropping *S. rugosoannulata* under rubber forests with different proportions of compost substrates are shown in Table 4. The results indicate that proportion F had the highest EUE (0.27), EP (0.057 kg MJ^{-1}) and HEPF (3.00) among all the proportions. Proportion F was significantly higher than proportions A, B, C, D, E, G and H in terms of EUE and EP and significantly higher than proportions A, B, E and I in terms of HEPF. Proportion I had the lowest EUE ($0.7*10^{-2}$), EP ($0.04*10^{-2}$ kg MJ^{-1}) and HEPF (0.07) among all the proportions.

Table 4. Energy use efficiency, energy productivity and human energy profitability under different proportions of compost substrates for intercropping *Stropharia rugosoannulata* under rubber forests.

Proportion	Energy use efficiency (EUE)	Energy productivity (EP, kg·MJ^{-1})	Human energy profitability (HEPF)
A	0.1bcd	0.022bcd	2.01bc
B	0.07d	0.016d	1.81c
C	0.15bc	0.032bc	2.35abc
D	0.16b	0.034b	2.66ab
E	0.09cd	0.020cd	1.98bc
F	0.27a	0.057a	3.00a
G	0.14bc	0.031bc	2.30abc
H	0.16b	0.035b	2.49abc
I	$0.7*10^{-2}$e	$0.04*10^{-2}$e	0.07d

Means followed by different lowercase letters are significantly different according to the least significant difference (LSD) test at a significance level of 0.05. The letters **A-I** stand for the different compost substrates proportions.

Discussion

Production

The yield of *S. rugosoannulata* in this study ranged from 0.05 to 8.51 kg m^{-2} (Fig. 1). The wide range of yield may be attributed to the diverse range of compost substrate and their proportions used in this study (18). The highest yield of 8.51 kg m^{-2} (Fig. 1) was obtained from proportion F, which is consistent with the findings of previous research in Hainan province (19), China. With a similar amount of compost substrate, the yield of the present study was slightly higher than that in the previous study.

The 2MCS, consisting of compost substrate with the addition of rubber sawdust and rice straw, yielded 2.18-5.22 kg m^{-2}. Proportion D had the highest yield of 5.22 kg m^{-2} (Fig. 1), attributed to the higher content of rubber sawdust in proportion D, which favors the growth of *S. rugosoannulata* at later stages. Research indicates that *S. rugosoannulata* is a grass-rotting edible fungus. Nutrient supply during the mycelial growth period primarily comes from rice straw and *S. rugosoannulata* also possess a robust ability to degrade lignocellulose (20). The main energy source for subsequent growth is the decomposition of rubber sawdust. In this study, the yields of proportion E and proportion A were low, measuring 2.18 kg m^{-2} and 2.98 kg m^{-2} respectively (Fig. 1). Among them, the main compost substrate used in proportion A was solely rice straw. The yield of proportion A was similar to that reported by (21), suggesting that a single compost substrate alone may not be sufficient to meet the nutritional requirements of *S. rugosoannulata*, leading to a mismatch between nutrient supply and demand for the growth of *S. rugosoannulata*.

Through the comparison of proportion D and proportion H, it was shown that the addition of rice chaff to the main compost substrate of cultivated *S. rugosoannulata* had a significant impact on yield, which was consistent with previous studies (22, 23). By comparing proportion F and proportion D, it was found that while proportion D could provide sufficient nutrients for the growth of *S. rugosoannulata* mycelium, the high density of rubber sawdust resulted in poor substrate permeability, which further hindered the growth of mycelium and the formation of fruit bodies.

Proportion F, G and H in 3MCS involved the addition of a specific quantity of rice chaff to rubber sawdust and rice straw. Among them, Proportion I was the pure rice chaff treatment and the yield was the lowest, only 0.05 kg m^{-2} (Fig. 1). This result indicated that using only rice chaff as the main compost substrate had the disadvantage of insufficient nutrients and was not suitable for the mycelial growth of *S. rugosoannulata*. This finding is consistent with the study conducted by (2). The yields of proportion G and H were 4.62 kg m^{-2} and 5.17 kg m^{-2} respectively (Fig. 1). This difference in yield could be attributed to the addition of rice chaff, which enhances the permeability of the main compost substrate. The improved permeability is beneficial for the formation and growth of fruit bodies.

Economic benefits

In terms of cultivation cost, the proportion cost of proportion F was 75.55 CNY m^{-2} due to the high labor cost (Table 3). The cost of proportion A is second only to that of proportion F, at 73.65 CNY m^{-2} (Table 3). This is that because rice straw (higher price than wood chips) is the main compost substrate in proportion A, and the high cost is associated with manual picking. The cost of the main compost substrate for proportion E was the lowest (54.25 CNY m^{-2}) (Table 3). This is because rubber sawdust was primarily used in proportion E, which has a lower unit price. The cost of proportion H, G and I gradually decreased with the decrease in rice chaff addition. Conversely, the cost of proportions B, C and D gradually decreased with the increase in rubber sawdust addition. From a net return perspective, only proportions D, E, F and H were profitable. Among them, proportion F had the highest net return, reaching 21.57 CNY m^{-2}, followed by Proportion E with a net return of 11.65 CNY m^{-2} (Table 3). The high net return of proportions F and E, which is low-cost and provide sufficient nutrients. Although the cost of proportion H is high, its yield is also high, resulting in profit similar to that of proportion D. In this experiment, the cost and profit of proportion D were relatively average. Proportions A, B, C, G and I are not profitable. Proportions A and I involve treating pure rice straw and pure rice chaff separately. However, these proportions have low yields and high costs, making them unprofitable. Additionally, the price of *S. rugosoannulata* significantly affects the benefit-to-cost ratio. Therefore, an in-depth analysis of market dynamics, pricing and strategies for reducing management and production cost must be conducted to increase the economic viability and competitiveness of intercropping *S. rugosoannulata* under rubber forests.

Energy efficiency

In terms of the energy input for 2MCS (proportions A-E), proportion E had the highest energy input (477.58 MJ m^{-2}) due to its main component, rubber sawdust. The energy per unit weight of rubber sawdust was higher than that of straw. Proportion A had the lowest energy input (397.08 MJ m^{-2}). The energy input of proportions A-D gradually decreased with the decrease in the proportion of rubber sawdust. When considering the energy input for 3MCS (proportions F-I), proportion F had the highest energy input at 445.20 MJ m^{-2}, while the energy input of the other proportions was similar. From the perspective of energy composition of different production methods, compost substrates are typically the primary source of energy consumption in crop production (24, 25). In our study, the spawn substrate ranked second only to the compost substrate in terms of energy input. Generally, the mass of the compost substrate and spawn substrate accounted for more than 90 % of the total energy consumption (Fig. 4). However, the compost substrate used in this experiment primarily consists of renewable agricultural and forestry straw, such as sawdust straw. The chemical fertilizers used in this study accounted for only 0.19 to 0.23 % (Fig. 4). The high consumption of non-renewable resources, such as diesel and machinery, in agricultural production has significantly reduced economic benefits and farmers' income. Additionally, this resource depletion has also had an impact on ecological and energy security (26, 27). However, the energy input of diesel and machinery in this study is low, approximately 0.03 % and 1.03 % respectively (Fig. 4). Reducing the use of fuel and machinery in the production of *S. rugosoannulata* can not only bring higher economic benefits to farmers but also mitigate environmental pollution.

From the perspective of energy input form, indirect energy input accounts for 94.16-96.23 % of the total energy input, which is higher than the 3.77-5.84 % of direct energy input (Fig. 4). The main reason for the higher proportion of indirect energy input is the extensive use of compost substrates, which are also utilized in the production of other types of edible fungi (28). In terms of energy renewability, all renewable energy inputs are much higher than non-renewable energy inputs (Fig. 4). Non-renewable energy, as a significant component of total energy input, can have detrimental effects on the environment and pose serious threats to the sustainability of agricultural ecosystems (29). Therefore, under-forest cultivation of *S. rugosoannulata* in a forest cultivation mode can ensure ecological and energy security. It can also promote the development of renewable energy in agricultural production activities and increase the utilization of renewable energy in agricultural resource production. As a result, it directly or indirectly reduces reliance on non-renewable energy in agriculture and minimizes the environmental impact. The EUE, EP and HEPF of *S. rugosoannulata* under-forest cultivation mode are mainly affected by the proportion of *S. rugosoannulata* cultivation and labor input. In this study, the EUE, EP and HEPF of proportion F were higher than those of other proportions (Table 4). This is because the substrate energy input of proportion F was lower than that of other proportions, while the energy output was higher than that of other proportions.

Conclusion

In conclusion, proportions D, F and H demonstrate greater comprehensive benefits. This is attributed to their higher yields, economic benefits and EUE, coupled with lower energy input requirements. Proportions D, F and H provide adequate nutritional requirements for the growth of *S. rugosoannulata* due to the balanced proportions of rice straw and rubber sawdust. Additionally, the optimal proportion of rice chaff in proportion F enhances the permeability of the compost substrate, further augmenting the yield.

Therefore, planting *S. rugosoannulata* under rubber forests proves to be an effective intercropping technique that enhances the overall benefits of rubber tree plantations. Coordinating the relationship between various inputs and improving their efficiency will further enhance the overall benefits of the rubber forest intercropping system.

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Authors’ contributions

Conceptualization, LN; Data curation, JT and WL; Funding acquisition, LN; Investigation, JT, WL, SC, RZ and QL; Methodology, JT, MNK; Software, JT; Supervision, LN and YT; Writing—original draft, JT; Writing—review and editing, YT, MNK and LN. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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