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Visualization Analysis of the Impact of Rubber Agroforestry Ecosystem on Soil Microbial Community

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Abstract

Rubber agroforestry systems positively impact soil microbial communities. This study employed a bibliometric approach to explore the research status, hotspots, and development trends related to these effects. Using CiteSpace software, we visually analyzed research literature from the Web of Science (WOS) core database, spanning 2004 to 2024. The focus was on the impact of rubber agroforestry ecosystems on soil microbial communities. The results indicate significant attention from Chinese researchers, who have published numerous influential papers in this field. Authors Liu Wenjie have contributed the most papers, although no stable core author group exists. The Chinese Academy of Sciences is the leading research institution in terms of publication volume. While there is close collaboration between different institutions and countries, the intensity of researcher cooperation is low. The most cited literature emphasizes soil nutrients and structure in rubber agroforestry, laying a foundation for soil microorganism studies. Most cited journals are from countries like Netherlands and the United Kingdom. Key research areas include the effects of rubber intercropping on soil microbial communities, agroforestry management, and soil health. Research development can be divided into three stages: the initial stage (2010-2015), the development stage (2015-2020), and the mature stage (2020-2024). Current studies show that rubber intercropping and rubber-based agroforestry systems enhance soil microbial communities, positively impacting soil health. This paper provides a theoretical basis for the sustainable development of rubber agroforestry systems and improved management plans. Future research could explore the effects of species composition on soil microbiological characteristics and develop methods for species interactions. An in-depth study of the soil microbial community's structure and function, and its relationship with rubber trees, is crucial. Developing effective, rationally designed rubber agroforestry systems and underground soil microbiome technology will promote sustainability and improve plantation productivity.

Keywords

Rubber (*Hevea brasiliensis*), Agroforestry Ecosystem, Microbe, CiteSpace, Bibliometrics, Rubber Intercropping

1. Introduction

Soil microorganisms are the most active organisms in soil ecosystems and play a crucial role in terrestrial ecosystems [1] [2]. These microbes, including bacteria, fungi, and bacteriovorous nematodes, drive ecosystem functions such as nutrient cycling and promote the biotransformation of carbon and nitrogen within soil food webs [3]. Plants interact with various soil microbial communities, forming interdependent relationships, such as symbiosis, which enhance plant productivity, below-ground biodiversity, and soil function [4]. Moreover, soil microorganisms initiate biological weathering, organic matter decomposition, and nutrient cycling, significantly impacting soil formation [5]. In today's changing environment, they play a vital role in helping plants resist abiotic stresses through various mechanisms [6]. Additionally, soil microbes are key players in greenhouse gas production and environmental purification, forming an essential part of various biogeochemical cycles [7]. Microbial community dynamics are widely used in evaluating soil quality and health due to their strong correlation with physicochemical properties like soil pH, nutrients, and the stability of soil organic matter [8]. Thus, the study of soil microorganisms has become a hot topic in nutrient cycling and environmental resource utilization.

Rubber trees are a vital source of natural rubber, a strategic material for economic development [9]. As the economy grows, the demand for rubber increases, leading to the conversion of tropical rainforests into monoculture rubber plantations. This results in negative consequences, such as reduced microbial and plant diversity, soil degradation, and decreased soil water retention [10]-[12]. With the expansion of rubber cultivation, studying the soil ecosystem of rubber plantations and finding solutions to alleviate these issues is crucial.

Previous studies have shown that combining rubber with intercropping or rubber-based agroforestry systems can enhance soil microbial communities [13]. This improvement is likely due to the high diversity of intercropping plants, which boosts soil moisture, carbon, and nitrogen content, supporting dominant soil organisms like bacteria and fungi [3]. In rubber agroforestry systems, the presence of herbs, shrubs, and small trees under rubber trees regulates plant resource input and provides suitable ecological niches for microorganisms [3].

Differences in plantation management practices also affect soil microorganisms. Rubber-leguminous intercropping systems use less chemical fertilizer than monoculture rubber plantations, promoting the growth of arbuscular mycorrhizal fungi [14]. Therefore, understanding the effects of rubber agroforestry systems on soil microorganisms is crucial. This study visually analyzed research literature on rubber agroforestry systems from the Web of Science (WOS) core database (2004-2024) using CiteSpace software. We examined the research status and development trends to provide a theoretical basis for the sustainable development and improved management of rubber agroforestry systems.

2. Data collection and Analysis Methods

2.1. Collection of Data

In this study, literature data were sourced from the Web of Science (WOS) core database, covering the period from January 2004 to July 2024. We used subject search terms such as "Rubber (Topic)" and "Soil (Topic)" and "Micro (Topic)" and "Intercrop (Topic)" or "Agroforestry (Abstract)", with the language set to "English". The literature type was restricted to "Article", a total of 6,841 related articles were retrieves, and 82 were included in the analysis after a secondary search, excluding those that did not meet the criteria.

2.2. Data Analysis Methods

Bibliometrics and CiteSpace 6.3.R1 visual analysis software were used to plot authors, institutions, countries, co-cited articles, co-cited journals, keyword co-occurrence, keyword clustering networks, and keyword timeline diagrams. By quantitatively analyzing this data, we revealed the hotspots and evolution trends of rubber agroforestry ecology on soil microbial communities. CiteSpace, a widely used bibliographic analysis tool, conceptualizes research space as a mapping between research domains and the knowledge base. It explains the quantitative relationships, distribution structures, and changes in documents, providing a quantitative method to analyze textual information for specific research projects over time [15]. Compared to qualitative analysis methods, such as direct observation, interviews, or literature review, this approach offers a more comprehensive and intuitive understanding of research developments [16].

3. Results

3.1. Authors Collaborated on the Analysis

Using CiteSpace software, we mapped 75 nodes and 136 lines of the research field of rubber agroforestry ecology on soil microbial communities from 2004 to 2024. **Figure 1** shows that cooperation in this field is relatively scattered, with many joint author groups. According to Price's law, a core author must publish at least MP papers, where $MP = 0.749\sqrt{NPMAX}$, and NPMAX is the highest number of papers published by a single author during the period. As shown in **Table 1**, Liu Wenjie are the most prolific authors, each with 26 papers, making

NPMAX 26. Thus, MP ≈ 3.82, meaning at least 4 papers are needed to be considered a core author. Table 1 identifies 9 core authors in the field. However, for a stable group of core authors, their publications must account for 50% of the total papers. Currently, the 9 core authors contribute 98 papers, about 41.9% of the total, indicating no stable core author group has formed.

Figure 1. Author cooperative network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 1. The part of authors and their literature number of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Author	Literature number
1	Liu, Wenjie	26
2	Wu, Junen	16
3	Chen, Chunfeng	16
4	Zhu, Xiai	12
5	Yang, Bin	8
6	Singh, Ashutosh Kumar	6
7	Zeng, Huanhuan	5
8	Jiang, Xiaojin	5
9	Zakari, Sissou	4

3.2. Research Institute Collaboration Analysis

When creating the network map of research institutes in rubber agroforestry ecology concerning soil microbial communities, a map was generated comprising 61 nodes and 76 connections (Figure 2). The network density of this map is 0.0339, suggesting relatively close cooperation among the institutions. The top three institutions with the highest number of publications were the Chinese Academy of Sciences (41 articles), University of Chinese Academy of Sciences (30 articles), and Chinese Academy of Tropical Agricultural Sciences (7 articles). CIRAD, China Agricultural University, and University of Göttingen each published 3 articles, while others published fewer than 3 articles (Table 2). As depicted in **Figure 2**, the top three institutions in terms of publication numbers exhibit strong collaboration with other institutions. Specifically, the University of Chinese Academy of Sciences holds a high centrality value (0.29) in the network map, indicating extensive cooperation with other institutions.

Figure 2. Institutions cooperative network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 2. The part of institutions and their literature number of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Research institution	Literature number
1	Chinese Acad Sci	41
2	Univ Chinese Acad Sci	30
3	Chinese Acad Trop Agr Sci	7
4	CIRAD	3
5	China Agr Univ	3
6	Univ Gottingen	3
7	Univ Western Australia	2
8	Yunnan Normal Univ	2
9	Assam Univ	2
10	Bogor Agr Univ	2
11	Xinjiang Univ	2
12	Univ Nottingham	2
13	Univ Putra Malaysia	2

3.3. Analysis of Country Cooperation

In the study of mapping the national network of the impact of rubber agroforestry ecology on soil microbial communities, a network map with 28 nodes and

33 lines was created (**Figure 3**). The network density is 0.0714, indicating relatively close cooperation between countries. According to **Table 3**, China (49 papers), Brazil (9 papers), and Germany (8 papers) are the leading countries in terms of published research, highlighting China's significant focus on this topic. China also has a high centrality value (0.76) in the network map, suggesting close collaboration with other countries and substantial influence. Notably, Japan, despite having fewer publications, has a high centrality value (0.57), reflecting its strong influence in this field. In contrast, while Brazil, France, and Australia have a notable number of publications, no centrality values were found for them.

Figure 3. Countries cooperative network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 3. The part of countries and their literature number of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Country/Region	Literature number	Central value
1	PEOPLES R CHINA	49	0.76
2	BRAZIL	9	0
3	GERMANY	8	0.34
4	FRANCE	5	0
5	AUSTRALIA	5	0
6	INDONESIA	5	0.18
7	THAILAND	5	0.53
8	INDIA	5	0
9	MALAYSIA	4	0.09
10	CANADA	3	0
11	BENIN	3	0
12	PHILIPPINES	2	0
13	JAPAN	2	0.57
14	ENGLAND	2	0.01
15	USA	2	0.09

3.4. Co-Cited Article Analysis

In mapping the national network of soil microbial communities in rubber agroforestry ecology, a map with 162 nodes and 449 connections was created (Figure 4 and Table 4). One of the most cited papers is "Can intercropping with the cash

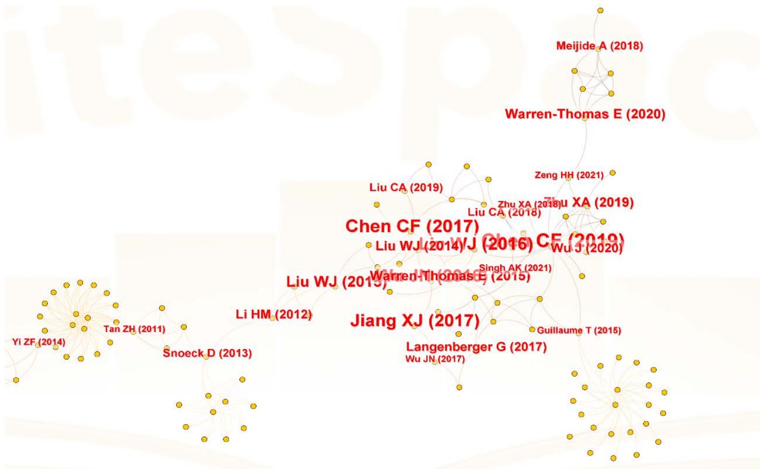

Figure 4. Cited references network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 4. The part of cited references and their count of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Literatures	Count
1	Can intercropping with the cash crop help improve the soil physico-chemical properties of rubber plantations?	16
2	Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: Implications for land use	13
3	Are rubber-based agroforestry systems effective in controlling rain splash erosion?	12
4	Can intercropping with the world's three major beverage plants help improve the water use of rubber trees?	11
5	Land degradation controlled and mitigated by rubber-based agroforestry systems through optimizing soil physical conditions and water supply mechanisms: a case study in Xishuangbanna, China	11
6	The effects of conversion of tropical rainforest to rubber plantation on splash erosion in Xishuangbanna, SW China	8
7	Increasing demand for natural rubber necessitates a robust sustainability initiative to mitigate impacts on tropical biodiversity	6
8	Can intercrops improve soil water infiltrability and preferential flow in rubber-based agroforestry system?	6
9	Rubber agroforestry in Thailand provides some biodiversity benefits without reducing yields	6
10	Vertical patterns of soil water acquisition by non-native rubber trees (*Hevea brasiliensis*) in Xishuangbanna, southwest China	6

crop help improve the soil physico-chemical properties of rubber plantations?" by Chen, CF *et al.*, published in 2018. Similarly, the 2017 article "Effects of rubber-based agroforestry systems on soil aggregation and associated soil organic carbon: Implications for land use," also by Chen, CF *et al.*, is highly cited. This research indicates that studies on the effects of rubber agroforestry ecosystems on soil microbial communities are largely based on soil nutrients and physical properties. It emphasizes that soil's physical and chemical properties significantly affect soil microorganisms. Continuous monitoring of soil characteristics and improvements in management programs are recommended.

3.5. Journal Co-Citation Analysis

Through co-citation analysis of journals, researchers can identify the core journals and countries involved in a specific research field. From 2004 to 2024, a total of 173 journals contributed to this area, with those having high citation frequencies shown in Figure 5 and Table 5. The AGROFOREST SYST highlights the role of agriculture and forestry in providing both commodity and non-commodity benefits, such as ecosystem services. It also explores how agriculture affects the environment and how environmental changes impact agricultural ecosystems.

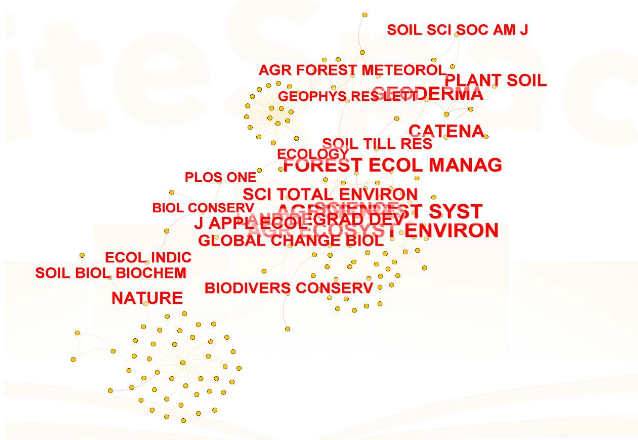

Figure 5. Published journals network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 5. The part of published journals and their count of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Journals	Country	Count
1	AGROFOREST SYST	Netherlands	55
2	AGR ECOSYST ENVIRON	Netherlands	55
3	FOREST ECOL MANAG	Netherlands	48
4	SCIENCE	American	41

Continued

5	GEODERMA	Netherlands	39
6	CATENA	Germany	35
7	SCI TOTAL ENVIRON	Netherlands	29
8	LAND DEGRAD DEV	England	29
9	J APPL ECOL	England	28
10	NATURE	England	27
11	PLANT SOIL	Netherlands	27
12	GLOBAL CHANGE BIOL	England	22
13	SOIL TILL RES	Netherlands	18
14	BIODIVERS CONSERV	Netherlands	18
15	ECOL INDIC	Netherlands	17
16	AGR FOREST METEOROL	Netherlands	16
17	SOIL BIOL BIOCHEM	England	16
18	SOIL SCI SOC AM J	American	16
19	ECOLOGY	Netherlands	14

3.6. Keyword Co-Occurrence Analysis

In mapping the keyword network of rubber agroforestry ecology's impact on soil microbial communities, a network with 106 nodes and 320 connections was created (Figure 6). The most frequent keywords included Xishuangbanna (16 times), Agroforestry Systems (15 times), Forest (9 times), *Hevea brasiliensis* (8 times), Land Use (8 times), and Rubber Plantations (8 times) (Table 6), indicating the primary research areas.

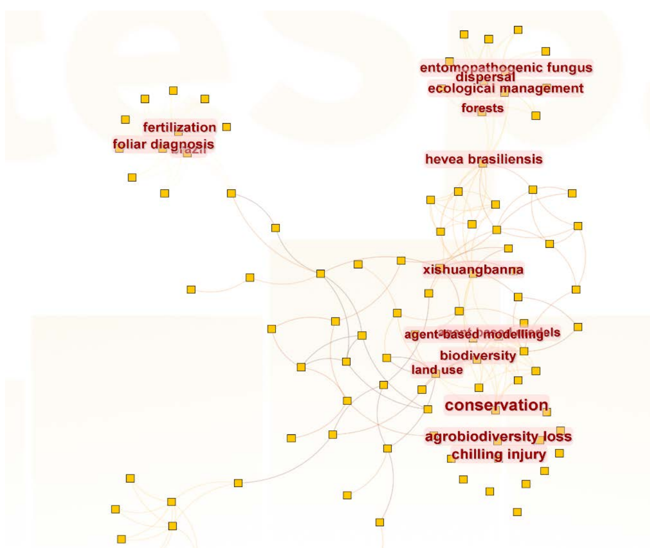

Figure 6. Keywords co-occurrence network of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Table 6. The part of keywords cooccurrence and their count of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

Code	Keywords	Count
1	xishuangbanna	16
2	agroforestry systems	15
3	forest	9
4	*Hevea brasiliensis*	8
5	land use	8
6	rubber plantations	8
7	agroforestry system	7
8	rain forest	7
9	diversity	7
10	plantations	6
11	community	5
12	biodiversity	5
13	agroforestry	5

3.7. Keyword Clustering

In this study, the clustering module achieved a Q value of 0.6209 and an average Silhouette value of 0.8486, confirming its significant structure and high reliability. Figure 7 illustrates several clusters in Yunnan, China, focusing on topics such as water use in agricultural biology, preferential flow, soil quality assessment, hirsutella, multi-strata agroforestry, tree cash crop plantation, and soil microbiome. These clusters highlight the predominant research themes in soil microbial communities within rubber agroforestry ecology from 2004 to 2024.

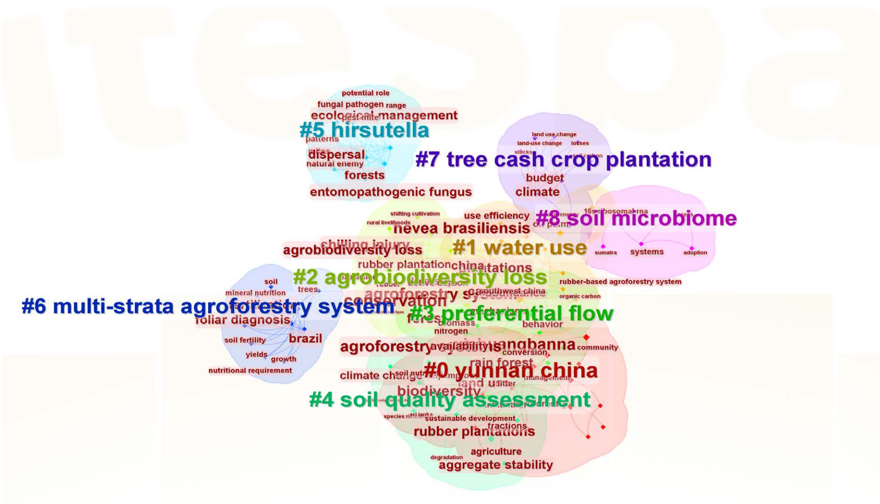

Figure 7. Keywords cluster of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

3.8. Key Word Timeline Graph Analysis

In this study, research topics are categorized into three time periods based on keyword clustering distribution (Figure 8):

(1) Initial stage (2010-2015): Keywords during this period include land use transition, rubber plantation, diversity, fertilization, ecosystem management, fungal pathogens, etc. This stage primarily investigates changes in biodiversity following the transformation of rubber plantations into rubber agroforestry systems, as well as management strategies for rubber agroforestry.

(2) Development stage (2015-2020): Keywords in this phase focus on biodiversity, rubber forests, agroforestry systems, litter, water infiltration, organic carbon, and agroforestry system management. Research during this period emphasizes the interactions between climate factors (such as precipitation), water dynamics, and soil microbial communities within rubber agroforestry systems.

(3) Maturity stage (2020-2024): Keywords include available phosphorus, soil nitrogen, community, competition, soil degradation, and biomass carbon. This stage primarily investigates factors influencing microbial communities in rubber agroforestry systems and how changes in microbial communities affect these systems.

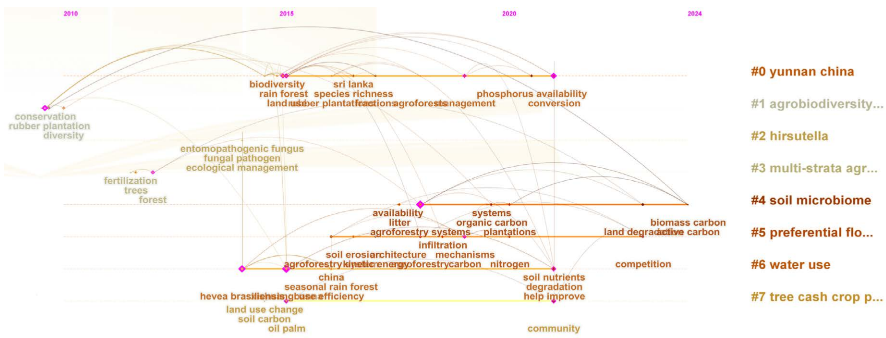

Figure 8. Keywords time plot analysis of research literatures of effects of rubber agroforestry ecosystems on soil microbial communities in 2004-2024.

4. Discussion

On the analysis of Authors collaborated, Figure 1, the cooperation in this field is relatively scattered, and there are many joint groups of authors. According to Price's law, to become a core author in the field, at least MP papers need to be published, $MP = 0.749\sqrt{NPMAX}$, where NPMAX is the number of papers published by the author with the largest number of papers published in the statistical period. From Table 1, it can be seen that the authors with the largest number of papers are Liu Wenjie, and the number of published papers is 26, that is, NPMAX is 26, then the MP ≈ is 3.82, that is, at least 4 papers have been published, in order to become the core authors in the field, and from Table 1, it can be seen that the core authors in this field are 8. But the number of papers published by core authors must account for 50% of the total number of papers published in the field in order to say that a stable joint group of core authors has been formed in the field [17]. **Table 1** shows that the 9 core authors have published a total of 98 papers, accounting for about 41.9% of the total publications in this field. This is less than 50%, indicating that a cohesive group of core authors has not yet formed in the research area of rubber agroforestry ecology on soil microbial communities. Through literature co-citation analysis, researchers can understand the citation relationships within a specific field, revealing key research findings, hotspots, and interdisciplinary links [18]. Keywords represent the core content of a paper, and a co-occurrence analysis can help researchers identify research hotspots and trends and keyword cluster analysis aids researchers in identifying correlations among frequently appearing keywords within a field, thereby uncovering prominent topics and themes [18]. Clusters in the figure, depicted with lines and nodes of the same color, represent cohesive groups. Using CiteSpace for keyword clustering mapping, researchers assess the mapping's effectiveness through modularity (Q value) and Silhouette (S value). A Q value > 0.3 signifies significant clustering structure, while an S value > 0.5 is considered reasonable and > 0.7 indicates convincing results [15]. Keyword timeline analysis is valuable for understanding the evolution and trends of keywords within related research fields [18]. In this study, research topics are three time periods including Initial stage (2010-2015), Development stage (2015-2020) and Maturity stage (2020-2024).

Effects of rubber intercropping on soil microbial communities: Qi D *et al*. demonstrated that intercropping with *Michelia macclurei* increased the bacterial and total microbial abundance in a single rubber plantation by an average of 75.51% and 48.42%, respectively. This indicates that rubber agroforestry ecosystems can enhance soil microbial communities and foster a soil environment conducive to tree growth [19]. Wen *et al*. found that these ecosystems improve soil water retention, leading to increased soil bacterial diversity, which is crucial for enhancing soil fertility [20]. Liu C *et al*. showed that introducing *Flemingia macrophylla* into a rubber plantation results in higher bacterial diversity, attributed to improved soil quality [21]. After establishing the rubber agroforestry system, the abundance and diversity of bacterial communities nearly returned to levels seen in young stands, demonstrating high resilience [21]. Experiments indicate that rubber in agroforestry ecosystems significantly boosts microbial biomass C and N compared to a single rubber plantation [22] [23].

This study found that rubber-based agroforestry systems significantly improve soil physical properties, structure, and enrich soil nutrients and moisture [24] (Chen C *et al*., 2019), which in turn affect soil microorganisms [20] (Wen Z *et al*., 2022). Additionally, it confirms that agroforestry systems support microbial activity by enhancing root density and distribution, and increasing biodiversity above and below ground [24]. Current research indicates that rubber intercropping or rubber-based agroforestry systems can enhance soil microbial communities and positively impact soil health. However, it is important to note significant variations in the effects of different rubber agroforestry systems on soil microbial communities. For instance, combined cropping systems such as rubber trees with cocoa can detrimentally affect soil microbial activity due to sulfur inputs from disease and weed management practices [25]. Similarly, cultivation of rubber trees with konjac has been found to decrease bacterial and actinomycete abundance in rhizosphere soil while increasing it in non-rhizosphere soil [26] (Li *et al*., 2019). Studies also highlight that annual forest practices in rubber agroforestry systems exert stronger impacts on bacterial communities than management types. Bacterial abundance and diversity are typically maintained in mature rubber agroforestry systems, whereas younger systems show increased diversity but reduced abundance compared to single rubber planting systems [21].

In the research of rubber agroforestry management and soil microbial community, Zakari S *et al*. proposed that rubber agroforestry management should prioritize upslopes, implementing terraces and weed farming systems to manage runoff and protect soil from elemental sulfur and erosion, thereby averting adverse effects on soil microorganisms [25]. Meanwhile, Liu *et al*. demonstrated that soil nutrients and pH significantly influence bacterial community structure. They found that establishing a rubber agroforestry ecosystem can mitigate the negative impacts of chemical fertilizers on bacterial diversity. They recommended appropriate lime treatment for acidic soils to maintain optimal pH levels conducive to bacterial growth [21].

Regarding soil microbial communities, previous research has predominantly focused on microbial biomass and community composition in single rubber planting systems and comparisons with rubber agroforestry systems. Few studies have explored how species composition within rubber agroforestry systems affects microbial properties and the mechanisms of interspecific interactions. Advancements in high-throughput sequencing technologies, such as the cost-effective and precise Illumina sequencing, have revolutionized research on soil microorganisms. This technology fragments genomic DNA into 200 - 500 bp segments, allowing simultaneous sequencing of hundreds of samples and generation of vast datasets [27]. These capabilities facilitate detailed investigations into soil microbial species composition, structural diversity, and functional characteristics under varying conditions. Despite existing challenges, significant strides have been made in understanding soil microbial communities through high-throughput sequencing technologies [28]. These advancements enable differential characterization of microbial species and structural diversity, providing insights into microbial community dynamics and functional diversity. Furthermore, sequencing of soil microbial metagenomes not only enhances our understanding of known microbial genetic diversity but also reveals potential new genes [29]. Moving forward, high-throughput sequencing technology will continue to play a pivotal role in analyzing intercropping soils, elucidating interactions between soil microbial communities and plants in rubber farming and forestry ecosystems [30], and advancing our knowledge of soil microbial properties and functions. This ongoing research aims to underpin sustainable development practices and improve management strategies for rubber farming and forestry systems.

5. Conclusions

In this study, CiteSpace software was utilized to visualize and analyze international research literature from the past 20 years concerning the impact of rubber agriculture and forestry ecosystems on soil microbial communities. The findings revealed significant engagement by Chinese researchers, reflected in numerous publications that underscore their influence. Leading the list of authors, Liu Wenjie has collectively contributed 26 papers, although no stable core author group has emerged. The Chinese Academy of Sciences emerged as the institution with the highest publication count, totaling 41 papers. While collaboration among different research institutions and countries is relatively close, researcher cooperation intensity remains low. The most cited literature focuses on soil nutrients and structure in rubber agriculture and forestry systems, forming a foundational basis for studying soil microorganisms. Most cited journals originate from Netherlands, the United Kingdom, and other countries. The research investigates the effects of rubber intercropping and agroforestry management on soil microbial communities across three phases: (1) Initial Stage (2010-2015): Emphasized changes in biodiversity following the transformation of rubber plantations into agroforestry systems, along with associated management strategies. (2) Development Stage (2015-2020): Explored interactions between litter, water dynamics, and soil microbial communities in agroforestry systems. (3) Maturity Stage (2020-2024): Investigated factors influencing microbial communities and their impact on rubber agroforestry systems.

Future research directions should focus on understanding the influence of species composition within rubber agroforestry systems on soil microbiological characteristics and methodologies for studying species interactions. Specifically, conducting comprehensive and systematic studies on the structure, function, and regulatory networks of soil microbial communities in relation to rubber trees will be crucial. This knowledge will facilitate the development of effective and well-designed rubber agroforestry systems. Systematic underground soil microbiome technologies can promote sustainability in rubber plantations and enhance productivity.

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Conflicts of Interest

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

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