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Role of Rubber-based Intercropping in Ensuring Sustainable Natural Rubber Production of Smallholders

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Abstract

Hevea brasiliensis has been traditionally grown as a monocrop in tropical equatorial climate regions to supply the global demand for natural rubber. The tremendous expansion of monocrop rubber plantations in mainland Southeast Asian countries in the 2000s has resulted in significant adverse environmental impacts, such as deforestation, soil erosion, local climate change, greenhouse gas and carbon dioxide emissions, and loss of natural resources. With the large involvement of smallholders, social-economic issues associated with the weakening of rubber prices, consequently low income, narrowing of income sources, raising the cost of production, and the shortage of workers have been generated as significant concerns to the sustainability of the natural rubber industry. As the nature of conventional rubber planting systems, large inter-row spaces between rubber trees are technically viable for adopting rubber-based intercropping and agroforestry systems, contributing to ecological and economic sustainability. In general, intercrops in rubber farms could be categorized into three groups: initial intercrops, permanent intercrops, and cover crops. Intercrops improve the growth and height of the young rubber plants and result in higher tappability per hectare of rubber, ensuring that a higher yield could be harvested. Rubber intercropping significantly enhances soil moisture, root density and distribution, and soil microbial activities. High carbon content in the soil, rich mulch litters, and lower soil erosion in rubber intercropping reduce greenhouse gas emissions. Rubber-based intercropping benefits the farmers mainly with respect to their incomes and resilience. Despite this, they have faced some constraints in adopting rubber-based intercropping systems and achieving the sustainability benefits of the systems. Thus, interventions with promoting intercropping schemes in supporting initial investments, transferring technologies, providing high-yield cultivars and other inputs, and creating potential markets for intercrops are suggested. Promoting the development of smallholders' rubber production through adopting rubber-based intercropping ensures agroecosystem, economic, and social improvements in the smallholder sector and could revitalize the sustainability of the natural rubber industry.
Keywords: *Hevea brasiliensis*, Rubber-based intercropping, Smallholder, Sustainable natural rubber

Introduction

Hevea brasiliensis has been traditionally grown as a monocrop in tropical equatorial climate regions since the early 1900s to supply the global demand for natural rubber. With the development of rubber technology and consumption, the traditional growing area gradually increased and became saturated. It covered a large region where most of Indonesia, Malaysia, southern Thailand, southern Myanmar, southern India, Sri Lanka, and some parts of Cambodia and Vietnam were included, except the dry areas in the region (Vijayakumar *et al*., 2000). However, the growth of the Chinese economy in the early 2000s led to a significant increase in demand for natural rubber (ERIA, 2016), which in turn resulted in a massive expansion of rubber growing areas in mainland Southeast Asian countries, namely northern Myanmar, north-eastern Thailand, Laos, Cambodia, Vietnam and South-western China (Li *et al*., 2008; Ahrends *et al*., 2015). According to Chen *et al* (2023), the rubber growing area in the countries escalated from 2.1 million hectares in 1990 to 6.7 million hectares in 2019.

Many studies have reported that the tremendous expansion of rubber monocropping has resulted in significant adverse environmental impacts, such as deforestation, soil erosion, local climate change, greenhouse gas and carbon dioxide emissions, and the loss of natural resources, including carbon stocks and biodiversity (Zhang *et al*., 2007, Ziegler *et al*., 2009; Umami *et al*., 2019; Vrignon-Brenas *et al*., 2019). Besides, due to the large participation of smallholders by monocropping in rubber-growing countries and their high dependency on rubber income, socio-economic issues associated with the weakening of rubber prices, consequently, low income, narrowing of income sources, raising the cost of production, and shortage of workers (Fu *et al*., 2010; Fox and Castella, 2013; Xu *et al*., 2014) have been generated as big concerns to the sustainability of the natural rubber industry.

However, natural rubber production following good agricultural practices with social and environmental responsibilities has technically delivered positive effects on economic return as well as ecological and social advantages. With realizing these scenarios, some concerned governmental institutes, international organizations, and international natural rubber buyers in natural rubber supply chain have committed to sourcing raw natural rubber produced in sustainable ways without degrading the environment and ecosystem in order to reduce the impacts and develop sustainability in natural rubber production (IRSG, 2014).

As the nature of conventional rubber planting systems, large inter-row spaces between rubber trees are a suitable structural environment for intercropping to seek additional on-farm income for the smallholders. With instability of rubber prices in the last two decades, some rubber farmers started converting to rubber-based intercropping systems from the conventional monocropping practices to widen the on-farm income sources and increase land productivity (Romyen *et al*., 2017; Hougni *et al*., 2018). It has been reported in many studies that rubber-based intercropping delivered ecological and economic benefits such as improvements in soil and microclimate conditions and land productivity, reduction in carbon emission and biodiversity loss, and increased incomes and resilient level of farmers (Werner *et al*., 2006; Zhang *et al*., 2007; Elmholt *et al*., 2008; Guardiola-Claramonte *et al*., 2008; Tan *et al*., 2011; Chen *et al*., 2019). This article explores the historical background, current practices, benefits, and constraints of rubber-based intercropping in smallholder natural rubber production.

1. *Development of rubber-based intercropping*

Since *Hevea* rubber (*Hevea brasilienisis*) is originally a forest tree and naturally thrives together with other trees in its origin, the Amazonian rain forest, its inherent nature is adaptable to growing alongside other plants (Wycherley, 1992; Budiman and Penot, 1997). When it was first introduced into Sri Lanka in the late 1870s, it was intended to be planted as an intercrop in perennial plantations such as tea and cocoa before its commercial cultivations, which were started in the East Asia countries around the 1900s (Rodrigo *et al*., 2005). Then, in the 1890s, due to the outbreak of coffee leaf rust disease in Ceylon and Malaya, *Hevea* rubber was started to plant by coffee growers for alternative sources of income (Thomas and Panikkar, 2000).

At the beginning of natural rubber cultivation development, however, the majority of rubber production was supplied by commercial estates owned monocropping plantations. Munro *et al*. (1981) reported that natural rubber production in 1914 was dominated by large monocropping plantations, accounting for 60% of the world's supply while the remaining came from wild sources and smallholders. Later, the development of plantation management such as planting, field-upkeeping, harvesting, and processing methods and high market prices attracted the involvement of smallholders in rubber production, resulting in wider diversification of holding sizes. Consequently, before the Second World War, rubber production by smallholders reached 50% of the world supply (Byerlee, 2014). Although increasing the production of smallholders, their productivity, quality, and land use efficiency were not improved. Thus, after the war, China, India, Malaysia, Sri Lanka, Thailand, and Indonesia started implementing smallholder development programs in which high-yield planting materials, technical supports, and subsidies were provided (Budiman and Penot, 1997; Fox and Castella, 2013). As a result, smallholders could supply a higher share of rubber production in the major rubber producing countries as a key industry player and have become unneglectable.

However, these programs only aimed at increasing the production amount of rubber, resulting in smallholders being driven into monocropping rubber growing (Budiman and Penot, 1997). Most smallholders faced an income gap during the long immature period of around seven years because they could not practice replanting cycle due to limited land availability (Laosuwan, 1996; Herath and Takeya, 2002). Since they depended only on the monocropping of rubber, the source of income generation was narrow; consequently, they were hard to survive, especially when rubber prices declined. Besides the long immature period without any income, unstable employment and uneven distribution of tapping days due to erratic weather were also inevitable issues impacting to livelihoods of the smallholders (Jayasena and Herath, 1986; Lin, 2011).

Realizing these issues, intercropping in rubber planting were promoted in major rubber-producing countries to diversify and maximize the on-farm incomes of the farmers. In 1957, India initiated a replanting subsidy scheme that also supported intercropping in rubber farms in Kerala to ensure food security, income generation, and employment opportunities (Siju *et al*., 2012). In China, rubber-based intercropping was strongly encouraged during the 1970s and 1980s as a means to generate additional income for farmers and mitigate the negative effects of typhoon damage on rubber trees (Zhou, 2000). It was reported that in Sri Lanka, rubber-based intercropping was first recommended for smallholders in 1979 (Chandrasekera, 1979). Then, many farmers adopted intercropping, and in the early 2000s, 50% of the smallholders had planted intercrops in immature stage of rubber farms (Rodrigo *et al*., 2001). In Malaysia, during the Japanese occupation in the 1940s, rubber smallholders and planters started planting food crops in rubber interrows to address food shortages (RRIM, 2009). In Indonesia, jungle rubber agroforestry has been practiced traditionally since rubber planting began around the 1920s and had covered over 2.5 million hectares in 1997 (Budiman and Penot, 1997). There were some on-farm activities of the combinations of rubber with fruit crops and livestock observed in Thailand in the 1980s (Somboonsuke and Wettayaprasit, 2013). Despite this, rubber intercropping has not yet been widely adopted, and it was estimated that only about 2 percent of smallholder rubber farmers practiced intercropping in the southern Thailand (Romyen *et al*., 2017).

2. Practices of rubber-based Intercropping

Smallholders practice rubber-based intercropping with various objectives. In general, based on the objectives, intercrops could be categorized into three groups: initial intercrops, permanent intercrops, cover crops (Table 1) (Langenberger *et al*., 2017). Available holding size, local market demand and price of intercrops, available family labour, and irrigation facilities were also major limiting factors to be considered in selecting the intercrops. According to the vegetative development nature of the selected intercrop and resource availability of the farmers, farming practices of the intercropping, such as establishing year, planting density, etc., are diverse (Table 1).

In most rubber intercropping systems, annual and short-term crops like upland rice, banana, pineapple, watermelon, maize, lemon grass, pea, mung bean, etc., are planted in the inter-row space with the normal rubber planting density in the early years after rubber planting due to their requirement of full sunlight (Figure 1a) (Laosuwan, 1996; Langenberger *et al*., 2017). Introducing initial intercrops during the immature period of rubber growth not only generates on-farm income but also optimizes land utilization and significantly reduces costs for fertilization and weed control (Vandermeer, 1992). However, wider shade from rubber trees at the end of the immature period reduced the yield and growth of the intercrops (Rodrigo, 2001). Permanent intercrops are grown to widen the source of income for long-term prospects, diversify crops to reduce the risk of depending on a single crop, and optimize land utilization. Horticulture, perennial and shade tolerant crops such as areca palm, coffee, tea, cocoa, cardamom, bamboo, pepper, salacca, ferns, ginger, turmeric, yam, etc. are mostly planted (Figure 1b) (Langenberger *et al*., 2017) at normal or wider interspace with double-hedge rubber rows planting design (Figure 1c). Cover crop is rarely used in smallholdings but in most plantations to control soil erosion, increase soil fertility and properties, the growth of rubber trees, and reduce the cost of weeding and fertilizer. It is planted at interspaces between rubber rows during the establishment and initial years of rubber plantation. Most planted leguminous cover crops are *calopogonium caeruleum, centrosema pubescens, pueraria phaseoloides,* and *muccuna bracteate* (Figure 1d) (Punnoose *et al*., 2000).

Table 1 Summary of common rubber-based intercropping practices

Rubber-based intercropping practices		Initial intercrops	Permanent intercrops			Cover crops
		annual/short-term crops	herb crops	fruit crops	timber crops	leguminous crops
Objectives of intercropping by rubber smallholders	to achieve income during the immature rubber period	✓	-	-	-	-
	to reduce the risk from depending on a single crop, and widen the source of income	✓	✓	✓	✓	-
	to maximize land utilization	✓	✓	✓	✓	-
	to increase growth of rubber	✓	-	-	-	✓
	to reduce cost of weeding and fertilizer	✓	-	-	-	✓
Associated crops		banana, pineapple, papaya, lemon grass, watermelon, eggplant, upland rice, pulses and beans, maize, sugar cane, cucumber, betel, cassava, sweet potato, etc.	ginger, turmeric, yam, cinnamon, cardamom, ferns, black pepper, etc.	coffee, tea, cocoa, salacca, areca-nut palm, rambutan, mangosteen, etc.	bamboo, acacia mangium, ironwood, rosewood, mahogany, teak, etc.	*calopogonium caeruleum, centrosema pubescens, pueraria phaseoloides, muccuna bracteate,* etc.
Establishing time of the intercrops		1st year of rubber planting	after 3 to 4 years of rubber planting			1st year of rubber planting
Planting pacing of rubber		normal spacing	normal spacing	normal, wide spacing (double rows of rubber tree)	normal, wide spacing (double rows of rubber tree)	normal spacing

Figure 1 First-year rubber plants intercropped with pineapple (a), mature rubber trees associated with cocoa intercrop (b), double-hedge rubber rows planting (c), and leguminous cover crops in the interrow space of immature rubber trees (d).

When rubber associates with the initial intercrops, resource partitioning is main consideration according to natures of rubber and the intercrops such as rooting system, shade adaptation, vegetative growth, harvested portion of the crops to reduce competition effects between the crops. In order to mitigate the competition effect, Punnoose *et al*. (2000) suggested that there should be sufficient distance between the intercrop strips and rubber rows, and if annual intercrops are grown repeatedly, planting density of the intercrop is recommended to reduce progressively in every subsequent planting. In young rubber associated with root crops like tapioca, sweet potato, etc., the intercrop was recommended to be planted two meters away from the rubber plants. The roots of the tapioca need to be confined to prevent the root invading to rubber roots (Somboonsuke and Wettayaprasit, 2013).

In permanent intercropping, the planting density of rubber is usually reduced to about 400 trees per hectare (RRIM, 2009) from the standard density of over 500 trees per hectare, particularly in perennial fruit and timber crops. The inter-rows of rubber are wider and arranged in double or triple hedge designs with triangular spacing (Figure 1d). However, Pathiratna and Edirisinghe (2004) reported that reducing the planting density could reduce the cumulative yield of rubber per area. It was found that east-west direction of rubber rows planting for intercropping could reduce the light competition between the two crops, but it was effective until about four to five years age of rubber trees under standard planting density regarding the yield of the intercrop (Pathiratna, 2006). In combination of rubber with shade-required herbs like ginger, turmeric and some herbs, the herbs are started to plant after three-four years of rubber planting in the middle of the interspace between the rubber rows (Table 1). Forest and timber trees such as mahogany, ironwood, acacia mangium and rosewood, etc. are also grown with rubber as permanent intercrops in wider interspace of rubber (Langenberger *et al*., 2017).

Rather than resource partitioning to mitigate the competition effects between the crops, facilitative complements among the above- and under-ground components in the intercropping system, especially in permanent intercropping, are an important consideration to ensure the ecological advantages together with the healthy physiological status of the crops and vegetative growth, and sustainable crop yields for long-term economic benefits (Zaw *et al*., 2022). In this type of intercropping, rubber and intercrops are complementary and interdependent, improving environmental conditions for their vegetative development (Bybee-Finley and Matthew, 2018). In combination with rubber and coffee, the shade of mature rubber benefits the coffee with less environmental pressure and greater photosynthetic performance (Araujo *et al*., 2016). Typically, the establishment of shade-grown Robusta (*Coffeea canephora*) is recommended when rubber reaches about the age of four years (Table 1), and the density of the coffee is around 450 plants per hectare (RRII, 1995). Zaw *et al*. (2023) observed that most shade-tolerant tropical palms, usually found in rubber growing areas, also could exhibit adaptive acclimatization to the understorey environment of rubber farms through morpho-physiological traits as a complementary result, leading to sustainable benefits to the agroecosystem.

3. Benefits of rubber-based intercropping

Generally, in an intercropping system, yields and growth rates of both crops could be improved when there is a complementary effect between the crops (Mousavi and Eskandari, 2011). A series of studies also confirmed that annual or short-term crops such as banana, sugarcane, pineapple, capsicum, and seasonal crops could improve the growth and height of young rubber plants with proper planting density (Rosyid *et al*., 1997; Rodrigo *et al*., 2005). A study by Rodrigo *et al*. (2005) showed that the immature period of rubber intercropped with banana was four months less, and the girth incremental rate of rubber trees was higher than those of rubber monocropping. In rubber-tea intercropping, latex harvesting could be started one year earlier than conventional rubber farms (Guo *et al*., 2006). With improved girth and height, and higher stands per hectare of rubber in the rubber-based intercropping system, it could be expected that not only a higher latex yield but also a larger volume of rubber wood per hectare at the end of the rubber economic lifespan, consequently a higher income to the farmers. In immature rubber intercropping associated with a high density of bananas, the yield of bananas increased by 25% compared to a low density of bananas in the first and second years, and it compensated for yield reduction in subsequent years (Rodrigo *et al*., 2001). According to a study by Guo *et al*. (2006), the rubber-tea combination resulted in a higher land use efficiency with a higher land equivalent ratio (LER) than those of monocultures. He also observed that permanent intercrops planting at wider rubber inter-rows with double hedge rubber rows spacing and standard rubber stands per hectare yielded a higher LER. By growing intercrops in the interspace of immature rubber plants as a crop intensification, activities for weed control, which is one of the highest costs in rubber upkeeping stage, are reduced significantly. With less weed growth, available resources such as nutrients, water, and light can be consumed efficiently by the planted crops, leading to improvement in the growth and yield of the crops. In multi-story rubber intercropping, efficient light distribution through rubber canopies allows greater light energy capture by under-shade crops. It creates an improved microclimate environment that enables the crops adapt to extreme weather changes. The shade from rubber trees lessened the environmental pressure on the coffee plants and incidences of Cercosporiosis in coffee leaves, and the coffee grains were larger with higher organoleptic quality. However, the yield of coffee under rubber trees was less than that of the sole coffee planted under full sun. (Araujo *et al*., 2016).

The better microclimate condition under the rubber-based intercropping system improves agroecosystem functions. It was observed that the system improves soil properties, root proliferation, and organic matter (Carson *et al*., 2014; Zaw *et al*., 2022). Chen *et al*. (2019) observed that intercropping with rubber trees improved soil physical properties and structure due to increased leaf litter production of overstory development in the above-ground environment. He reported also that rubber-intercropping significantly improved soil moisture in the dry season because of its moisture holding capacity of capillary porosity in the average soil depth. Sufficient intakes of soil moisture by plant impart the translocation of nutrient and mineral assimilates (Deng *et al*., 1990; Kudoyarova *et al*., 2015). The presence of significant soil moisture remaining in rubber intercropping could maintain functional tree physiological conditions and reduce water shortage consequences while rubber monoculture has a higher evapotranspiration rate, resulting in water deficits during the dry season. Since soil water content and plant water use efficiency are mutually related with plant's growth and productivity, the water cycle in the system became efficient, ensuring the healthy physiological status of the crops (Guardiola-Claramonte *et al*., 2008; Tan *et al*., 2011). Under rubber intercropping, improved root development in density and distribution contributed to soil aggregate stability, hydraulic conductivity, and infiltration, which improve the air and water exchanges in the soil, thus increasing organic carbon content with soil microbial activities (Elmholt *et al*., 2008; Chen *et al*., 2017; Chen *et al*., 2019).

These improvements consequently ensure efficient nutrient uptakes and decrease attacks of soil pathogens on the crops (Bybee-Finley and Matthew, 2018). A study by Chen *et al*. (2019) found significant increases in total carbon, nitrogen, and phosphorus in the average soil depth under rubber-based intercropping. Agroforestry system, like rubber-based intercropping, maintains high nutrient content by increasing natural inputs from biomass and vegetative litter (Carson *et al*., 2014) and reducing nutrient leaching (Bergeron *et al*., 2011) and soil erosion (Lei *et al*., 2021). Thus, it also enhances carbon sequestration, thus leading to a reduction in carbon dioxide and greenhouse gas emissions (Zhang *et al*., 2007; Kumara *et al*., 2016).

Rubber-based intercropping benefits farmers mainly with respect to their income and resilient levels as direct impacts on their livelihoods. A study by Cherdehom *et al*. (2002) conducted in southern Thailand found that all rubber intercropping systems, including rubber with livestock, resulted in higher economic performances, such as net farm income, return to fixed cost, and variable cost, and gross margin, than the performances of rubber monocropping. The study also reported that excellent farm efficiency, which indicates the utilization of available resources within the farm, was significant in rubber intercropping with fruit crops and rubber-integrated farming systems. Also, farmers' resilience to price fluctuations and climate change is higher in rubber-based intercropping through crop diversification. High resilience of a farm is strategically imparted by the economic flexibility, influenced by some factors such as density and cultivar of intercrops, harvesting practices, agricultural management, and range of knowledge on diverse crops. Jongrungrot and Thungwa (2014) indicated that rubber-timber intercropping with low operational costs could support farmers as a reserved source of extra on-farm income when rubber prices decrease and labour wages become high.

4. Constraints in smallholders' rubber-based intercropping

Although rubber-based intercropping delivers many benefits in terms of agroecosystems, including the livelihood of rubber farmers, there are some adverse effects and limitations on the ground conditions.

Certain combinations of rubber intercropping have been observed to result in reduced yields of both intercrops and rubber. Increased shading effects and reduced light transmission rates by the age of rubber trees are the main limiting factors for the short-term associated crops' yields (Laosuwan, 1996). In a report by Rodrigo *et al*. (2001), the yields of bananas planted with immature rubber were unstable and declined in the later years of the rubber immature period. Also, some studies found that the yield of coffee under mature rubber trees was not comparable to that of coffee monoculture at full sun (Araujo *et al*., 2016; Wintgens, 2004). The associated crops such as coffee and cocoa have similar root systems to rubber, which can lead to competition for water and nutrients in high-density plantations (Newman, 1985). Certain root-harvested crops like cassava were found to inhibit the growth of rubber roots. In addition, the residues from the harvested cassava roots induced soil-borne pathogens in rubber roots (Blencowe, 1989). As the nature of rubber intercropping has greater diversification and high complexity, it could be managed efficiently by farmers who have considerable skills and wise knowledge in diverse agriculture management. Intercropping requires integrating various kinds of knowledge (Bybee-Finley and Matthew, 2018) and technical management, such as selecting cultivars, planting spacing, upkeeping, pruning, fertilization, disease control, and harvesting, etc. (Guo et al., 2006). These requirements could be one of the constraints as most rubber smallholders have narrow knowledge and experience only on conventional rubber monocropping practices. Somboonsuke and Wettayaprasit (2013) noted that most rubber smallholders were unable to adopt advanced agricultural practices and innovations. Romyen *et al*. (2017) also reported that the main reasons that farmers were reluctant to implement the rubber-intercropping system were their misunderstanding of the system and bad experiences with failed results due to improper combinations.

Rubber-intercropping needs additional costs for culturing the intercrop, such as seedlings, planting, fertilization, upkeeping, irrigation and harvesting, etc. Although intercropping provides greater benefits, it incurs higher fixed and operating costs compared to rubber monocropping (Cherdehom *et al*., 2002). Guo *et al*. (2006) noted that intercropping rubber with tea would not be profitable without a significant financial supply, as the labor cost of tea plucking was 100% higher than rubber tapping cost. He also pointed out that the rubber-intercropping system might lead to a lower profit margin while the prices of the crops declined with higher labour costs if the selected intercrop was high labour demanded.

In the rubber smallholder sector, the shortage of labour is the main problem since hired labours, mainly comprised of migrant workers (Somboonnsuke and Wettayaprasit, 2013), are dominant but unstable due to higher alternative opportunities from off-farm jobs. In addition, most rubber smallholders, particularly in Thailand, practice high-frequency tapping systems with a traditional product-sharing payment method (Zaw *et al*., 2017), despite recommendations for an alternate daily tapping system. Many studies have found that highly intensive tapping systems lead to high tapper requirements, low productivity, and increased tapping costs (Chan *et al*., 1983; Hassan *et al*., 1999; Nugawela *et al*., 2000; Vijayakuma *et al*., 2001). Hence, in some cases, implementation of the high-labour-demanded intercropping at rubber smallholdings, in which a high-frequency tapping system is practiced, may result in higher labour requirements and higher production costs than those of rubber monoculture. Thus, adopting a low-frequency tapping system, which requires less labour (Zaw *et al*., 2017), is recommended to help distribute the workload evenly between tapping and intercropping tasks, especially when labour availability is limited.

Conclusion

In the natural rubber industry, smallholders, the major producers, are the most vulnerable, have low resilience, and bear the burdens of unsustainable industry costs. However, the structural environment of their rubber farms is technically viable for intercropping and agroforestry systems, which contribute to ecological and economic sustainability. Despite this, they have faced some constraints in adopting rubber-based intercropping systems and achieving the sustainability benefits of the systems.

In this context, interventions with promoting intercropping schemes in supporting initial investments, transferring technologies, providing high-yield cultivars and other inputs, and creating potential markets for intercrops are suggested. In addition, trainings are recommended regarding not only agricultural technologies to manage different intercrops but also processing technology of value-added products from raw agricultural products and marketing management.

It is advisable to conduct further applied research with a needs-oriented basis, considering various agroclimatic conditions and different types of smallholders, focusing on selecting suitable intercrops, developing efficient agricultural practices, and studying the market demand and capabilities of smallholders.

It is inevitable that promoting the development of smallholders’ rubber production through adopting rubber-based intercropping not only ensures agroecosystem, economic, and social improvements in the smallholder sector but also could revitalize the sustainability of the natural rubber industry.

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