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Exploration and Practice of Rubber Based Agroforestry Complex Systems in China

Dongling Qi[1,2,3*], Zhixiang Wu[1,2,3], Chuan Yang[1,2,3], Zhongliang Tao[1,2,3], Linlin Zhao[1,2,3], Yingying Zhang[1,2,3], Qingmao Fu[1,2,3]

[1]Rubber Research Institute, Chinese Academy of Tropical Agricultural Sciences, Haikou, China
[2]Danzhou Investigation & Experiment Station of Tropical Crops, Ministry of Agriculture and Rural Affairs, Danzhou, China
[3]Hainan Danzhou Agro-Ecosystem National Observation and Research Station, Danzhou, China
Email: *donglingqi@163.com

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Abstract

Agroforestry ecosystems are constructed by simulating natural ecosystems, applying the principles of symbiosis in nature, and organizing multiple plant populations to coexist, while conducting targeted cultivation and structural control scientifically. Rubber agroforestry complex ecosystems aim for sustainable development in terms of industry, ecology, resource utilization, and the livelihoods of producers. Rubber agroforestry complex ecosystems create a complex production structure system that integrates biology, society, and the economy through species combinations. Rubber trees and associated biological components coordinate with each other, mutually promote growth, and yield a variety of products for producers. Cultivation techniques and patterns of rubber agroforestry are essential components of these ecosystems. This study analyzes the production practices of rubber agroforestry complex cultivation, with a focus on the development and characteristics (complexity, systematicity, intensity, and hierarchy) of rubber agroforestry systems using a literature analysis and a survey approach. It explores the types and scales of complex planting, specifications and forms, and major effects of complex cultivation. This study identifies successful rubber agroforestry cultivation patterns and practical techniques, as well as the potential benefits of developing rubber agroforestry cultivation. It also points out the shortcomings in the development of complex planting, including an emphasis on production practices but insufficient theoretical research, a focus on production but inadequate attention to the market, and an emphasis on yield while overlooking the improvement of standards, brands, and added value. There are various complex patterns for young rubber plantations, but relatively fewer for mature plantations. Based on this analysis, this study suggests that future efforts should focus on in-depth research on interspecies and environmental interactions in rubber agroforestry ecosystems, clearly define key roles, accelerate the innovation of development patterns, and strengthen the foundation for development. It recommends promoting and demonstrating successful rubber agroforestry complex patterns and providing technical training, developing product branding for rubber agroforestry patterns, enhancing product value, expanding the application functions of rubber-forest mixed crop products, and establishing a stable and sustainable industry chain. This study provide practical experience and theoretical insights in rubber agroforestry complex systems from China the potential to enrich the knowledge of rubber agroforestry composite systems, provide practical experience to improve the operating income of smallholders, and even promote the sustainable development of rubber plantations.

Keywords

Rubber Tree (*Hevea brasiliensis*), Agroforestry Ecosystem, Rubber Intercropping, Complex Ecological Cultivation, Land Resource

1. Introduction

In the 21st century, many countries around the world have successively begun to research the theory and practice of sustainable development. Issues related to agriculture, rural areas, and farmers, as the most crucial components of sustainable development, have been gradually promoted. With the emergence of global common issues such as population growth, resource scarcity, food shortages, environmental pollution, energy crises, and climate change, human society faces unprecedented development pressures [1]. The reasons for these problems are diverse, and the direction and path of development in agriculture and forestry have become a focal point of global attention. Since the end of World War II, some countries have actively explored and proposed new concepts, theories, and practices in agriculture and forestry based on a careful review of experiences and lessons in the development of these sectors, examples including agroforestry, mixed farming, ecological agriculture, and sustainable agriculture [2]-[8]. In 1991, the Food and Agriculture Organization of the United Nations(FAO) introduced three goals for sustainable agriculture during the Agriculture and Environment Conference in the Netherlands: first, the development of sustainable agriculture should prioritize increasing food production to ensure global food security and eliminate hunger; second, sustainable agriculture should promote comprehensive rural development, increase farmers' income, and alleviate poverty; third, it should focus on protecting, improving, and judiciously using natural resources to create a favorable natural environment conducive to the survival and development of future generations [9].

When looking at the global development practices as a whole, there are generally two paths for the development of agriculture and forestry. One path relies on continually expanding agricultural land area, while the other path emphasizes improving per-unit area crop yield, product quality, and increasing land resource output, while leveraging the various services provided by agricultural and forestry ecosystems. Therefore, the future trend for the sustainable development of agriculture and forestry, especially in a country like China with limited arable land and not a high per capita land resource quantity, is primarily on the latter path. Among various planting systems, agroforestry, intercropping, mixed cropping, complex planting and crop rotation are important components [10] [11] [12] [13] [14]. Agroforestry systems are a pattern for sustainable land use and enhancing food security [15] [16] [17], as they coordinate the development of agricultural and forestry production systems for efficient and sustainable resource utilization [18] [19] [20]. Consequently, the overall productivity of the entire agroforestry system can be increased [21]-[29].

2. Production Practice of Rubber Agroforestry Complex Cultivation

2.1. The Historical Evolution of Rubber Agroforestry Complex Ecological Cultivation

Rubber monoculture plantations not only result in low structural stability but also lead to inefficient utilization of resources in tropical regions, contributing to the wastage of climate and land resources [30]-[37]. Exploration of rubber agroforestry cultivation patterns and techniques began overseas in the early 20th century and saw rapid development after the 1950s [38]-[45]. Since 1910, rubber plantation operators in Southeast Asian countries such as Malaysia, Indonesia, Sri Lanka, and Thailand have been engaged in exploratory practices in the field of agroforestry cultivation with the "jungle rubber pattern" [46]. In China, the exploration and application of rubber agroforestry patterns started in the 1950s and quickly developed. By the 1980s, rubber agroforestry complex patterns had achieved a high level of development in terms of technology, scale, and overall benefits. Various mature complex cultivation patterns including rubber–tea and rubber–banana, have been successively explored within China [47] [48]. The exploration and application of rubber agroforestry cultivation patterns have enriched the practice of rubber agroforestry management, improved land utilization efficiency in rubber plantations, and increased economic income for operators [49]-[54].

2.2. Development Characteristics of Rubber Agroforestry Complex System in China

The rubber agroforestry complex system is constructed by simulating natural ecosystems, applying the principles of symbiosis found in nature, and intentionally organizing several plant populations to coexist. It involves directed nurturing and rational structural control within a specific time frame, ecological space, and population composition. Additionally, it follows the principles of material cycling, enabling multiple levels and pathways for recycling [55]. The transformation of rubber plantations to multi-crop compound plantations are to select crop species that are suitable for the biological characteristics of rubber trees and have high economic and ecological value, and to construct a three-dimensional planting community structure between rubber plantation rows, intercropping, compound planting, mixed cropping, crop species and rubber trees. Rubber trees and these crops form important member species in the planting system, and the synergy between species promotes soil and water conservation and improves soil quality, the vegetation productivity, stability and environmental protection ability of the original monoculture rubber plantation can be improved. The rubber agroforestry complex system possesses the following fundamental characteristics (**Figure 1**).

2.2.1. Complexity of Rubber Agroforestry Complex System

It encompasses both the layout in terms of space and time, integrating multiple levels and populations into an artificial agroforestry system. It combines ecology, technology, and economics to create diverse agricultural and forestry products. The rubber complex system mimics natural community structures, resulting in relatively complex species compositions that enhance the system's overall resilience and stability [28] [54].

2.2.2. Systematicity of Rubber Agroforestry Complex System

The rubber agroforestry complex system reflects an integrated structure and function. It involves the exchange of matter, energy, and information between the components of the system, following principles of maximizing overall benefits and sustainability in rubber plantation production systems and growth environments.

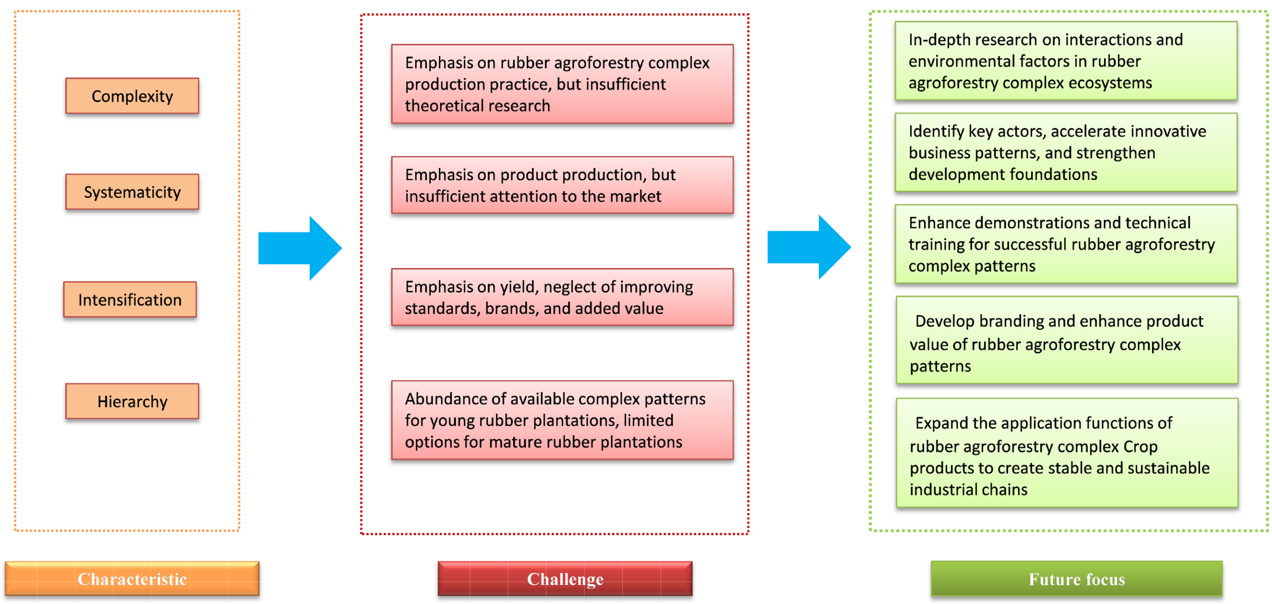

Figure 1. Characteristics, challenges faced and the focus of future efforts for rubber based rubber agroforestry complex system.

2.2.3. Intensity of Rubber Agroforestry Complex System

The entire rubber agroforestry complex system involves deep-level development in terms of sunlight, varieties, land, space, and time. It also requires higher investments in diverse technologies and production inputs.

2.2.4. Hierarchy of Rubber Agroforestry Complex System

The rubber agroforestry complex system can be categorized into mountainous agroforestry complex rubber plantations, plain agroforestry complex rubber plantations, young agroforestry complex rubber plantations, and mature agroforestry complex rubber plantations.

2.3. Main Achievements in the Development of Rubber Agroforestry Complex Planting Pattern

2.3.1. Exploration of Successful Rubber Agroforestry Complex Planting Patterns

Through several decades of production practices, a number of successful rubber agroforestry complex planting patterns have been explored and summarized. These patterns include Rubber—*Alpinia oxyphylla*, Rubber–banana, rubber—*Amomum villosum*, Rubber—*Amorphophallus*, Rubber—*Phrynium hainanense*, Rubber—Tea, Rubber—kudzu vine and Rubber–pineapple complex ecological planting patterns (Figure 2). Among the above patterns complex planting

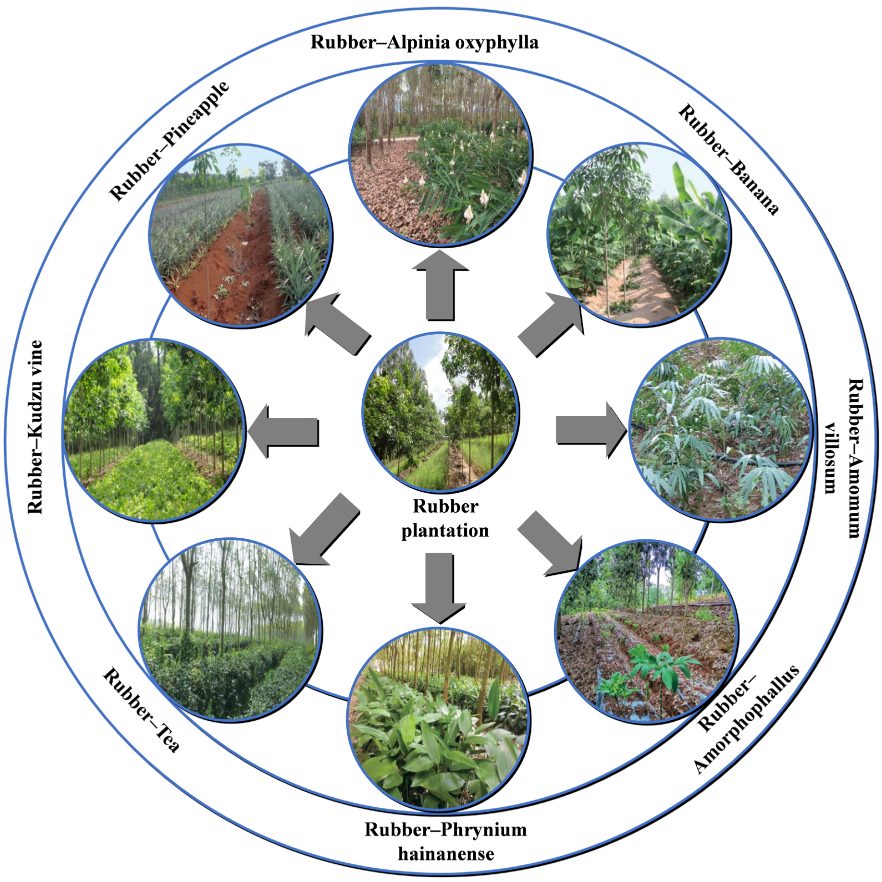

Figure 2. Main patterns complex planting of rubber based agroforestry in China.

of rubber based agroforestry, the rubber—*Alpinia oxyphylla* plantation shows relatively high yield and economic benefits, which can significantly improve the economic income of smallholders' rubber plantations, and the economic income growth rate reaches 64% after two years of complex planting [52]. Rubber—*Alpinia oxyphylla* plantation, Rubber—Tea plantation, Rubber—kudzu vine plantation can all promote the growth of rubber trees, especially Rubber—kudzu vine plantation has a significant promoting effect [56] [57]. They have been applied in rubber cultivation production and greatly enriched the source of income for rubber plantation producers.

2.3.2. Summation of Practical Techniques in Rubber Agroforestry Complex Planting Patterns

Main practical techniques have been summarized for rubber-pineapple complex planting techniques, rubber—*Alpinia oxyphylla* complex planting techniques, rubber–Banana complex planting techniques, and rubber—*Phrynium hainanense* complex planting techniques [9]. This has resulted in the establishment of technical standards like the "Technical code of practice for cultivation of *Ficus hirta* Vahl. under rubber forest", "Technical cultivation regulation on intercropping of rubber with ginger in rubber producing area of Hainan Province" and the "Technical regulations for cultivation of interplanting pandanus under forest" [58] [59]. These practical techniques and technical standards have promoted the standardization and normalization of rubber agroforestry complex cultivation, facilitating improved quality, efficiency, and the further release of production potential in rubber agroforestry complex planting.

3. Shortcomings in the Development of Rubber Agroforestry Complex Planting Patterns

China has been exploring rubber agroforestry complex planting patterns since the 1950s. Under the active promotion of many parties, including governments, scientists, and production managers, significant achievements and outcomes have been attained in various aspects of rubber agroforestry complex planting, including optimal combination of complex crops selection for rubber based agroforestry, complex patterns, cultivation techniques, resource utilization efficiency, and complex system performance evaluation. Timely summaries and assessments have been conducted on these achievements, resulting in the establishment of a relatively comprehensive production technology system. Despite these accomplishments in rubber agroforestry complex systems, there are still several areas requiring further improvement, development, and enhancement in practical production management of rubber agroforestry complex systems (**Figure 1**).

3.1. Emphasis on Rubber Agroforestry Complex Production Practice, but Insufficient Theoretical Research

The transformation of rubber plantations from single-crop planting to complex planting involving multiple crops has altered both the aboveground and underground environments. Aboveground, it raises questions about how rubber trees and the complex crops compete and collaborate in terms of spatial and solar resources, resulting in the formation of distinct microclimatic conditions. Belowground, the mechanisms governing the distribution of roots, water, and nutrient utilization between rubber trees and complex crops remain insufficiently explored.

3.2. Emphasis on Product Production, but Insufficient Attention to the Market

Production managers often prioritize the production, management, and investments in agricultural products within the rubber agroforestry system. However, they do not enough focus on market demand for the produced products, including their quantity, quality, product structure, and regional demand.

3.3. Emphasis on Yield, Neglect of Improving Standards, Brands, and Added Value

Throughout the entire production process of rubber agroforestry complex systems, production managers tend to prioritize yield. However, there is not enough emphasis on establishing production standards, creating brands, marketing, and enhancing benefit. There is a lack of an effective system for quality control encompassing yield, quality, standards, brands, and benefit.

3.4. Abundance of Available Complex Patterns for Young Rubber Plantations, Limited Options for Mature Rubber Plantations

Various complex patterns have been explored for young rubber plantations, mainly including rubber—banana plantation, rubber—cassava plantation, rubber—pineapple plantation, rubber—kudzu vine plantation, rubber—sweet potato, rubber—sugarcane plantation, rubber—peanut plantation, rubber—pepper plantation, rubber—pumpkin plantation, rubber—corn plantation, rubber—ginger plantation, rubber—roselle plantation and rubber—passionfruit plantation [9] [59]. In contrast, fewer complex patterns have been developed for mature rubber plantations, including rubber—tea plantation, rubber—*Alpinia oxyphylla* plantation and rubber—*Amorphophallus* plantation.

4. Suggestions and Policy

4.1. In-Depth Research on Interactions and Environmental Factors in Rubber Agroforestry Complex Ecosystems

The transformation from rubber monoculture to rubber agroforestry introduces new species combinations and environmental conditions. In-depth research on the interactions between species composition units in rubber agroforestry complex ecosystems and the competition and synergy between rubber trees and companion crops for spatial and light-heat resources is crucial to provide theoretical support for rubber agroforestry complex production and ecological management. The important practical experience of high-yield cultivation of rubber trees in China's rubber planting areas, which involves the coordination of environmental, rubber tree clone, and management measures during the cultivation process of rubber trees, is fully integrated with the rubber agroforestry ecosystem to achieve high and stable yields [60].

4.2. Identify Key Actors, Accelerate Innovative Business Patterns, and Strengthen Development Foundations

Local governments play a crucial role by facilitating and supporting the establishment of agricultural cooperatives, promoting agricultural development funds, and collaborating with professional institutions, research organizations, sales companies, industry associations, processing enterprises, and product demand stakeholders. This collaborative approach encourages the development of moderately scaled rubber agroforestry complex planting bases, pooling resources from various parties, defining key roles, accelerating the innovation of development patterns, and solidifying the foundations for further growth.

4.3. Enhance Demonstrations and Technical Training for Successful Rubber Agroforestry Complex Patterns

Efforts should be made to excel in demonstrating rubber agroforestry complex patterns. It is essential to avoid hasty promotion of techniques that are subject to significant controversy, not yet matured, or lacking adequate conditions for expansion. Instead, these techniques should be carefully demonstrated and resolved before gradual promotion.

For established successful rubber agroforestry complex patterns, it is necessary to further refine and optimize them. This includes enhancing land utilization, especially in mature rubber agroforestry with suitable conditions. This might involve the cultivation of shade-loving cash crops including *Alpinia oxyphylla* and ginger. Notably, the *Alpinia oxyphylla* industry in Baisha County, Hainan, provides a substantial scale, and the government, enterprises, and farmers are collaboratively exploring how to develop branding, production management quality control, the formation of the industrial chain, and strategies for connecting with the market.

4.4. Develop Branding and Enhance Product Value of Rubber Agroforestry Complex Patterns

Achieving standardization and simplification of rubber agroforestry complex pattern technology is essential. With industrialization and urbanization, the agricultural labor force is undergoing a transition, leading to labor shortages and increased labor cost. Scaling, standardizing, simplifying, mechanizing, digitalizing, and industrializing agricultural production are essential trends. Therefore, it is necessary to develop and standardize the technologies of existing successful rubber agroforestry complex patterns and provide training for standardization and simplification.

Exploration of standardized production of rubber agroforestry complex crops should be conducted, aligning with local resources and special advantages to create product brands. Hybrid sales patterns that combine online and offline sales, e-commerce live streaming, and product promotions should be explored to boost product market sales. An excellent example of this is the success of the rubber and banana complex planting pattern in Longjiang Subsidiary of Hainan Rubber, which has remained consistent with the pattern for over 30 years. This pattern has steadily developed into a large-scale production operation with increasingly standardized techniques and, in the process, has formed a robust brand effect, attracting banana buyers from Shandong, Shaanxi, Zhejiang, Jiangsu, and other regions.

4.5. Expand the Application Functions of Rubber Agroforestry Complex Crop Products to Create Stable and Sustainable Industrial Chains

By leveraging research institutions and establishing production and research bases, it is essential to expand the development of multifunctional products within the rubber agroforestry complex products. This expansion should be based on existing products, leading to the formulation of corresponding standards, as well as full-product life-cycle traceability systems.

For example, the thousands of hectares of rubber and *Alpinia oxyphylla* complex planting in Qingsong Township, Baisha County of Hainan Province in China, have leveraged the region's favorable natural environmental conditions and long-term development foundation. They established an *Alpinia oxyphylla* functional product research and development center in partnership with a large pharmaceutical company in Beijing. By focusing on current and future market trends and harnessing local resource advantages, they have organized a powerful research and development force, substantial financial resources, and are now developing a series of *Alpinia oxyphylla* functional products. This endeavor has expanded and elongated the industrial chain, forming a robust and stable supply and demand industrial chain.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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