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Investigation of environmental aspects of various rubber-based farming systems in Thailand

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Abstract: This study investigates various environmental aspects of different rubber farming systems (i.e. conventional monoculture, integrated rubber-based farming, and agroforestry plantations) across three regions, namely Northeast, East and South in Thailand. These regions are enriched with diverse soil types, weather conditions and a diverse spectrum of agricultural practices. The study conducted a cross-sectional survey in the above-mentioned regions to collect primary data from the selected respondents. A purposive sampling technique was employed to select the samples. A total of 30 representative rubber farmers were interviewed using a structured and standardized questionnaire. In addition, the study employed qualitative methods to assess the environmental aspects of different rubber farming systems. Based on socio-economic and production criteria, the study identified five types of rubber farms, ranging from single-crop para-rubber to highly diversified operations. The analyses revealed that integrated rubber farms and rubber agroforestry farms demonstrated overall better performance compared to rubber monoculture farms, particularly in areas having higher organic matter content, DRC of rubber fresh latex, water holding capacity (WHC), and soil moisture. The study also found that ecosystem service ratings varied widely, with monoculture farms scoring low (1.98) and integrated systems scoring high (4.60). In addition, the study assessed the farmers' desire/concern toward biodiversity of different rubber farming systems. The farmers expressed significant concern for biodiversity (average score is 4.23 indicating a consensus at the "very much" level). These findings highlight the environmental advantages of integrated rubber farming and agroforestry, emphasizing the need for sustainable, diverse approaches to rubber production in Thailand.

Keywords: Agriculture; Sustainability; Environment; Farming; Biodiversity.
Abbreviations: WHC_ Water Holding Capacity; DRC_ Dry Rubber Content; RAOT_ Rubber Authority of Thailand.

Introduction

Monoculture practice in rubber farming typically provides fewer ecosystem services due to its focus on a single crop. These services may include carbon sequestration, soil retention, and water regulation. Monoculture practice in rubber farming is often associated with reduced provisioning of ecosystem services compared to more diverse land use practices. This reduction highlights the importance of single crop cultivation and the removal of natural vegetation. The study by Wei et al. (2020) revealed that monoculture rubber plantations had lower ecosystem service values compared to mixed rubber-agroforestry systems. The study also found that monoculture farms were less effective in regulating water flow, sequestering carbon, retaining soil, and providing habitat opportunities for wildlife. Carbon sequestration is a vital ecosystem service that helps mitigate the adverse impacts of climate change by capturing and storing carbon dioxide from the atmosphere. Besar et al. (2020) conducted a research in rubber-growing regions of Malaysia and found that monoculture rubber plantations had limited carbon sequestration capacity compared to mixed agroforestry systems. The diversity of tree species in agroforestry systems enhances carbon storage, demonstrating how monoculture rubber farming may compromise this crucial ecosystem service. In addition, monoculture rubber farming adversely affects soil retention and water regulation. Hammond et al. (2017) found that monoculture rubber plantations in China were more prone to soil erosion, while mixed cropping systems showed better soil retention due to diverse coverage of vegetation. Effective water regulation is crucial for flood control and stable water levels. The study by Joshi et al. (2006) demonstrated that diverse agroforestry systems, including rubber agroforestry, outperformed monoculture rubber farms in terms of water regulation. Moreover, monoculture rubber plantations also reduce habitat opportunities, impacting wildlife diversity and associated ecosystem services, as noted by Sreekar et al. (2016). Monoculture farming, characterized by the cultivation of a single crop over extensive areas, has long been a prevailing agricultural practice worldwide. In Thailand, monoculture rubber farming has gained prominence due to its economic significance. In addition, it contributes significantly to rubber production in the country. However, though monoculture rubber farming may yield high rubber production, it often comes at a substantial cost to biodiversity. One of the primary concerns associated with monoculture rubber farming is habitat fragmentation, a result of converting natural landscapes into large rubber plantations. This transformation disrupts the ecological balance and leads to a loss of biodiversity. Singh et al. (2021) conducted a comprehensive study in Southeast Asia and explored the detrimental effects of monoculture rubber plantations on both plant and animal diversity. Their research found that the conversion of diverse natural vegetation into monoculture rubber farms significantly reduced habitat availability for native species. The study by Nath et al. (2013) in Sri Lanka reported that monoculture rubber farming disrupts ecosystems and negatively impact soil microorganisms and nutrient cycling, consequently affecting soil health and biodiversity. It also lacks habitat diversity, reducing insect and bird species, as seen in the study by Yahya et al. (2022) in Malaysia. Chemical inputs like pesticides and fertilizers harm biodiversity. Wei et al. (2020) found that usage of Chemical inputs reduced non-target insects, disrupting ecosystems in China. The study also reported that the conversion of landscapes into rubber plantations leads to habitat fragmentation, ecosystem changes, and chemical inputs, contributing to biodiversity loss. The researcher opined that sustainable practices like integrated rubber farming and agroforestry are vital for mitigating the above-mentioned effects in rubber-producing regions.

In contrast, integrated rubber-based farming and rubber agroforestry systems have demonstrated the potential to support biodiversity conservation. One of the key advantages of integrated rubber farming is its potential to enhance habitat complexity within rubber plantation environment. Beukema et al. (2007) conducted a study in Indonesia that focused on rubber agroforestry systems. Their research revealed that incorporating diverse tree species alongside rubber trees significantly increased habitat complexity within the plantation environment. The enriched habitat complexity provide various niches for different bird and insect species, resulting in greater biodiversity. In line with the previous study, Lemaire et al. (2014) emphasized the importance of diverse crop interactions within integrated farming systems. These systems involve intercropping rubber with various crops, creating a mosaic of vegetation types. The increased variety of crops not only contributes to diversified sources of income for farmers but also maintains higher levels of biodiversity due to increased habitat diversity. This approach highlights the synergy between agriculture and biodiversity conservation. Integrated rubber farming not only benefits biodiversity but also provides crucial ecosystem services. Murthy et al. (2013) found that rubber agroforestry systems improved soil fertility, reduced erosion, and enhanced habitat conditions for wildlife. Diverse vegetation coverage in these systems supports soil health, highlighting the synergy between ecosystem services and biodiversity conservation. Moreover, integrated rubber farming often includes agroforestry practices, combining rubber with tree species that support biodiversity. Research by Pierre et al. (2010) in Cameroon showed that such systems enhanced carbon sequestration and provided refuge for various wildlife species, including birds and small mammals, within agricultural landscapes.

Conversely, monoculture rubber farming can have adverse effects on water quality. One of the primary concerns associated with monoculture rubber farming is the extensive use of pesticides and agrochemicals. These chemicals are utilized to control pests and enhance crop yields but can have detrimental effects on water quality. Pesticides and agrochemicals used in conventional monoculture plantations may leach into nearby water bodies, causing serious contamination. Song et al. (2022) reported that water samples collected from areas adjacent to monoculture rubber farms contained higher levels of chemical pollutants. In addition, the leaching of pesticides and agrochemicals from rubber plantations into nearby water bodies poses significant risks to aquatic ecosystems and human health. The contamination of water bodies by chemical pollutants from monoculture rubber farming can have far-reaching consequences for aquatic ecosystems. Dsikowitzky, et al. (2014) conducted a study in rubber-growing regions in India and revealed adverse effects of pesticide runoff on aquatic biodiversity. The study also reported that the presence of chemical contaminants in water can harm aquatic species, disrupt food chains, and lead to long-term ecological imbalances. Apart from chemical contamination, monoculture rubber farming can contribute to soil erosion and sedimentation in water bodies. The removal of natural vegetation and the establishment of extensive rubber plantations can lead to increased runoff during heavy rainfall events. Sediments carried by runoff can enter rivers and streams, negatively impacting water quality. In this circumstance, several studies have explored that mitigation strategies can be applied to reduce the adverse effects of monoculture rubber farming on water quality. For instance, Babel et al. (2021) investigated the use of vegetative filter strips in rubber plantations to intercept and filter out chemical contaminants before they enter nearby water bodies. Their research demonstrated that vegetative filter strips effectively reduced the concentration of pesticides and agrochemicals in runoff, thereby safeguarding water quality.

To the best of our knowledge, there is no study yet to focus on environment aspects of various rubber farming systems in Thailand. Therefore, this study aims to assess and analyze various environmental aspects, including biodiversity, water quality, and soil quality of different rubber-based farming systems in three regions of Thailand, namely Northeast (Beungkan and Nongkhai Province), East (Rayong, Chanthaburi, and Trat Province), and South (Suratthani and Songkhla Province). The research focused on integrated rubber-based farming, agroforestry plantations, and monoculture practices. In order to collect data, a total of 30 representative samples were carefully chosen and subsequently interviewed using structured questionnaires. This approach was instrumental in enabling a thorough and comprehensive analysis of various environmental perspectives. Both qualitative and quantitative methods were employed to evaluate the benefits and challenges associated with these rubber-based farming systems. This included comparison and prospective analyses.

Results

Distinct Categories of Rubber farming Systems in Thailand: A Comparison

Upon analyzing the socio-economic characteristics and production practices of the rubber farming systems in Thailand (Figure 1), it was observed that there existed five distinct categories or types of rubber integrated farms and agroforestry farms. These categories were delineated based on the number of agricultural production activities associated with para-rubber cultivation of the farms. The proportional distribution of agricultural production activities associated with respective farming system was as follows:

Table 1. The farmers' opinion on biodiversity of integrated rubber Farm and rubber agroforestry farm.

Environment aspect	Average	S.D.	Criteria
1.Having more biodiversity in above ground of rubber plantation plot (bird, bee, insect, butterfly, nocturnal animal, and snake etc.)	4.10	1.06	Much
2. Having more biodiversity in the ground of rubber plantation plot (worm, earthworm, and termite etc.)	4.20	0.89	Much
3. Having biodiversity of plants and canopy in rubber plantation plot	4.20	0.92	Much
4. Increase soil fertility	4.13	0.97	Much
5. Soil erosion protection	4.17	0.91	Much
6. Decrease and avoid chemical, chemical fertilizer, pesticide or chemical that used in household and decrease discharge wastewater to public water resources	4.27	0.91	Very much
7. Decreasing the impact to water resource in community	4.23	0.90	Very much
8.Decreasing plentiful material burning and garbage	4.30	0.84	Very much
9.Having more moisture and Ago-ecological equilibrium in rubber plantation plot	4.33	0.96	Very much
10.More Sustainability and environment in rubber production	4.37	0.76	Very much

Remark: (1) Criteria: 1.00-1.85: None get beneficial, 1.81-2.60: Little get beneficial, 2.61-3.40: Moderate get beneficial, 3.41-4.20: Much get beneficial, and 4.21-5.00: Very much get beneficial.

Table 2. The Comparison of biodiversity and beneficial characteristics among various rubber farming systems.

Items*	Monocultured rubber farms	Integrated rubber farm and rubber agroforestry farm
Perennial species (Numbers)	23	26
Diversity indicators	2.467	2.533
Evenness index	0.787	0.777
Ground floor species plant type	25	20
Average dry weight humus(gm)	191.9	198.7
Soil PH	3.4	3.7
Nitrogen (% of dry weight)	0.10	0.21
Phosphorus (mg/L of dry weight)	174	198
organic matter (% of dry weight)	0.14	0.23
Found plant species type	6	5
Diffused seed type	1	1
Water Holding Capacity (WHC)	27.4	30.92
soil moisture (% of dry weight)	0.93	1.28
DRC of rubber fresh Latex (%)	31.7	33.0
Cup lump weight per tree (gm)	55.5	80.35

Source: Intarasirisawat et al. (2013). (1) Monocultured rubber farms, integrated rubber farm and rubber agroforestry farm are fertilized and weed control based on RAOT. (2) Scrap rubber price was 21 baht in 2018.

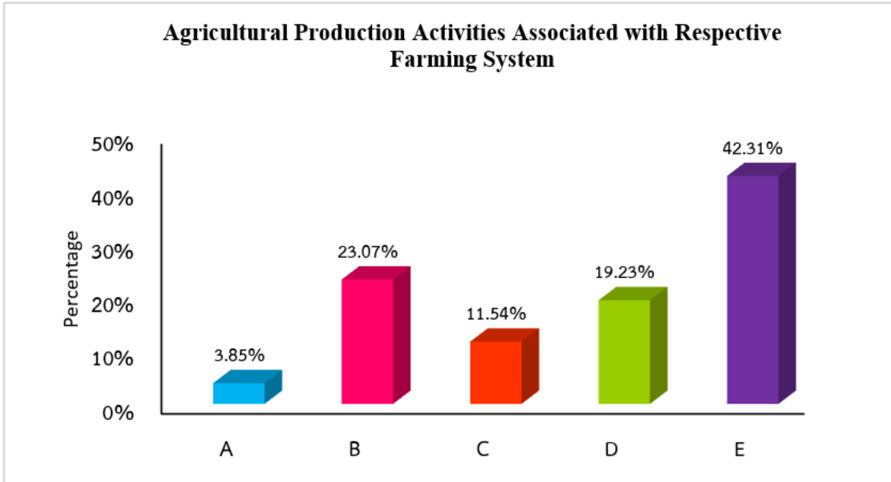
Category A: Para-rubber farming associated with **single** agricultural production activity. This category involves 3.85% agricultural production activity.
Category B: Para-rubber farming associated with **two** agricultural production activities. Nearly 23.07% agricultural production activities are involved with category B.
Category C: Para-rubber farming associated with **three** agricultural production activities. This category involves comparatively a lower portion (11.54%) of agricultural production activities.
Category D: Para-rubber farming associated with **four** agricultural production activities. This category involves 19.23% agricultural production activity.
Category E: Para-rubber farming associated with **at least five** agricultural production activities. This category involves the highest portion (42.31%) of agricultural production activities.

The comprehensive comparative analysis has facilitated a thorough assessment of the socioeconomic characteristics and production outcomes across three distinct categories of rubber farming systems: Integrated Rubber Farms, Rubber Agroforestry Farms, and Monoculture Rubber Farms. This analysis has revealed significant differentiators in several pivotal economic indicators. Upon juxtaposing Integrated Rubber Farms and Rubber Agroforestry Farms with Monoculture Rubber Farms, it becomes evident that both Integrated and Agroforestry farming systems exhibit notable strengths in terms of various economic parameters. These include higher family income, increased agricultural revenue, enhanced earnings derived specifically from para-rubber farming activities, augmented income generated through diversified farming activities, and elevated earnings stemming from employment within the agricultural sector.

These findings underscore the pronounced economic advantages associated with Integrated Rubber Farms and Rubber Agroforestry Farms when compared to the more specialized Monoculture Rubber Farms. The results point towards the tangible benefits of diversifying agricultural activities and embracing an integrated approach that incorporates rubber cultivation within a broader agricultural framework. This strategic shift not only enhances economic resilience but also contributes to sustainable agricultural development, aligning with broader objectives of economic growth and environmental sustainability.

Biodiversity of Integrated Rubber Farm and Rubber agroforestry farm

Farmers have indeed demonstrated a praiseworthy level of awareness and commitment to biodiversity within the expansive landscapes of rubber plantations, encompassing the



Para-rubber farming associated with
A: Single agricultural production activity
B: Two agricultural production activities
C: Three agricultural production activities
D: Four agricultural production activities
E: At least five agricultural production activities

Figure 1. The proportional distribution of agricultural production activities associated with respective farming system.

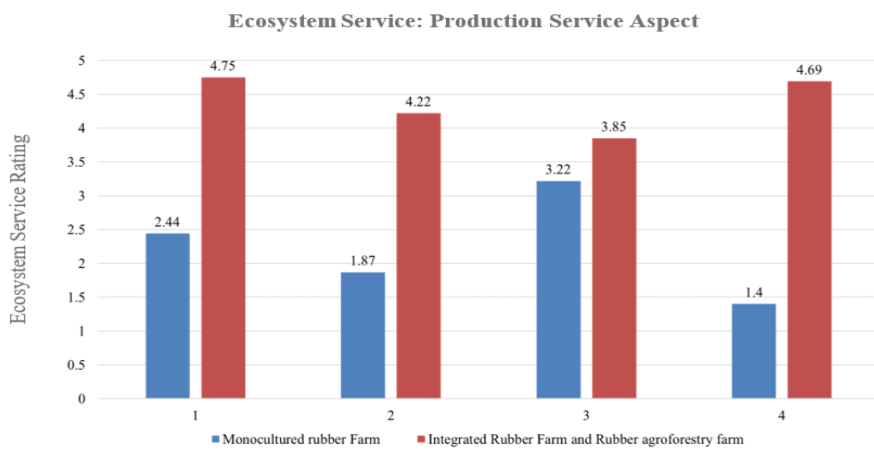


Figure 2. Ecosystem Service: Production service aspect. Remark: (1) Criteria: 1.00-1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service. (2) Number of Rubber Monocultured farm: 32 farms and Number of Integrated rubber farm and rubber Agroforestry farm: 30 farms. (3) 1: Food source, 2: Herb source, 3: Wood source and 4: Collected local and alien genetics plant species.

intricate tapestry of life above and below the soil's surface. Above ground, they have astutely identified a diverse array of wildlife species, including the melodious chorus of birds, the tireless pollinators such as bees and butterflies, the elusive nocturnal creatures that come to life after dark, and even the enigmatic presence of snakes. These creatures, often overlooked in agricultural settings, contribute substantially to the ecological balance by aiding in pollination and acting as natural agents of pest control. Such recognition emphasizes the vital role of rubber plantations as vibrant habitats that foster the coexistence of agriculture and the natural world.

Beneath the Earth's surface, farmers have extended their appreciation to the often-unseen heroes, such as worms, earthworms, and termites, which diligently toil to maintain the soil's health and facilitate the essential nutrient cycling processes. Their acknowledgment of the significance of these soil organisms illuminates the profound connection between biodiversity and soil quality. This realization highlights the potential for rubber plantations to not only thrive economically but also to contribute to broader environmental objectives by enhancing soil fertility and, consequently, plantation resilience.

While the positive strides taken by farmers in embracing biodiversity are commendable, it is essential to recognize that these actions are not without their challenges. Farmers, however, remain resolute in their commitment to responsible farming practices. They actively seek to reduce chemical inputs, thereby minimizing the environmental footprint and potential harm to surrounding ecosystems. Additionally, their dedication to effective waste management practices and the reduction of material burning and garbage within rubber plantations contribute to a cleaner and healthier environment. Furthermore, their conscientious efforts extend to the preservation of local water resources, understanding the critical role that these resources play in both agricultural sustainability and community well-being. Sustainable water use and reduced pollution are paramount to maintaining the quality and availability of water within their communities.

In the pursuit of agro-ecological equilibrium, farmers are actively engaged in practices aimed at maintaining higher moisture levels and fostering resilience within rubber plantations. These strategies reflect an eco-conscious ethos that not only safeguards the plantations against environmental

Table 3. The farmers' opinion on ecosystem service of various rubber farming systems.

Ecosystem Service aspect	Monocultured rubber Farm (N=32)		Integrated rubber farm and rubber agroforestry farm (N=30)	
	Average	Criteria	Average	Criteria
Production service aspect				
1.Food source	2.44	Little	4.75	Very much
2.Herb source	1.87	Little	4.22	Very much
3.Wood source	3.22	Moderate	3.85	Much
4.Collect genetics plant (both local plant species and alien species)	1.40	None	4.69	Very much
Average	2.23	Little	4.38	Very much
Control service aspect				
1. soil moisture control	1.22	None	4.95	Very much
2 soil erosion protection	1.96	Little	4.96	Very much
3. Absorption of Carbondioxide	3.23	Moderate	4.56	Very much
4.pollination	1.56	None	3.45	Much
5.seed distribution	3.11	Moderate	4.65	Very much
Average	2.22	Little	4.51	Very much
Cultured service aspect				
1.Preservation of Local Wisdom of garden	1.35	None	4.93	Very much
2.educational value (Long term plot)	1.92	Little	4.68	Very much
3.oriented tourism Agriculture/Community Tourism	2.11	Little	4.38	Very much
Average	1.79	None	4.66	Very much
Supporting service aspect				
1.Food source/Soil fertility/ nitrogen fixation	1.89	Little	4.76	Very much
2.Biodiversity	1.65	None	4.99	Very much
3.Habitat of animals for help seed distribution	1.25	None	4.69	Very much
4.Habitat for food for creature	1.93	Little	4.88	Very much
Average	1.68	None	4.83	Very much
Overall Average	1.98	Little	4.60	Very much

Remark: Criteria: 1.00 -1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service.

Table 4. The comparison on soil quality among various rubber farming systems.

Tests	pH (1:5)		$EC_{1:5}$(dS m^{-1})		OM (g kg^{-1})	
	0-30 cm	**30-60 cm**	**0-30 cm**	**30-60 cm**	**0-30 cm**	**30-60 cm**
R_1	5.0	5.1	0.02	0.01	8.6	5.9
RBa	5.0	5.4	0.02	0.01	8.6	5.2
T-test	ns	ns	ns	ns	ns	ns
R_2	5.2	5.1	0.02	0.01	16.2	9.3
RGn	5.2	5.1	0.02	0.01	15.7	9.4
T-test	ns	ns	ns	ns	ns	ns
R_3	5.0	4.9	0.01	0.01	13.1	7.4
RSa	5.1	4.5	0.03	0.01	11.2	5.8
T-test	ns	ns	ns	ns	ns	ns

Source: Saeteng et al. (2022). Remark: R_1: Rubber monocultured farm; R_2: Integrated rubber farm; R_3: rubber agroforestry farm RBa: Rubber associate with bamboo; RGn: Rubber associate with genetume; RSa: Rubber associate with Salaga; ns: non-significant where the significant level is 0.05.

fluctuations but also promotes long-term sustainability in rubber production. Ultimately, the actions of these dedicated farmers resonate with the broader goals of sustainable agriculture and environmental preservation. Their holistic approach, integrating biodiversity conservation, reduced chemical usage, efficient waste management, water resource conservation, and agro-ecological equilibrium, showcases their unwavering commitment to nurturing the land they steward while harmonizing agricultural productivity with the preservation of our planet's natural heritage.

From Table 1, the average farmer opinion score on biodiversity stands at 4.23, indicating a consensus at the "very much" level. Notably, the opinion regarding the desire for more sustainability and an improved environment within rubber plantations receive the highest average score, standing at 4.37 (also at the "very much" level). In contrast, the opinion related to increasing biodiversity above ground of rubber plantation plots records the lowest average score of 4.10 (falling within the "much" level).

The results of the survey on farmer opinions regarding biodiversity and sustainable practices in rubber plantations reveal significant insights into the strategic priorities and concerns of rubber farmers.

The unanimous agreement among farmers that having more biodiversity above ground is of utmost importance signifies a recognition of the vital role that diverse wildlife, such as birds, insects, and snakes, plays in maintaining a balanced ecosystem.

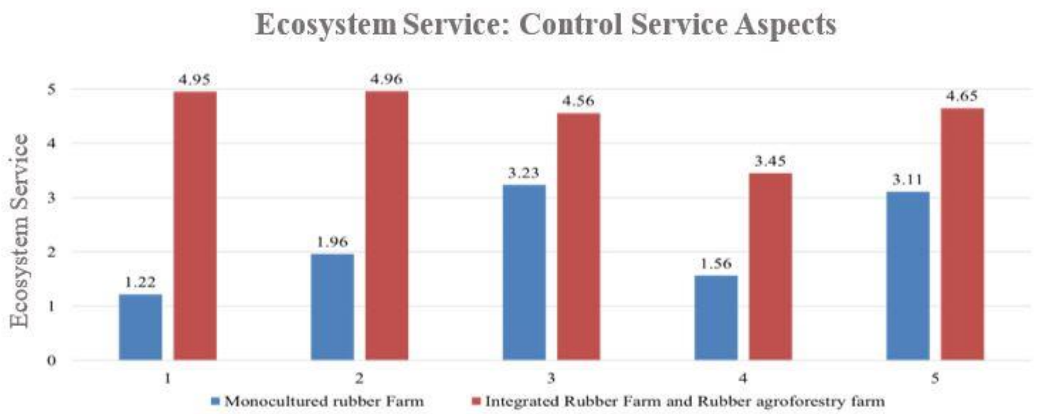


Figure 3. Ecosystem Service: control service aspect. Remark: (1) Criteria: 1.00-1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service (2) Number of Rubber Monocultured farm: 32 farms and Number of Integrated rubber farm and rubber Agroforestry farm: 30 farms (3) 1: soil moisture control, 2: soil erosion protection, 3: Absorption of Carbon dioxide, 4: pollination and 5: seed distribution.

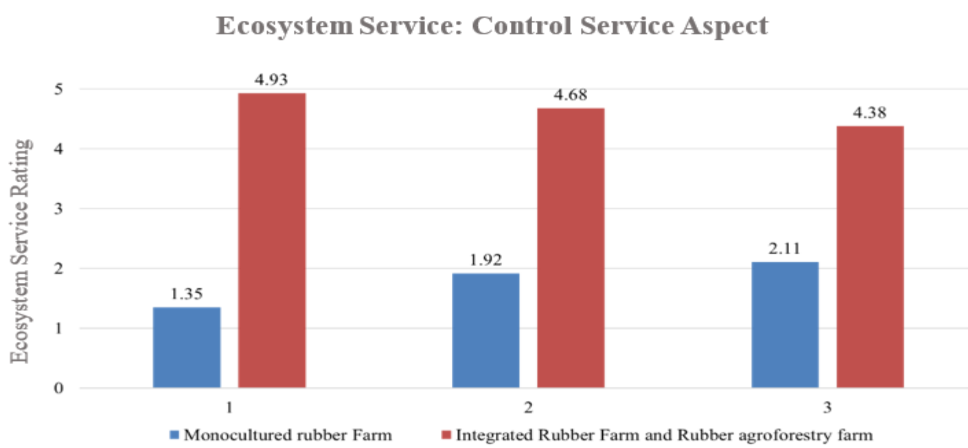


Figure 4. Ecosystem Service: control service aspect. Remark: (1) Criteria: 1.00-1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service (2) Number of Rubber Monocultured farm: 32 farms and Number of Integrated rubber farm and rubber agroforestry farm: 30 farms (3) 1: Preservation of Local Wisdom of garden, 2: Educational value (Long term plot) and 3: Oriented tourism Agriculture/Community Tourism.

This aligns with strategic goals of enhancing ecological health and promoting natural pest control and pollination.

The acknowledgment of the significance of below-ground biodiversity, including soil organisms like worms and termites, underscores the critical role these creatures play in soil health and nutrient cycling. This recognition reflects a strategic focus on improving soil quality, an essential foundation for sustainable rubber production.

Farmers' emphasis on having biodiversity within the plantation canopy and diverse plant species highlights a strategic approach to creating resilient and ecologically balanced systems. Such diversity not only provides habitat and sustenance for wildlife but also contributes to the overall health and productivity of rubber plantations.

The unanimous agreement on the need to increase soil fertility indicates a strategic commitment to sustainable soil management. Biodiverse ecosystems are known to support healthier soils through natural nutrient cycling, reducing the dependence on chemical fertilizers.

The unanimous recognition of the importance of soil erosion protection reflects a strategic goal of safeguarding valuable topsoil. Biodiversity, both above and below ground, plays a pivotal role in preventing soil erosion, reinforcing the resilience of the plantation.

The overwhelming consensus on the need to decrease chemical usage and minimize chemical discharge into public water resources demonstrates a strategic shift toward environmentally responsible practices. This approach aligns with broader sustainability objectives and emphasizes the importance of reducing chemical-related environmental impacts.

The unanimous agreement on the necessity of reducing the impact on local water resources aligns with a strategic focus on water conservation and quality. Sustainable rubber farming practices are seen as essential for maintaining the overall well-being of local water sources.

The unanimous commitment to reducing material burning and waste generation within rubber plantations underscores a strategic intent to promote a cleaner and healthier environment. Implementing waste management and recycling practices is considered a strategic imperative.

The unanimous desire for more moisture and agro-ecological equilibrium within rubber plantations reflects a strategic approach to enhancing plantation resilience. These practices

Table 5. The comparison on soil nutrient in rubber leaf among various rubber farming systems.

Tests	Concentration (g kg^{-1})				
	N	P	K	Ca	Mg
R_1	26.7 ± 0.9 a	2.2 ± 0.1 b	11.7 ± 0.5	10.9 ± 2.2	2.7 ± 0.4
RBa	26.5 ± 1.2 a	2.6 ± 0.19 ab	12.1 ± 1.1	10.2 ± 1.9	3.0 ± 0.2
R_2	24.8 ± 0.1 ab	2.7 ± 0.0 ab	15.3 ± 1.1	8.7 ± 1.0	2.4 ± 0.4
RGn	21.9 ± 0.5 c	2.1 ± 0.1 b	15.0 ± 1.2	8.5 ± 0.4	2.5 ± 0.2
R_3	22.4 ± 0.9 bc	2.4 ± 0.3 b	12.7 ± 2.0	12.9 ± 1.4	2.8 ± 0.7
RSa	23.1 ± 0.4 bc	3.3 ± 0.4 a	13.3 ± 1.7	10.8 ± 0.7	2.8 ± 0.1
F-test	**	*	ns	ns	ns
CV (%)	7.8	17.5	19.2	26.1	21.9

Source: Saeteng et.al (2022). Remark: R_1: Rubber monocultured farm; R_2: Integrated rubber farm; R_3: rubber agroforestry farm. RBa: Rubber associate with bamboo; RGn: Rubber associate with Genetume; RSa: Rubber associate with salaga. **Significant level 0.01, *Significant level 0.05 and ns: non-significant

Table 6. The comparison on soil nutrient in rubber latex among various rubber farming systems.

Tests	Concentration (g kg^{-1})				
	N	P	K	Ca	Mg
R_1	1.8 ± 0.2 a	0.9 ± 0.1	2.0 ± 0.4	0.06 ± 0.0	0.4 ± 0.1
RBa	2.1 ± 0.5 a	0.7 ± 0.1	1.9 ± 0.0	0.05 ± 0.0	0.5 ± 0.1
R_2	1.1 ± 0.1 b	1.1 ± 0.1	2.3 ± 0.3	0.09 ± 0.0	0.5 ± 0.0
RGn	1.2 ± 0.1 b	1.0 ± 0.2	1.7 ± 0.2	0.07 ± 0.0	0.5 ± 0.2
R_3	1.9 ± 0.7 a	0.6 ± 0.1	1.3 ± 0.1	0.05 ± 0.0	0.2 ± 0.1
RSa	1.9 ± 0.1 a	0.7 ± 0.1	1.5 ± 0.5	0.06 ± 0.0	0.3 ± 0.2
F-test	**	ns	ns	ns	ns
CV (%)	26.1	29.3	30.1	45.2	58.6

Source: Saeteng et.al (2022). Remark: R_1: Rubber monocultured farm; R_2: Integrated rubber farm; R_3: rubber agroforestry farm RBa: Rubber associate with bamboo; RGn: Rubber associate with Genetume; RSa: Rubber associate with salaga. **Significant level 0.01, *Significant level 0.05 and ns: non-significant

are seen as instrumental in adapting to changing environmental conditions.

The unanimous aspiration for more sustainability and an improved environment in rubber production is the overarching strategic objective. Integrating biodiversity, reducing chemical usage, minimizing waste, and conserving water resources collectively contribute to sustainable agriculture and environmental preservation.

In summary, the farmers' unanimous emphasis on biodiversity and sustainable practices in rubber plantations reflects a strategic shift towards environmentally responsible and economically viable rubber farming. These strategic priorities align with broader sustainability goals and signify a commitment to both agricultural success and environmental preservation.

Characteristics of biodiversity and beneficial

The table below presents a comparison of biodiversity characteristics and benefits between rubber monoculture farms and integrated rubber farms, as well as rubber agroforestry farms, based on the research study conducted by Ranganath et al. (2004). The results indicate that, overall, integrated rubber farms and rubber agroforestry farms outperform rubber monoculture farms. This difference is particularly pronounced in aspects such as organic matter content (% dry weight), DRC (Dry Rubber Content) of rubber fresh latex, water holding capacity (WHC), and soil moisture (% of dry weight).

Ecosystem service: production service aspect

The comprehensive assessment of the production service aspect underscores significant disparities between rubber monoculture farms and integrated rubber farms, along with rubber agroforestry farms. The total average score for production service in rubber monoculture farms registers at a relatively modest 2.23, reflecting a relatively low level of production service. In contrast, integrated rubber farms and rubber agroforestry farms exhibit a notably higher total average score of 4.38, indicating a very high level of production service. This marked contrast highlights the substantial advantages associated with integrated rubber farming and agroforestry practices over traditional monoculture methods concerning various aspects of the production process. These findings underscore the potential for improved production services and overall sustainability by embracing diversified and environmentally friendly approaches within the rubber production sector.

Ecosystem service: Control service aspect

The comprehensive evaluation of the control service aspect highlights notable distinctions between rubber monoculture farms and integrated rubber farms in conjunction with rubber agroforestry farms. The total average score for control service in rubber monoculture farms stands at a relatively modest 2.22, indicative of a somewhat limited level of control. Conversely, integrated rubber farms and rubber agroforestry farms exhibit a significantly higher total average score of 4.51, denoting a very high level of control. This substantial contrast underscores the pronounced advantages associated with integrated rubber farming and agroforestry practices over traditional monoculture methods when it comes to controlling various aspects of the farming process. These findings emphasize the potential for enhanced control services and overall sustainability through the adoption of diversified and environmentally friendly approaches within the rubber production sector.

Ecosystem service: cultured service aspect

The comprehensive analysis of the cultured service aspect reveals significant disparities between rubber monoculture farms and integrated rubber farms along with rubber agroforestry farms. The total average score for rubber monoculture farms stands at a modest 1.79, signifying a relatively low level of support. In stark contrast, integrated rubber farms and rubber agroforestry farms exhibit a substantially higher total average score of 4.66, denoting a very high level of support. This substantial discrepancy underscores the pronounced advantages associated with integrated rubber farming and agroforestry practices over traditional monoculture methods. These findings emphasize the potential for improving support services and overall sustainability by transitioning to diversified and environmentally friendly approaches within the rubber production sector.

Ecosystem service: Support service aspect

The overall average score for the support service aspect of rubber monoculture farms is notably lower at 1.68, indicating a relatively low level of support. In contrast, when considering integrated rubber farms and rubber agroforestry farms, the total average score rises significantly to 4.83, signifying a very high level of support. This substantial difference underscores the considerably enhanced support services associated with integrated rubber farming and agroforestry practices compared to traditional monoculture methods, highlighting the potential benefits of adopting more diversified and sustainable approaches within the rubber production sector.

Table 3 provides an insightful comparison of ecosystem services across rubber monoculture farms, integrated rubber farms, and rubber agroforestry farms. These ecosystem services encompass four key aspects: production service, control service, cultured service, and supporting service. The comprehensive evaluation reveals a substantial discrepancy in the overall average ecosystem service levels among these farming systems. Rubber monoculture farms exhibit a relatively modest overall average score of 1.98, indicating a rather limited level of ecosystem service provision. In stark contrast, integrated rubber farms and rubber agroforestry farms showcase a significantly higher overall average score of 4.60, signifying a very high level of ecosystem service. This pronounced disparity underscores the considerable ecological advantages offered by integrated rubber farming and agroforestry practices compared to conventional monoculture techniques. Embracing these diversified and environmentally conscious approaches holds the potential to enhance ecosystem services significantly, contributing to sustainability and environmental well-being in rubber production.

The soil quality between rubber monocultured farm and Integrated Rubber farm and rubber agroforestry farms

The findings presented in Table 4 illuminate a comprehensive comparison of soil quality attributes (pH, EC, and OM in 2 soil depth levels; 0-30 cm and 30-60cm) among rubber monoculture farms, integrated rubber farms, and rubber agroforestry farms, as documented in the study conducted by Pranchalee et al. (2022). The data unequivocally reveal that, pH $_{(1:5)}$, $EC_{1:5}$(dS m^{-1}), and OM (g kg^{-1}) in soil depth level 0-30 cm in all treatments of Integrated farm and Agroforestry farm are higher than rubber monocultured farm.

This substantial divergence underscores the superior soil quality and enhanced organic matter content associated with integrated rubber farming and agroforestry practices in the topsoil layer. Such improvements in soil quality signify a promising pathway toward sustainable and environmentally friendly rubber production.

The soil nutrient between rubber monocultured farm and integrated rubber farm and rubber agroforestry farms

The outcomes presented in Tables 5 and 6 provide a comprehensive assessment of soil nutrient levels, both in rubber leaves and rubber latex, within the contexts of rubber monoculture farming, integrated rubber farming, and rubber agroforestry practices. These findings unequivocally demonstrate that across all treatments within Integrated rubber farming and rubber agroforestry systems, soil nutrient concentrations in rubber leaves and rubber latex consistently surpass those observed in rubber monoculture farming. This substantial disparity underscores the superior nutrient enrichment achieved through integrated rubber farming and agroforestry practices, emphasizing the potential for enhanced productivity and overall sustainability in rubber production. These findings signify a promising avenue for elevating the nutritional quality of rubber plantations while concurrently minimizing environmental impacts.

Discussions

Thailand is the largest rubber producing country in the world. A vast majority of the lowland forest in the country has been converted to rubber fields. Smallholders grow nearly 90% of total production of Thai natural rubber (Somboonsuke & Wettayaprasit, 2013). About 90% of the rubber plantations in Thailand were monoculture (Delarue and Chambon, 2012). Intensification of rubber production to monocultures was incentivized via the Rubber Authority of Thailand (RAOT) (Romyen, Satsue, & Charenjiratragul, 2018). This practice of rubber plantations gives satisfactory income, employment and economic growth whenever the rubber price is high but sometimes it causes negative impacts and suffer perturbations during economic and climatic uncertainties (Jongrungrot 2021). However, the current study revealed that both integrated and agroforestry farming systems not only provide economic benefits but also contribute to sustainable agricultural development and environmental sustainability. The study by Stroesser, et al. (2016) revealed almost similar findings. The study reported that rubber agroforestry systems can generate income diversification and better resilience. In line with the previous study, Pierret et al. (2011) and Daru et al. (2023) found that rubber agroforestry systems provide environmental services, for instance, land and water conservation, micro-climate improvement and soil organic carbon stocks.

The current study revealed that expansion of monoculture practices in rubber farming does not provide any beneficial impacts on biodiversity. The other studies also reported that monoculture systems of rubber farming caused forest and biodiversity loss, carbon emissions and environmental degradation (Thomas et al., 2019). In contrast, the present study found that both integrated rubber farming and agroforestry rubber farming can play a crucial role in maintaining biodiversity, and consequently contribute substantially to the ecological balance. Similarly, the study by Thomas et al. (2019) found that Thai agroforests can offer benefits for both rubber yields and biodiversity, using three contrasting taxa (i.e. birds, fruit-feeding butterflies, and reptiles) because they are taxonomically resolved, relatively well studied in other agroforestry systems and likely to respond to different aspects of management. Firstly, whether yield, species richness and species composition differed between agroforests and monocultures. Secondly, whether richness and composition varied in response to understored vegetation, and the types and densities of non-rubber crops and trees. Thirdly,

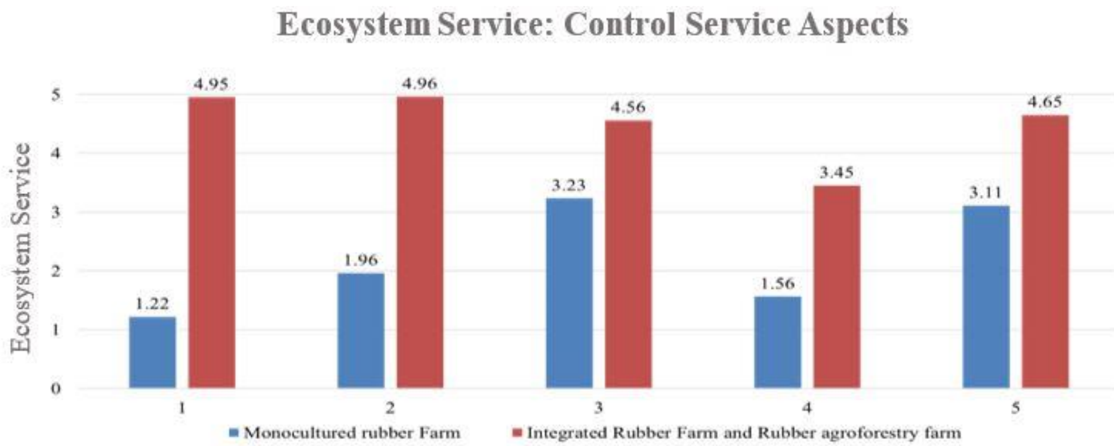


Figure 5. Ecosystem Service: control service aspect. Remark: (1) Criteria: 1.00-1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service. (2) Number of Rubber Monocultured farm: 32 farms and Number of Integrated rubber farm and rubber agroforestry farm: 30 farms. (3) 1: Food source/Soil fertility/ nitrogen fixation, 2: Biodiversity, 3: Habitat of animals for help seed distribution and 4: Habitat for food for creature.

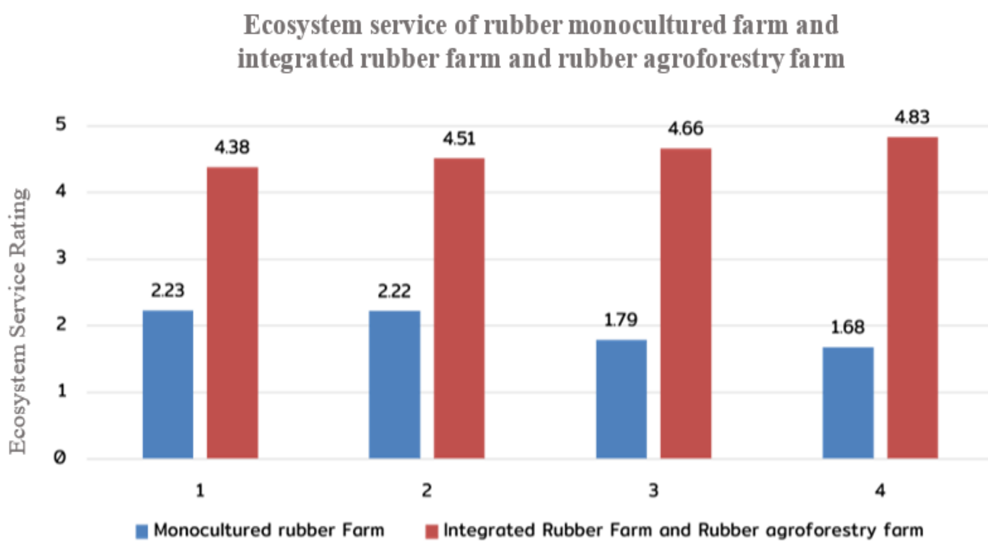


Figure 6. Average of ecosystem service of rubber monocultured farm and integrated rubber farm and rubber agroforestry farm. Remark: (1) Criteria: 1.00-1.85: No ecosystem service, 1.81-2.60: Little ecosystem service, 2.61-3.40: Moderate ecosystem service, 3.41-4.20: Much ecosystem service, and 4.21-5.00: Very much ecosystem service. (2) Number of Rubber Monocultured farm: 32 and Number of Integrated rubber farm and rubber Agroforestry farm: 30 (3) 1: Production service aspect, 2: Control service aspect, 3: Cultured service aspect and 4: Supporting service.

how richness and composition were influenced by landscape composition, and potential interactions with plot management. The current study found that monoculture rubber farming typically provides fewer ecosystem services due to its focus on a single crop. These services may include carbon sequestration, soil retention, and water regulation. Monoculture rubber farming is often associated with reduced provisioning of ecosystem services compared to more diverse land use practices. This reduction can be attributed to the intensive focus on a single crop and the removal of natural vegetation. The study by Wei et al. (2020) highlighted that monoculture rubber plantations had lower ecosystem service values compared to mixed rubber-agroforestry systems. These monoculture farms were less effective in regulating water flow, sequestering carbon, retaining soil, and providing habitat opportunities for wildlife. Carbon sequestration is a vital ecosystem service that helps mitigate climate change by capturing and storing carbon dioxide from the atmosphere. Research by Besar et al. (2020) conducted in rubber-growing regions of Malaysia found that monoculture rubber plantations had limited carbon sequestration capacity compared to mixed agroforestry systems. The diversity of tree species in agroforestry systems enhances carbon storage, demonstrating how monoculture rubber farming may compromise this crucial ecosystem service.

In addition, the present study found that monoculture rubber farming adversely affects soil retention and water regulation. Hammond et al. (2017) found that monoculture rubber plantations in China were more prone to soil erosion, while mixed cropping systems showed better soil retention due to diverse vegetation coverage. Effective water regulation is crucial for flood control and stable water levels. Joshi et al. (2006) demonstrated that diverse agroforestry systems, including rubber agroforestry, outperformed monoculture

Table 7. Characteristics of soil, temperature, precipitation, weather, and agriculture in various regions in Thailand.

Region	Province	Soil Type	Ave. Temp. (^0C)	Annual Precipitation (mm)	Weather condition	Agricultural Condition	References
Northeast	Beugkan	Sandy loam, lateritic soils	26-28	1200-1400	Hot and humid, distinct dry season	Diverse agricultural practices	Department of Land Development (2018); Thai Meteorological Department (2021)
	Nongkhai	Sandy loam, alluvial soil	25-27	1500-1700	Tropical savanna climate	Mixed farming systems	Department of Land Development (2018); Thai Meteorological Department (2021)
East	Rayong	Clayey soils, red-yellow podzolic	27-29	2000-2500	Warm and humid, high rainfall	Predominantly fruit orchards, rubber monoculture	Department of Agricultural Extension (2019); Office of Agricultural Economics (2020)
	Chanthaburi	Sandy clay loam, red-yellow podzolic	26-28	2500-3000	Tropical rainforest climate	Fruit orchards integrated systems	Department of Agricultural Extension (2019); Office of Agricultural Economics (2020)
	Trat	Clayey soils, red-yellow podzolic	27-29	2800-3200	Warm and humid, heavy rainfall	Rubber agroforestry	Department of Agricultural Extension (2019); Office of Agricultural Economics (2020)
South	Suratthani	Sandy loam, lateritic soils	27-29	2000-2500	Tropical monsoon climate	Mixed farming systems	Department of Land Development (2017); Thai Meteorological Department (2022)
	Songkhla	Sandy clay loam, lateritic soils	27-30	2400-2800	Hot and humid, consistent rainfall	Integrated rubber-based farming	Department of Land Development (2017); Thai Meteorological Department (2022)

rubber farms in water regulation. Monoculture rubber plantations also reduce habitat opportunities, impacting wildlife diversity and associated ecosystem services, as noted by Sreekar et al. (2016).

In contrast, integrated rubber farming and rubber agroforestry systems, which incorporate diverse plant species and mimic natural ecosystems, have been shown to offer a wide range of ecosystem services. Carbon sequestration, the capture and storage of carbon dioxide from the atmosphere, is a critical ecosystem service with implications for climate change mitigation. Singh (2018) conducted research in Swidden, specifically focusing on integrated rubber agroforestry systems. The findings of the study highlighted that these systems supported higher levels of carbon sequestration compared to monoculture rubber farming. The presence of diverse tree species alongside rubber trees enhanced the overall carbon storage capacity of the ecosystem. This underscores the potential of integrated rubber farming to contribute to global efforts to reduce greenhouse gas emissions.

The current study revealed that soil health and nutrient cycling are closely linked to ecosystem services, as they influence crop productivity and overall ecosystem stability. Diverse vegetation in integrated systems creates habitats for various species, as highlighted in Daru et al. (2023) study in Indonesia. These habitats increase biodiversity, benefit pollinators, natural predators, and nutrient cycling agents, further supporting ecosystem services. Integrated rubber farming's features like riparian zones and vegetative buffers, observed in Mohamad (2012) study in Malaysia, offer valuable wildlife habitat services. These areas act as refuges, conserving biodiversity and providing habitat-related ecosystem services.

Water quality is a crucial environmental parameter, and the impact of agricultural practices on water quality is a subject of growing concern. Integrated rubber farming, characterized by a combination of rubber cultivation with multiple crops and environmentally friendly practices, has gained attention for its potential to improve water quality in agricultural areas. One of the key factors contributing to improved water quality in integrated rubber farming systems is the reduction in the use of harmful chemicals. The current study revealed that integrated rubber farming systems often adopt more sustainable and environmentally friendly practices, reducing the use of harmful chemicals. This can lead to improved water quality in the surrounding areas. Integrated rubber farming enhances nutrient cycling by intercropping diverse crops, as seen in Edwards et al. (1993) study in India. It also features vegetative buffers and riparian zones that act as natural filters, reducing nutrient and sediment runoff into water bodies. Moreover, promoting biodiversity through diverse crops and vegetation in integrated systems indirectly improves water quality. Diverse tree species alongside rubber trees enhance habitat complexity, supporting insect populations involved in water purification and nutrient cycling, ultimately benefiting water quality.

Materials and methods

Survey design and study area

To fulfill its objective, the present study conducted a cross-sectional survey to gather primary data from the selected respondents. In addition, the study took into consideration three common rubber cultivation practices in Thailand: a) integrated rubber-based farming, b) agroforestry plantations, and c) monoculture practices. The survey was conducted in three distinct regions of Thailand: The Northeast, East, and South. Specifically, the Northeast region included Beungkan and Nongkhai Province, the East region comprised Rayong, Chanthaburi, and Trat Province, while the South region covered Suratthani and Songkhla Province. One of the reasons of selecting the above-mentioned regions as the study area is that these regions are enriched with diverse soil types, weather conditions and agricultural practices (Table 7). Secondly, these

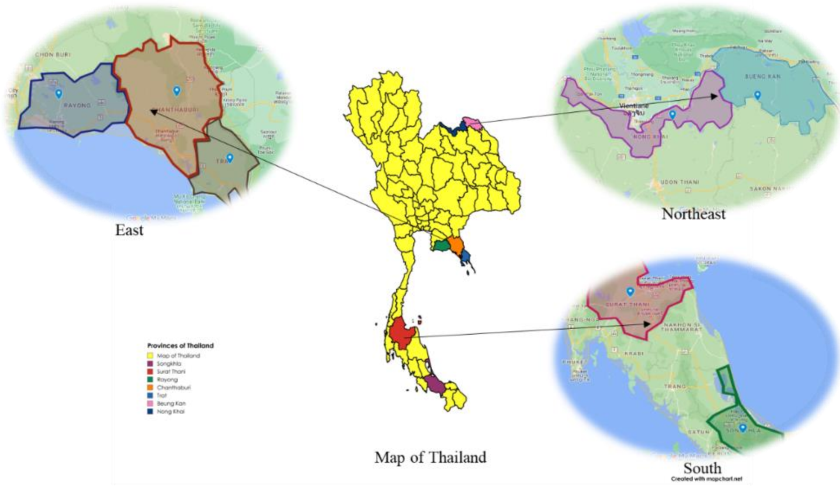


Figure 7. Geographical location of Thailand as well as the study areas.

regions follow three different rubber cultivation practices, namely integrated rubber-based farming, agroforestry plantations, and monoculture. For better understanding of the study areas, a schematic map has been provided showing the geographical location of the country and various regions, and environmental differences (i.e. environmental classification) (Figure 7).

Population, sample size and sampling technique

The population of this study is the rubber farmers who are engaged in various rubber farming practices in the above-mentioned study areas. In other words, the rubber farmers are the unit of analysis for this study. A purposive sampling technique was employed to select the samples. This sampling technique allows for the selection of knowledgeable participants, ensuring depth and representativeness in the study (Creswell and Creswell, 2017). In addition, this method facilitates the deliberate selection of participants possessing valuable insights into the research subject. A total of 30 representative farmers were carefully selected to fulfill the purpose of the study. In other words, the sample size for the current study was 30 rubber farmers.

Questionnaire preparation and data collection

A structured and standardized questionnaire was developed to collect the data from the selected samples. The questionnaire was meticulously designed with several round meetings among the researchers. The questionnaire was tailored to capture data and information on a diverse range of economic, environmental, and social perspectives relevant to the study. The study developed the questionnaire in English and subsequently translated into Thai language to conduct the survey at the field level. The study employed a self-administered survey to collect the data from the respondents. In other words, the selected samples were invited to participate in the survey. After that, the questionnaire was distributed to the selected respondents, and sufficient time was allocated to respond. The respondents provided their free and fair responses.

Statistical analysis of data

The study employed a multifaceted approach, combining both qualitative and quantitative methods to analyze the data. Qualitative analysis provided in-depth insights into various aspects of rubber-based farming systems in Thailand. Concurrently, quantitative analysis employed descriptive statistics and financial assessments to quantify and measure the benefits and challenges associated with the various rubber farming systems. Moreover, a comparative analysis was conducted that enabled a thorough understanding of the various dimensions of the rubber farming practices, offering valuable insights for sustainable development and decision-making within the agricultural sector.

Conclusion

This study provides efforts to assess and analyze various environmental aspects in different rubber-based farming systems, namely, monoculture farming, integrated farming, and agroforestry practices in Thailand. Analysis of ecosystem services reveals a notable distinction among the three different types of rubber farming in terms of their contribution to ecological well-being and sustainability within the rubber production sector. The study found outperformance of integrated rubber farming and agroforestry systems than monoculture methods by a considerable margin, accentuating their ecological benefits. Moreover, the comparison of soil quality attributes (pH, EC, and OM) highlights that integrated rubber farming and agroforestry practices result in superior soil quality and higher organic matter content, particularly in the topsoil layer. These improvements in soil quality signify a promising pathway towards sustainable and environmentally friendly rubber production. Furthermore, integrated rubber farming and agroforestry practices consistently lead to higher soil nutrient concentrations compared to traditional monoculture methods. This disparity underlines the potential for enhanced productivity and sustainability in rubber production through diversified and environmentally conscious approaches. Overall, this article underscores the significant advantages and strategic priorities associated with integrated rubber farming and agroforestry practices in Thai rubber industry. Therefore, it can be concluded that the transition from traditional monoculture methods to diversified and environmentally friendly approaches holds the huge potential for improved production efficiency, control, support, and overall sustainability within the rubber production sector in Thailand.

Acknowledgement

The authors are thankful to the rubber farmers in in three distinct regions of Thailand: The Northeast, East, and South.

These regions featured diverse agricultural practices, encompassing integrated rubber-based farming, agroforestry plantations, and monoculture. Specifically, the Northeast region included Beungkan and Nongkhai, the East region comprised Rayong, Chanthaburi, and Trat, while the South region covered Suratthani and Songkhla Province in Southern Thailand to participate willingly in the survey without any financial and other forms of benefits.

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