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Research article

Sustainable Rubber Production Intercrop with Mixed Fruits to Improve Physiological Factors, Productivity, and Income

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Abstract: This study investigated the impact of various rubber intercropping models on productivity, income, and physiological factors, compared to rubber monocropping in Tamod subdistrict, Phatthalung province, Thailand. Three intercropping models from rubber smallholder farms with mature *Hevea* trees were evaluated: rubber with timber trees (RT), rubber with timber and fruit trees (RTF), and rubber with timber, fruit, and shrub trees (RTFS). The rubber monoculture served as the control treatment. Data was collected from May 2021 to April 2022. Results revealed that intercropping had an 11.3% lower Tapping Panel Dryness incidence than monocropping (88.7%). The RTFS model had the highest latex yield at 1,866.31 kg/ha/year and dry rubber content at 40.11%, outperforming the other models. In the RTF model, fruit yields were 809, 92, 458, and 61 kg/ha/year for *Durio zibethinus* L., *Lansium domesticum*, *Garcinia mangostana*, and *Nephelium lappaceum* L. The RTFS model had a *Salacca zalaca* fruit yield of 1,220 kg/ha/year. Environmentally, the RTFS model had the lowest average temperature (30.5°C), highest humidity (68.8%), and lowest light intensity (2,955 lux) compared to the other models. Soil moisture tension was also least negative in RTFS at -5.7 kPa and -5.3 kPa at 30cm and 50cm depths. Economically, the RTF model had the highest net profit at 4,892 USD/ha/year with a benefit-cost ratio of 2.75 and a return on investment of 176%. Sensitivity analysis showed RTF maintained the highest profits even with ±10% changes in revenue and costs. Rubber intercropping, particularly the RTFS model, improved productivity, income, and environmental conditions compared to monocropping.

Keywords: Sustainable rubber production; Intercropping systems; Smallholder farmers; Tapping Panel Dryness; Livelihood diversification

1. Introduction

Natural rubber is a vital agricultural commodity, with Thailand being the global leader in production, accounting for approximately 5.15 million tonnes annually from over 3.9 million hectares of rubber plantations [1]. The rubber industry has significantly contributed to Thailand's socio-economic stability for over a century [2]. Rubber latex is a fundamental raw material for products like tires, medical gloves, condoms, rubber bands, and flexible tubing

[3]. Cultivating natural rubber has been a significant driver of Thailand's agricultural economy, with an annual growth rate of 5.52% from 1960 to 2013. This growth was primarily driven by high rubber prices, which reached a yearly increase of 16.03% from 1999 to 2011 [4]. However, the expansion of rubber plantations has raised environmental sustainability concerns. The increasing demand for rubber products has led to higher costs, incentivizing Thai farmers and the government to expand rubber plantations, primarily focusing on enhancing productivity rather than ensuring sustainability. The encroachment of cultivation into forested and agricultural lands has become a pressing issue. Moreover, focusing on productivity enhancement rather than sustainable practices has led to long-term environmental degradation [5].

Since 2012, raw rubber prices have steadily declined, with an average of 2.1 and 1.53 USD per kilogram in 2013 and 2023, respectively. The decline is primarily due to the supply of natural rubber exceeding industry demand. Additionally, this may grow as countries like China, the USA, Japan, and various European nations reduce their domestic tire production [6]. Rubber smallholder farmers are the most vulnerable group to these economic and social impacts. In response to falling rubber prices, the government implemented measures in 2014 to assist farmers, encouraging them to cut down rubber trees, reduce cultivation during price crises, and encourage rubber intercropping plantations or another cash crop [7]. However, no specific intercrop model is available to support them in terms of livelihood, culture, and household area [8]. However, only research reports that the rubber intercropping immature and mature rubber with economic crops would assure security for rubber growers under price fluctuations and loss of productivity in rubber trees. This provides a practical solution to all these problems by generating additional income from the land during the immature phase of rubber [9]. Integrating *Hevea* with other tree crops was studied to develop guidelines for farmers interested in diversifying their income streams and optimizing land use. The *Hevea*-coffee and *Hevea*-cocoa combinations proved significantly more profitable than other associations until the 12th year. The additional gross margins became positive from the third year onwards for the *Hevea*-coffee association and from the fourth year onwards for the *Hevea*-cocoa association. *Hevea* only reached the breakeven point in the eighth year when grown as a mono-crop. *Hevea* revenues made up 88% of the total revenues, while intercrops contributed between 4% (cola) and 25% (coffee) [10]. In Thailand, it has been reported that a rubber intercropping system offers an alternative approach to agriculture, enhancing biological integrity, crop diversity, and financial stability. This system can be categorized into three types: 1) rubber intercropped with food crops, 2) rubber intercropped with fruit crops, and 3) rubber intercropped with timber species [6,11].

Rubber intercropping, particularly with mixed fruits, has emerged as a potential solution to address rubber production's economic, environmental, and social complexities [12]. The study aims to evaluate factors such as socio-economic, rubber yields and quality parameters, soil and environmental parameters, and economic analysis of the intercropping system that influence rubber farmer productivity in rural regions and contribute to the sustainable livelihoods of smallholder rubber farmers.

2. Materials and Methods

2.1 Location of experimental site

The experimental site is in the Tamod district of Phatthalung province, Southern Thailand. The study area was deliberately selected due to local rubber farmers' adherence to the rubber intercropping criteria. The research on rubber smallholder farms was conducted from May 2021 to April 2022. The Asian monsoon and prevailing winds from the northeast and southwest directions influence the climate in Phatthalung province. The area experiences two distinct seasons: a dry season from late March to mid-September and a rainy season from mid-September to mid-March. Over the past 30 years, the average temperature in Phatthalung province during the dry season has been around 28.1°C, with an average maximum temperature of 37.3°C and a minimum of 24.1°C. The average annual rainfall in Phatthalung province over the past 30 years has been 2,071.8 mm, but in 2019, the annual rainfall was measured at approximately 1,523.6 mm [13].

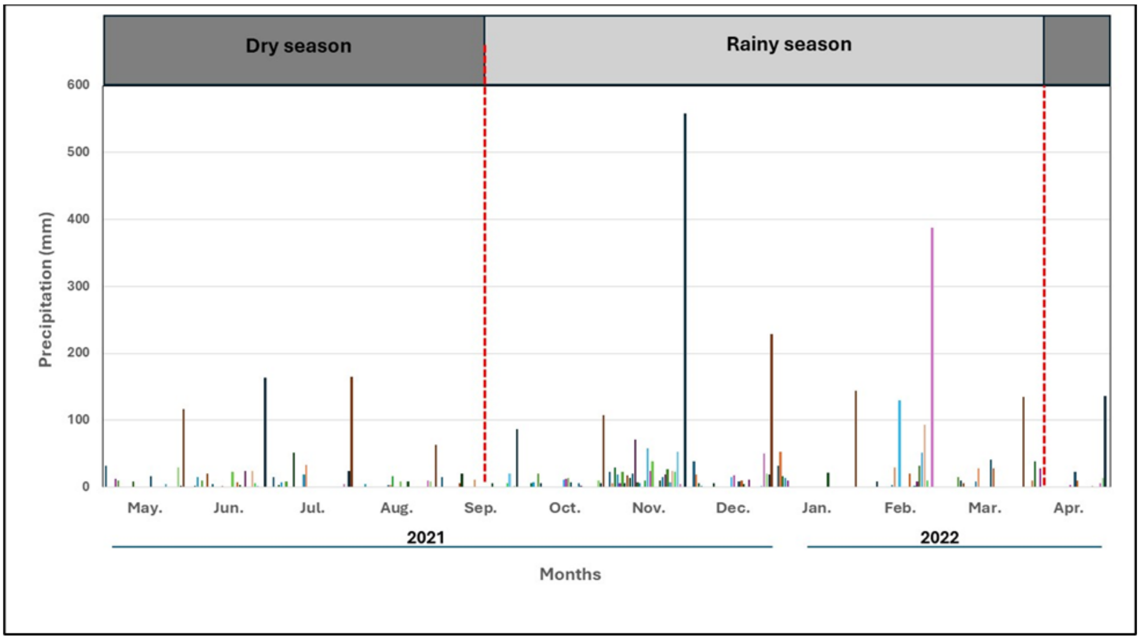

Figure 1. Daily precipitation during the experimental period (May 2021- April 2022), data from the Thai Meteorological Department at Phatthalung province station. The bar at the top of the figure indicates the difference between the seasons of the Thamod district. The dashed line indicates the division between the dry and rainy season. The image is a bar graph representing precipitation data for twelve months, from May 2021 to April 2022.

2.2 Existing rubber plantation details

The experimental site consists of rubber smallholder farms with mature rubber trees (*Hevea brasiliensis*) of varying ages. Most of the rubber trees in the study area are of the RRIM 600 clone, widely cultivated in Southern Thailand due to its high latex yield potential and adaptability to local conditions [14]. The rubber trees in the selected farms were planted between 1990 and 2010, with ages ranging from 11 to 34 years at the time of the study. The planting density of the rubber trees varies among the smallholder farms, with an average of 450 trees per hectare [15]. The typical spacing between rows is 7 meters, and the spacing within rows is 3 meters.

2.3 Experimental design

The study included three rubber intercropping systems and a monoculture control (Figure 1). Three rubber intercrop systems were selected for this study (Figure 2): (1) rubber trees with intercropped timber trees; RT (*Swiettenia macrophylla* King., *Shorea roxburghii* G.Don., and *Hopea odorata* Roxb.) (2) rubber trees with intercropped timber trees (*Swiettenia macrophylla* King., *Shorea roxburghii* G.Don. and *Hopea odorata* Roxb.) and fruits tree; RTF (*Durio zibethinus* L., *Lansium domesticum, Garcinia mangostana,* and *Nephelium lappaceum*) (3) rubber trees intercropped with timber trees (*Hopea odorata,* and *Eurycoma longifolia*), fruits trees (*Salacca zalaca)* and shrub trees; RTFS (*Gnetum gnenom*). We also studied a rubber monoculture site as a control. Rubber trees clone RRIM600 in this study sites were 20 years old and were arranged in single rows and planted at a density of 7x3 m, separated by 7 m wide interiors, such that rubber trees in all four treatments had the same density of 450 *Hevea* trees per hectare. In each model, there were differences in quantity and types of interplants grown in each model.

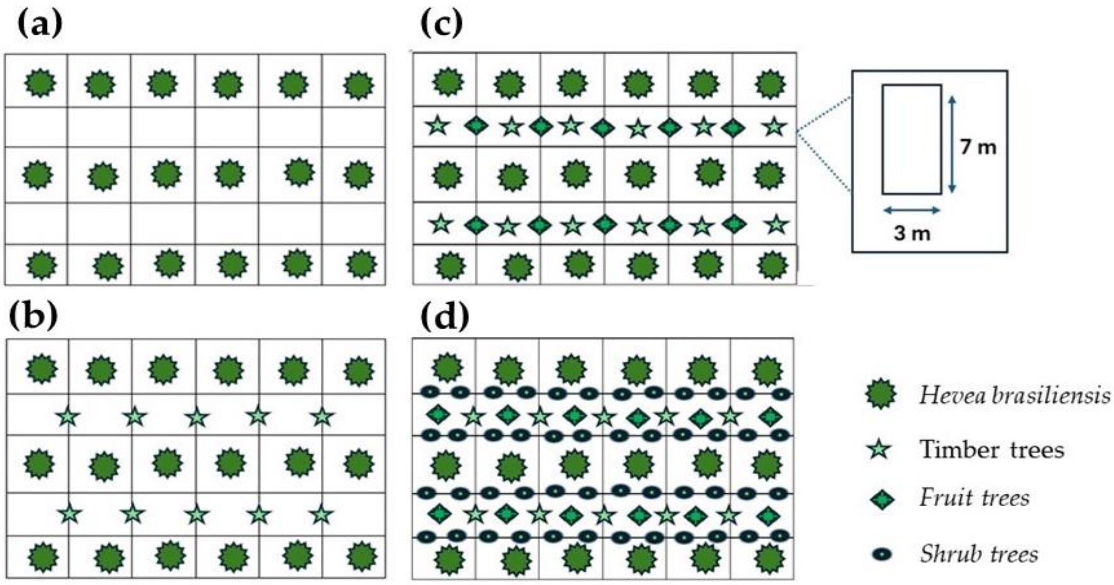

Figure 2. Provides a top view of the different rubber plantation patterns, illustrating the spatial arrangement of the rubber trees and intercrops in each treatment: (a) rubber monoculture (monocrop), (b) RT, (c) RTF, and (d) RTFS intercropping system.

2.4 Sampling and sample size

The study employed a random sampling method to select 300 rubber smallholder farmers from a population of approximately 1,112 households engaged in rubber plantations across 12 villages in the Tamod subdistrict of Phattalung Province, Thailand. The sample size was determined using Yamane's method [16] with a 95% confidence level and a 5% margin of error. This particular location was chosen due to the adherence of the rubber farms to the criteria of rubber intercropping and their exposure to Tapping Panel Dryness (TPD). A semi-structured questionnaire was utilized to gather socio-economic information, and face-to-face interviews were conducted with the farmers. Additionally, surveys and focus group analyses were employed to gain insights into the farmers' perspectives on the rubber intercropping model. Following the method of Somboonsuke and Cherdchom [17]. The sampling method for fruit trees in the intercropping systems (RTF and RTFS) was based on a systematic sampling approach, with a minimum of 10% of each plot's total fruit tree population sampled to ensure statistical significance [18].

2.5 Data collection and analysis

Data was collected from 6 rubber plantations to conduct a comparative analysis between rubber intercrop models and rubber monocrops. The analysis focused on the impact of soil moisture, temperature, humidity, and light intensity on tree growth during both the rainy and dry seasons. Soil moisture analysis was used in the Tensiometers (RainDrop, Thailand) with different lengths of cylindrical tubes viz. 30 and 60 cm, which were used to observe soil moisture tension at different depths. The tubes within the row were 1 m from the nearest tree, and the corresponding tube in the interrow was 1 m away from the tree row, opposite this tree. Each access tube was calibrated gravimetrically in situ for various soil layers in the dry and rainy seasons to assess the dry and nearly saturated soil water content accurately. Following the method of Kumar and Kumari [19]. The air temperature (°C) and the relative humidity (RH,%) of the rubber plantation were measured with a Thermo-Hygrometer (Testo 608-H1, Germany). The illuminance in the rubber plantation was measured once a week, between 9.00 -11.00 a.m. in the center of the permanent plot (approx. 1.5-1.8 m AGL), using a Digital lux meter (LX101B, China) [20].

Rubber productivity and income were collected every day. The data on interplant tree products were collected from the yield and calculated with income. The fresh latex volume per replication for each treatment was measured daily. The dry rubber content (DRC) of the latex from each treatment was measured by microwave (Toshiba, MWP-MG20P(WH) method, followed by Tillekeratne et al. [21]. Agricultural Land Economic Group followed the economic analysis of the intercropping system. That analyzed the economic returns of farmers who grow rubber cash crops in Surat Thani Province according to the suitability class of land in the production year 2021/2022 [22] and Udom et al. [23].

2.6 Statistical analysis

The experimental design employed a randomized block design, and the means were further examined using Duncan's Multiple Range Test (DMRT) analysis with a significance level of $P<0.05$. The data was analyzed using SPSS (IBM SPSS statistics 29) software.

3. Results and Discussion

3.1 The socio-economics of rubber farmer respondents and survey data

The survey conducted among rubber farmers in the Tamod subdistrict of Phatthalung province, Thailand, revealed that 79% of the plantations followed a monocropping system, while 21% practiced intercropping (Table 1). Among the intercropping models, Model 2 (rubber-timber-fruit trees) was the most prevalent at 77%, followed by Model 3 (rubber-timber-fruit-shrub trees) at 12.28%, and Model 1 (rubber-timber trees) at 10.72%. The dominance of Model 2 suggests that farmers in the study area have a higher preference for this intercropping system, possibly due to its potential benefits in terms of productivity, sustainability, or economic returns [24]. Regarding the *Hevea* clones, RRIM600 was the most widely used at 89.7%, followed by RRIT251 at 8.7% and BPM24 at 1.6% (Table 1). The widespread adoption of RRIM600 indicates its suitability to the local conditions and its popularity among farmers [25]. The tapping system 1/3S 3d/4 was the most common at 80.4%, followed by 1/3S 2d/3 at 13.3%, and 1/3S d/2 at 6.3%. The preference for lower tapping frequency suggests that farmers aim to reduce labor costs and minimize the risk of over-exploitation, which can lead to TPD [26]. Interestingly, none of the plantations in the study area used irrigation (Table 1), which could be attributed to the sufficient rainfall in the region or the lack of access to irrigation facilities. TPD was found to be a significant issue, with 88.7% of the plantations affected by this disorder. The high prevalence of TPD in the study area highlights the need for better management practices and research to mitigate this problem [26]. The use of ethephon, a rubber yield stimulant, was rare, with only 11.6% of the plantations using it (Table 1). Among the users, 88.4% applied a 0.5% concentration, while 1% used a 5% concentration. The low adoption of ethephon could be due to the lack of awareness, high costs, or concerns about its potential negative impacts on tree health and latex quality [27].

3.2 Rubber yield and quality parameters

The study revealed that intercropping systems (RT, RTF, and RTFS) generally produced higher latex yields than monocropping (Table 2). The RTFS intercropping system exhibited the highest latex yield at 1,866 kg/ha/year, followed by RTF at 1,608 kg/ha/year, RT at 1,269 kg/ha/year, and monocropping at 1,115 kg/ha/year. These findings suggest that intercropping systems, particularly RTFS, can significantly improve latex yield in rubber plantations. DRC is a crucial parameter in determining the quality and value of natural rubber [28]. The study found that the RTFS intercropping system had the highest DRC at 40.1%, followed by RTF at 37.7%, RT at 36.4%, and monocropping at 29.5% (Table 2). Higher DRC values indicate better rubber quality, representing the percentage of solid rubber in the latex after removing water and other impurities [28]. The superior DRC in the RTFS system suggests that intercropping with timber, fruit, and shrub trees can enhance latex yield and quality. Several factors can influence rubber yield and quality, including climatic conditions, soil properties, and management practices [8]. In this study, the intercropping systems demonstrated better latex yield and DRC performance than monocropping. This improvement can be attributed to the positive effects of intercropping on soil moisture retention, nutrient availability, and microclimate regulation [29]. Additionally, the lower incidence of TPD in intercropped plantations (Table 1) may have contributed to the higher latex yield and quality, as TPD affects rubber production negatively [26].

Table 1. Characteristics of rubber plantations and management practices in the study area

Characteristics	Categories	Frequency	Percentage
Rubber plantation system	Monocrop	237	79
	Intercrop	63	21
Total		300	100
Rubber intercrop model	RT[1]	11	10.72
	RTF[2]	42	77
	RTFS[3]	10	12.28
Total		63	100
Hevea clone	RRIM600	269	89.7
	RRIT251	26	8.7
	BPM24	5	1.6
Total		300	100
Tapping system	1/3S 3d/4	241	80.4
	1/3S 2d/3	40	13.3
	1/3S d/2	19	6.3
Total		300	100
Irrigation in a rubber plantation	Use	0	0
	Not use	300	100
Total		300	100
Tapping panel dryness (TPD affected trees)	Presented	266	88.7
	Absented	34	11.3
Total		300	100
Ethephon (rubber yields inducer chemical)	Use	35	11.6
	0.5%	20	
	5%	15	
	No	265	88.4
Total		300	100

Note: [1] model 1, [2] model 2, and [3] model 3

Table 2. Rubber yield parameters in different cropping systems

Cropping Systems	Latex Yields (kg/ha/year)	Dry rubber content (%DRC)
Monocrop	1,115 ± 93d	29.5 ± 0.7d
RT Intercrop	1,270 ± 87c	36.4 ± 2.1c
RTF Intercrop	1,608 ± 73b	37.7 ± 1.1b
RTFS Intercrop	1,866 ± 43a	40.1 ± 1.0a

Significant differences at $P<0.05$, different letters to show statistical significance

3.3 Fruit and shrub tree yields in intercropping systems

The RTF intercropping system, which combines rubber trees with timber and fruit trees, demonstrated significant fruit yields. The study found that *Durio zibethinus* L. had the highest yield at 809 kg/ha/year, followed by *Garcinia mangostana* at 458 kg/ha/year, *Lansium domesticum* at 92 kg/ha/year, and *Nephelium lappaceum* L. at 61 kg/ha/year (Table 3). These findings highlight the potential of the RTF system to provide additional income to rubber farmers through fruit production. The RTFS intercropping system, which integrates rubber trees with timber, fruit, and shrub trees, also showed notable yields. *Salacca zalaca*, a fruit tree, yielded 1,220 kg/ha/year, while shrub trees (yielded 803 kg/ha/year (Table 3). Including shrub trees in the RTFS system provides additional income and contributes to the intercropping system's overall biodiversity and ecological benefits [12]. Intercropping systems, such as RTF and RTFS, play a crucial role in diversifying the income sources of rubber farmers. The additional income generated from fruit and shrub tree yields can help mitigate the economic risks associated with fluctuations in rubber prices [30]. The RTF system's combined fruit yield of 1,420 kg/ha/year (Table 3) can provide a significant supplementary income to rubber farmers. Similarly, the RTFS system, with its salak fruit yield of 1,220 kg/ha/year and shrub tree as a *Gnetum gnenom* yield of 803 kg/ha/year (Table 3), offers an opportunity for farmers to enhance their income stability and resilience [6].

Table 3. Fruit yield parameters in different intercropping systems

Fruit Species	Monocrop	RT Intercrop	RTF Intercrop	RTFS Intercrop
Durian (*Durio zibethinus* L.)	-	-	809±53	-
Longkong (*Lansium domesticum*)	-	-	92±39	-
Mangosteen (*Garcinia mangostana*)	-	-	458±69	-
Rambutan (*Nephelium lappaceum* L.)	-	-	61±10	-
Salak (*Salacca zalaca*)	-	-	-	1,220±79
Shrub tree (*Gnetum gnenom*)	-	-	-	803±63

Note: Values are means ± standard deviations, expressed in kg/ha/year. Icon - means no data.

3.4 Soil and environmental parameters

The study found notable differences in temperature among the various cropping systems. The RTFS intercropping system had the lowest average temperature at 30.5°C, followed by the RTF system at 32.0°C, the RT system at 32.2°C, and the monocropping system at 33.1°C (Table 4). These temperature variations can be attributed to the different levels of shading and microclimate regulation provided by the intercropping systems [31]. Lower temperatures in the RTFS system may reduce heat stress and improve plant growth [31]. Relative humidity also varied significantly among the cropping systems. The RTFS system had the highest average humidity at 68.8%, followed by the RTF system at 64.8%, the RT system at 62.4%, and the monocropping system at 61.4% (Table 4). The higher humidity levels in the intercropping systems can be attributed to the increased vegetation cover and reduced evaporation [32]. Improved humidity levels can help maintain soil moisture and create a more favorable microclimate for plant growth [33]. Light intensity differed considerably among the cropping systems. The monocropping system had the highest light intensity at 28,901 lux, followed by the RT system at 4,235 lux, the RTF system at 4,032 lux, and the RTFS system at 2,955 lux (Table 4). The lower light intensity in the intercropping systems can be attributed to the shading effect of the additional trees [34]. While reduced light intensity may limit photosynthesis, it can also help protect plants from excessive heat and water loss [35]. Soil moisture tension, an indicator of soil water availability, varied among the cropping systems at different depths. At a depth of 30 cm, the RTFS system had the least negative soil moisture tension at -5.7 kPa, followed by the RTF system at -7.7 kPa, the RT system at -10.9 kPa, and the monocropping system at -45.4 kPa (Table 4). A similar trend was observed at a depth of 50 cm. The less negative soil moisture tension values in the intercropping systems indicate better soil moisture retention, which can benefit plant growth and reduce irrigation requirements [36].

Table 4. Temperature and humidity in different rubber intercropping models

Model	Average Temperature (°C)	Average Humidity (%)	Light intensity (lux)	Soil moisture tension (kPa)	
				Depth 30 cm	Depth 50 cm
Monocrop	33.1 ± 0.8a	61.4 ± 3.5c	28,901 ± 2400a	-45.4 ± 13a	-19.0 ± 12.9a
RT Intercrop	32.2 ± 1.1b	62.4 ± 5.2c	4,235 ± 1515b	-10.9 ± 1.0b	-17.8 ± 1.2b
RTF Intercrop	32.0 ± 1.0b	64.8 ± 4.9b	4,032 ± 1053c	-7.72 ± 3.8c	-6.6 ± 3.6c
RTFS Intercrop	30.5 ± 0.9c	68.8 ± 4.8a	2,955 ± 872d	-5.70 ± 3.7d	-5.3 ± 4.5d

Significant differences at $P<0.05$, different letters to show statistical significance

3.5 Economic analysis of the intercropping system

The economic analysis revealed significant revenue and net profit differences among the cropping systems. The RTF intercropping system generated the highest total revenue at 7,674 USD/ha/year, followed by the RTFS system at 5,544 USD/ha/year, the RT system at 2,784 USD/ha/year, and the monocropping system at 2,397 USD/ha/year (Table 5). The net profit followed a similar trend, with the RTF system achieving the highest net profit at 4,892 USD/ha/year, followed by the RTFS system at 3,282 USD/ha/year, the RT system at 1,000 USD/ha/year, and the monocropping system at 941 USD/ha/year. These findings highlight the economic benefits of intercropping systems, particularly the RTF system, in enhancing the profitability of rubber plantations [12]. The benefit-cost ratio (BCR) and return on investment (ROI) are essential indicators of the economic viability of the cropping systems. The RTF system had the highest BCR at 2.75, followed by the RTFS system at 2.45, the monocropping system at 1.64, and the RT system at 1.56 (Table 6). Similarly, the RTF system had the highest ROI at 176%, followed by the RTFS system at 145%, the monocropping system at 65%, and the RT system at 56%. The higher BCR and ROI values in the RTF and RTFS systems demonstrate their superior economic performance compared to the monocropping and RT systems. A sensitivity analysis was conducted to assess the robustness of the cropping systems' net profits under different scenarios. Three scenarios were evaluated: a 10% decrease in revenue, a 10% increase in costs, and a combination of both. The RTF system maintained the highest net profit across all scenarios, ranging from 3,846 USD/ha/year to 4,613 USD/ha/year. The RTFS system had the second-highest net profit, followed by the RT and monocropping systems. The sensitivity analysis demonstrates the resilience of the RTF and RTFS systems in maintaining profitability even under adverse economic conditions [30]. Crop diversification through intercropping provides numerous financial benefits to rubber farmers. The additional income generated from the sale of timber, fruits, and shrub products in the RTF and RTFS systems can help mitigate the impact of fluctuations in rubber prices [37]. Furthermore, intercropping can improve cash flow during the immature phase of rubber trees, as the income from intercrops can offset the establishment and maintenance costs. Diversification also reduces the financial risk associated with monoculture systems, as farmers can rely on multiple income sources [38].

Table 5. Annual revenue and costs of different rubber intercropping models from 2021 to 2023

Model	**Rubber Revenue** (USD/ha/year)	**Intercrop Revenue** (USD/ha/year)	**Total Revenue** (USD/ha/year)	**Production Costs** (USD/ha/year)	**Net Profit** (USD/ha/year)
Monocrop	2,397	-	2,397	1,456	941
RT Intercrop	2,729	-	2,784	1,783	1,000
RTF Intercrop	3,457	4,217	7,674	2,782	4,892
RTFS Intercrp	4,013	1,532	5,544	2,262	3,282

Table 6. Benefit-cost ratio (BCR) and return on investment (ROI) of different rubber intercropping models

Model	**BCR**	**ROI (%)**
Monocrop	1.64	65
RT Intercrop	1.56	56
RTF Intercrop	2.75	176
RTFS Intercrop	2.45	145

3.6 Challenges and opportunities for sustainable rubber production

Rubber monocropping systems face several limitations that hinder their sustainability and resilience. Monocultures are more susceptible to price fluctuations, as farmers rely on a single commodity for their income. Additionally, monocultures can lead to soil degradation, reduced biodiversity, and increased vulnerability to pests and diseases [39]. To overcome these limitations, farmers can adopt intercropping systems that diversify their income sources, improve soil health, and enhance ecosystem service. Intercropping systems, such as the RTF and RTFS models, offer a promising approach to promoting sustainable livelihoods for rubber farmers. By integrating timber, fruit, and shrub trees into rubber plantations, farmers can diversify their income, reduce dependence on a single crop, and enhance their resilience to market fluctuations [40]. Intercropping can also contribute to food security, as farmers can harvest fruits and other products for consumption or sale in local markets. Moreover, intercropping systems can provide ecosystem services, such as carbon sequestration, soil conservation, and biodiversity conservation, which contribute to the overall sustainability of the farming system [41]. Farmers may face challenges adopting these practices despite the numerous benefits of intercropping systems. One major challenge is the lack of technical knowledge and skills to manage complex intercropping systems. Farmers need training and extension services to learn about appropriate tree species selection, planting arrangements, and management practices [42]. Another challenge is the initial investment costs associated with establishing intercropping systems, as farmers must purchase seedlings and allocate land for intercrops [43]. Access to credit and financial support mechanisms can help farmers overcome these initial investment barriers. Policymakers can implement various measures to support sustainable rubber production through intercropping systems. First, providing targeted extension services and capacity-building programs can help farmers acquire the necessary knowledge and skills to adopt intercropping practices [44]. Second, establishing financial incentives, such as subsidies or low-interest loans, can encourage farmers to invest in intercropping systems. Third, promoting market linkages and value chain development can help farmers access profitable markets for their intercrop products. Finally, integrating intercropping systems into national and regional agriculture policies can create an enabling environment for sustainable rubber production [45].

3.7 Implications for Smallholder Rubber Farmers

Intercropping systems offer smallholder rubber farmers a viable strategy to enhance their income stability through diversification. By incorporating timber, fruit, and shrub trees into their rubber plantations, farmers can generate additional income streams that complement their rubber production [6]. The average annual income from intercropping in the RTF system was 4,217 USD/ha/year, while in the RTFS system, it was 1,532 USD/ha/year (Table 4). This additional income can help buffer farmers against volatile rubber prices and provide a more stable financial foundation. Adopting intercropping systems can improve soil health and environmental sustainability in rubber plantations. Intercropping can help reduce soil erosion, improve soil fertility, and increase soil organic matter content [46]. The study found that the RTFS system had the least negative soil moisture tension at -5.70 kPa and -5.30 kPa at 30 cm and 50 cm depths, respectively (Table 4), indicating better soil moisture retention. Furthermore, intercropping can enhance biodiversity, provide habitat for beneficial organisms, and promote ecosystem services [47]. Intercropping systems can help build the resilience of smallholder rubber farmers against market fluctuations and climate change. Diversifying income sources through intercropping can reduce farmers' vulnerability to price shocks and market uncertainties. Moreover, intercropping can improve the adaptive capacity of rubber plantations to climate change by moderating temperature, humidity, and light intensity. The study found that the RTFS system had the lowest average temperature (30.5°C), highest humidity (68.8%), and lowest light intensity (2,955 lux) (Table 3), indicating a more favorable microclimate for plant growth [48]. Adopting sustainable practices, such as intercropping, can empower smallholder rubber farmers by improving their livelihoods, enhancing their decision-making power, and promoting active participation in the value chain. Intercropping systems can also foster social capital and knowledge sharing among farmers as they collaborate and learn from each other's experiences. Empowered smallholder farmers are more likely to invest in sustainable practices, adopt new technologies, and engage in collective action to address common challenges [46].

3.8 Limitations and Future Research Directions

While this study provides valuable insights into the benefits of rubber intercropping systems, it has some limitations. First, the study was conducted in a specific location (Tamod subdistrict, Phatthalung province, Thailand). It may not represent other rubber-growing regions' diverse agroecological conditions and socio-economic contexts [17]. Second, the study focused on a limited number of intercropping models (RT, RTF, and RTFS) and did not explore other potential combinations of crops and management practices. Third, the economic analysis was based on current market prices and did not account for potential price fluctuations or government policy changes that may affect the profitability of intercropping systems [46]. Future research should consider the following recommendations to address the current study's limitations and advance the knowledge on sustainable rubber production. First, conducting similar studies in different rubber-growing regions with diverse agroecological and socio-economic conditions can help validate the findings and identify context-specific challenges and opportunities [49]. Second, exploring a wider range of intercropping models, including novel combinations of crops and management practices, can provide farmers with more options to suit their specific needs and preferences [50]. Third, long-term studies that monitor the performance of intercropping systems over multiple years can help assess their sustainability and resilience to climate change and market fluctuations [51]. Several potential areas for further investigation can be identified based on the findings of this study. First, assessing the ecosystem services provided by rubber intercropping systems, such as carbon sequestration, biodiversity conservation, and water regulation, can help quantify their environmental benefits and support the development of payment for ecosystem services (PES) schemes [52]. Second, investigating the social and cultural aspects of intercropping adoption, including farmers' knowledge, attitudes, and practices, can help identify the barriers and enablers of sustainable rubber production [53]. Third, analyzing intercropping products' value chain and market potential, such as timber, fruits, and shrubs, can help identify opportunities for value addition and income generation for smallholder farmers [54].

4. Conclusions

This study investigated the impact of different rubber intercropping systems on productivity, income, and environmental factors compared to rubber monocropping in the Tamod subdistrict of Phatthalung province, Thailand. The results demonstrated that intercropping systems, particularly the RTFS model (rubber-timber-fruit-shrub), outperformed monocropping in terms of latex yield, dry rubber content, fruit and shrub yields, and economic returns. The RTFS system also exhibited better environmental conditions, such as lower temperature, higher humidity, lower light intensity, and improved soil moisture retention, compared to other cropping systems. The economic analysis revealed that the RTF (rubber-timber-fruit) and RTFS intercropping systems had higher total revenue, net profit, benefit-cost ratio, and return on investment than the monocropping and RT (rubber-timber) systems. The sensitivity analysis further confirmed the resilience of the RTF and RTFS systems in maintaining profitability under various scenarios of changes in revenue and costs. Adopting intercropping systems can benefit smallholder rubber farmers, including income diversification, improved soil health, enhanced resilience to market fluctuations and climate change, and empowerment through sustainable practices. However, challenges such as lack of technical knowledge, initial investment costs, and the need for supportive policies and extension services must be addressed to promote the widespread adoption of rubber intercropping. Future research should validate these findings in different agroecological and socio-economic contexts, explore various intercropping models, and investigate these systems' long-term sustainability and resilience. Additionally, assessing the ecosystem services, social and cultural aspects, and value chain potential of rubber intercropping can provide valuable insights for developing sustainable rubber production strategies. This study highlights the potential of rubber intercropping systems, particularly the RTFS model, as a viable approach to enhance the productivity, profitability, and sustainability of smallholder rubber farming in Thailand. Promoting the adoption of these systems through targeted policies, extension services, and research can improve rural livelihoods and the environmental sustainability of the rubber sector.

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