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Review

Rubber-Based Agroforestry Systems Associated with Food Crops: A Solution for Sustainable Rubber and Food Production?

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Abstract: Agroforestry is often seen as a sustainable land-use system for agricultural production providing ecosystem services. Intercropping with food crops leads to equal or higher productivity than monoculture and results in food production for industry and subsistence. Low rubber price and low labor productivity in smallholdings have led to a dramatic conversion of rubber plantations to more profitable crops. The literature analysis performed in this paper aimed at better understanding the ins and outs that could make rubber-based agroforestry more attractive for farmers. A comprehensive search of references was conducted in March 2023 using several international databases and search engines. A Zotero library was set up consisting of 415 scientific references. Each reference was carefully read and tagged in several categories: cropping system, country, main tree species, intercrop type, intercrop product, level of product use, discipline of the study, research topic, and intercrop species. Of the 232 journal articles, 141 studies were carried out on rubber agroforestry. Since 2011, the number of studies per year has increased. Studies on rubber-based agroforestry systems are performed in most rubber-producing countries, in particular in Indonesia, Thailand, China, and Brazil. These studies focus more or less equally on perennials (forest species and fruit trees), annual intercrops, and mixed plantations. Of the 47 annual crops associated with rubber in the literature, 20 studies dealt with rice, maize, banana, and cassava. Agronomy is the main discipline in the literature followed by socio-economy and then ecology. Only four papers are devoted to plant physiology and breeding. The Discussion Section has attempted to analyze the evolution of rubber agroforestry research, progress in the selection of food crop varieties adapted to agroforestry systems, and to draw some recommendations for rubber-based agroforestry systems associated with food crops.

Keywords: industrial crop; annual crop; fruit tree; intercropping; plantation

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1. Introduction

The United Nations created seventeen sustainable development goals (SDGs) as part of the Post-2015 Development Agenda. Agroforestry can contribute to the implementation of nine of the SDGs, with four having strongest potential impacts on poverty reduction (SDG 1), hunger alleviation (SDG 2), climate action (SDG 13), and life on land (SDG 15) [1,2]. Agroforestry refers to a sustainable method of land management using the integration of both agricultural and forestry practices in the same place [3]. According to the Food and Agriculture Organization (FAO) of the United Nations, there are three essential types of agroforestry systems: agrisilvicultural systems combining trees and crops, silvopastoral systems combining forestry and the grazing of domesticated animals, and agrosilvopastoral combining trees, animals, and crops [4]. In many studies, the diversification of activities and consequently of incomes in agroforestry systems (AFSs) makes them more profitable than monocultures [5,6]. Agroforestry is recognized as a sustainable and environmentally friendly practice playing a role in climate change mitigation [7].

Hevea brasiliensis Muell. Arg. is the most economical source of natural rubber (NR). Rubber grows in subtropical zones in Asia, Africa, and America. Rubber plantations are mostly a monoculture system. Rubber production faces socio-economic issues and climate change. Smallholders produce 85% of the natural rubber consumed in the world. Fluctuation and low rubber price make rubber plantations less attractive to farmers. Urbanization pressure in some areas and the growing demand for arable land for food production and more profitable crops have led to the conversion of rubber plantations. In 2016, an outbreak of the new disease called circular leaf disease involving Pestalotiopsis fungus species has led to a decline in the rubber production by 30% in Indonesia (source: Indonesian Investment, 2018). Today, rubber-processing plants are running at half capacity in Indonesia and could affect the employment of more than 60,000 workers (source: Gapkindo, 2023). In the context of climate change, the sustainability of the NR production is currently threatened.

Rubber-based agroforestry systems (RASs) can represent a solution to improve the profitability, sustainability, and resilience of farmers. RASs reduce the vulnerability of smallholders to volatile markets [8]. RASs showed better land productivity through income diversification [9] and increased biodiversity in plantations, including timber, pharmaceutical, bird, butterfly and reptile species [10,11]. In this way, agroforestry might be a solution to compensate for the low rubber price and low land productivity. Rubber cultivation includes a 5- to 7-year immature period before NR production and a 25- to 30-year production cycle using a standard plant spacing system of 6 m $\times$ 3 m [12]. Smallholders often develop intercropping with other crop species during the first two years of the immature period, when the canopy is not closed [13]. Tree or crop species can be associated with rubber for a longer period when they tolerate shade or when a wide spacing system between rubber rows provides greater sunlight for intercropping.

Global food production must increase by 70% to feed the rapidly growing population [14]. Land conversion from natural ecosystems to agriculture has historically been the best way to increase arable land (source: FAO, 2020). Today, land conversion is a major driver of biodiversity loss and land degradation. The use of available space in industrial crop monoculture plantations represent a challenge to increase food production and reduce deforestation. Huang and collaborators estimated that 12.3 M ha of rubber plantations are available for agroforestry systems in the world [8]. The conversion of rubber plantations into efficient RASs is essential to contribute to food security through the extensification of food crops. This issue was particularly observed in Indonesia where agroforestry can help rubber farmers to improve their income as well as improve food security, health, and environmental stability [15].

The aim of this literature review is to gain a better understanding of the factors that could make rubber agroforestry systems more attractive to farmers. The development of high-efficient RASs and the conversion of monoculture into RASs raise crucial questions about the adaptation of rubber clones and food varieties in relation to the competition for soil resources in a context of climate change. Little is still known about the effect of competition in agroforestry systems for the use of water, nutrients, and light utilization between species. The present study is a meta-analysis of the literature on agroforestry systems, in particular on rubber-based agroforestry associated with food crops. Four-hundred-and-fifteen references were collected. In the Results Section, the structure of the library by year and by country was analyzed, as well as the types of intercropping and the disciplines of these studies. In the Discussion Section, we reviewed what is known about RASs, breeding, and crop management, then attempted to provide some recommendations for effective rubber cultivation.

2. Materials and Methods

A comprehensive search of references was conducted in March 2023 using several methods, including searching international databases (AGRICOLA, CAB Abstracts, Econlit, Web of Science, PubMed, and Google Scholar). This search was performed with several search equations with the keywords agroforest, food and crop, rubber, or hevea. References were exported in RIS format and imported into an online Zotero group library (open source reference management software, Corporation for Digital Scholarship, Version 6.0.36). Reports, thesis manuscripts, and proceedings from CIRAD, IRRI (Indonesian Rubber Research Institute), BRIN, and UGM researchers were also collected and added to the Zotero library. Duplicates were eliminated. Soft copies of each reference were searched and attached to the references in the Zotero library. A total of 415 unique references were stored in the Zotero library (Supplemental Table S1).

Papers of each reference were carefully read and then tagged for several categories: cropping system, country, main tree species, intercrop type, intercrop product, level of product use, discipline of the study, research topic, and intercrop species. The tags for each category are described in Table 1. References of each paper were exported from the Zotero library in csv format. The dataset is presented in Supplemental Table S1. The different tag categories were classified and counted after filtering using Microsoft Excel (v. 2019) [16]. The data were used for the presentation of figures and tables in the Results Section.

Table 1. Description of tags used in the reference library.

Category	Tag
Cropping system	Monoculture, intercropping, agroforestry, jungle rubber, annual associated crop, etc.
Country	Brazil, Cameroon, China, Colombia, Ghana, India, Indonesia, Laos, Malaysia, Thailand, etc., and world (for review papers combining research from several countries)
Main tree species	Rubber, oil palm, cocoa, coffee, teak, kayu putih, eucalyptus, etc.
Intercrop type	Perennial intercrop, annual intercrop, multi-species intercrop, etc.
Intercrop product	Industrial, medicinal purpose, food, timber, mushroom, fodder, etc.
Level of product use	Commercial, subsistence, etc.
Discipline of the study	Agronomy, plant protection, agro-ecology, sociology, economy, breeding, soil science, ecophysiology, etc.
Research topic	Farming system, cropping practices, ecosystem services, socio-economic services, etc.
Intercrop species	Rice, maize, soybean, elephant foot yam, coffee, pepper, etc.

The first filter used was “Item Type” to select the 232 journal articles from the 415 unique references. The second filter was “Cropping System” to select papers related to agroforestry and intercropping, and then “Main tree species” to select only papers studying rubber. A total of 141 papers were selected for further analyses. For Figures 3 and 4, we filtered used the “Country” and “Intercrop type” columns, respectively. For Tables 2 and 3, the count of journal articles was performed using the filters of “Main tree species” and “Discipline of the study”, respectively. For Figures 5–7, we used the columns of “Intercrop species", "Intercrop products", and "Usage of intercrop product", respectively. Finally, for Figure 8, we filtered using the column "Research topic".

3. Results

3.1. Structure of the Library

The reference search resulted in 415 non-redundant scientific works on agroforestry systems associated with food crops (Supplemental Table S1). They were collected from CAB Abstracts, Econlit, and Agricola databases, as well as from personal libraries. These references were saved in an online Zotero library. This library consists of references from books, book sections, conference papers, review papers (called encyclopedia), journal articles, presentations, reports, thesis, audio recordings, and magazine articles. The library counts 232 journal articles (55.9%) followed by 53 encyclopedia articles or review papers (12.8%), 53 conference papers (12.8%), 35 reports (8.4%), and the remaining references represent less than 5% (Figure 1). In order to reduce the bias related to the gray literature (reports, theses, etc.) mainly collected from Indonesian and Thai scientists, we focused further analyses on journal articles. Of the 232 journal articles, 141 papers were rubber studies used for further analysis (Supplemental Table S1). The gray literature was used in the discussion and prospects. The journal articles were used for the following analyses.

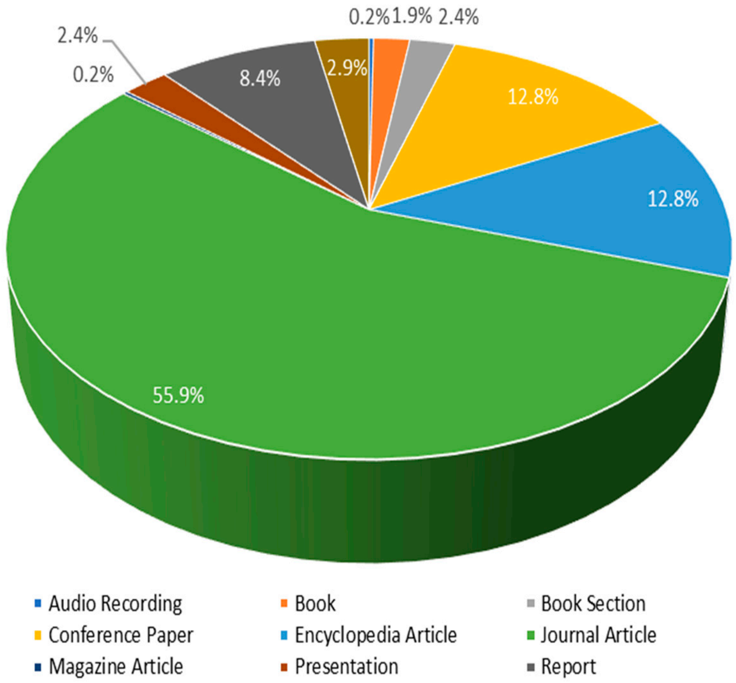

Figure 1. Proportion of references collected in this study.

3.2. Evolution of the Number of Research Studies Related to Rubber-Based Agroforestry

The number of RAS-related research studies has evolved dynamically, with an upward trend over the last 30 years (Figure 2). The first publication in this library was released in 1989. Only one journal article per year was published in 1989, 1996, and 1997. A significant increase was observed from 2000 to 2006 with about five references per year. The number of publications has increased again from 2014 to peak at 16 references in 2021. The slight decrease in 2022 could be an effect of the COVID-19 pandemic. Most of the references studied agroforestry (association during all the plantation cycle) and intercropping (association during the immature period of the plantation). Although twenty-four references were collected on jungle rubber, four journal articles were published on this topic.

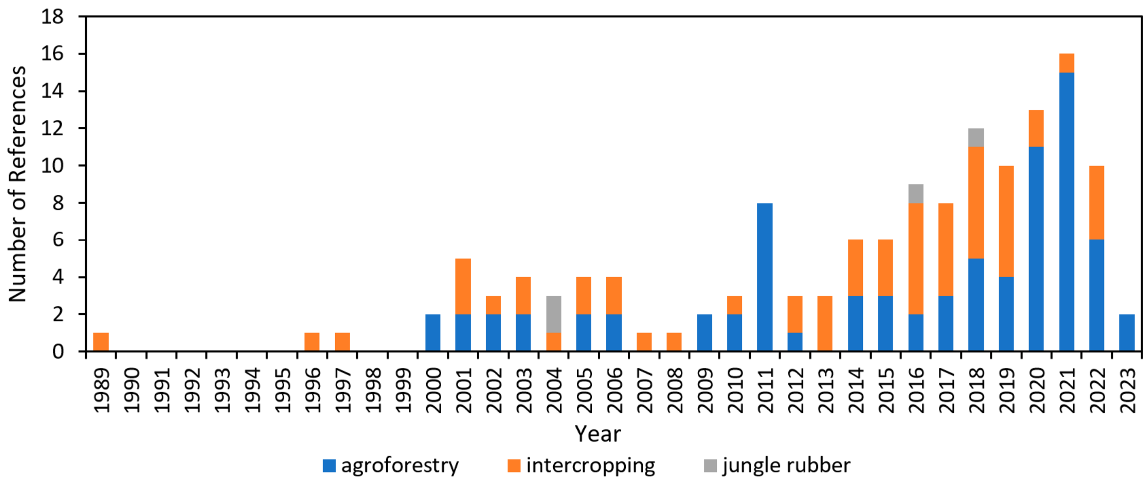

Figure 2. Number of journal articles per year and per intercropping system for rubber as the main tree crop.

The analysis of the cropping system revealed that 56.7% of journal articles deal with agroforestry systems during the full rubber production cycle, 40.4% with the intercropping system during the immature period, and 2.8% with jungle rubber. This analysis was followed by an analysis of journal article per country.

3.3. Number of Journal Articles on Rubber Per Country

Countries with the highest number of journal articles on RASs were Indonesia (39), followed by Thailand (25), China (22), Brazil (17), and Sri Lanka (10) (Figure 3). Less than 6 journal articles were published in other countries, representing 24 papers, and 4 studies conducted in several countries. In order to better understand the studies conducted in these countries, an analysis of intercrop types was carried out.

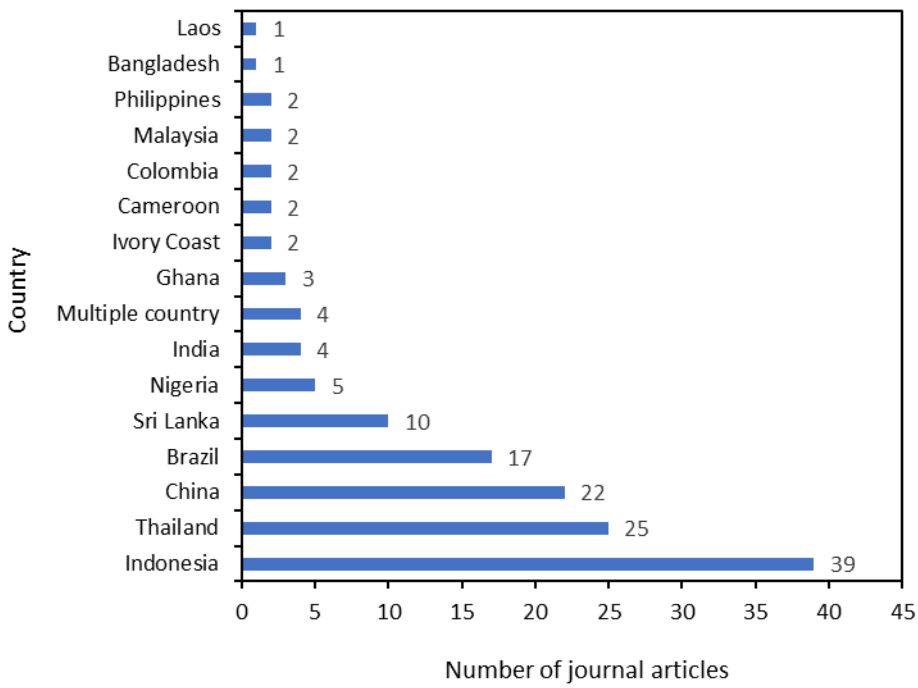

Figure 3. Number of journal articles per country for rubber as the main tree crop.

3.4. Analysis of Intercrop Types in Rubber Agroforestry Systems

In RASs, rubber trees can be combined with perennial crops (trees and other non-tree perennials) only, with annually harvested crops only or with both types of crop, respectively, referred to in this document as perennial intercrops, annual intercrops, and multi-species intercrops. Annual intercrops are intercrops that are harvested less than a year after being planted. The proportion of journal articles per intercrop type shows that 34.8% of studies are on perennial intercrops, 34% on annual intercrops, and 22.7% on multi-species intercrops (Figure 4).

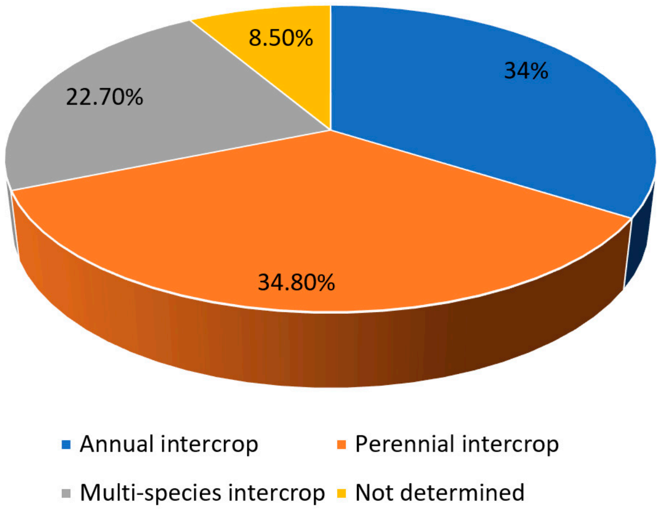

Figure 4. Proportion of journal articles per intercrop type.

Rubber is used as the main tree crop in 127 journal articles and in combination with other perennial tree crops in 14 journal articles (Supplemental Table S1). Rubber is often associated with cocoa in eight articles, oil palm in four articles, and sometimes with albizia, arecanut, coconut, coffee, durian, gmelina, neem, palaquium, pongamia, and simarouba (Table 2).

Table 2. Number of journal articles for each perennial tree species planted with rubber.

Tree Species Associated with Rubber	Journal Articles (No)
Albizia	1
Arecanut	1
Cocoa	8
Coconut	1
Coffee	1
Durian	1
Gmelina	1
Neem	1
Oil palm	4
Palaquium	1
Pongamia	1
Simarouba	1

Food crop species can be planted between rows during the immature and mature periods of rubber plantations. Forty-seven annual crops were associated with rubber in the literature. Twenty species were studied in minimum two papers, and twenty-four additional species in only one paper (Figure 5). The most frequently studied crops are rice (33), maize (24), banana (16), cassava (15), soybean (10), plantain (7), peanut (7), pineapple (5), sorghum (4), vegetables (4), chili (4), and sugarcane (3). This indicates that these food crops are suitable to be planted with rubber as intercrops. The usage of these intercrop species is shown below.

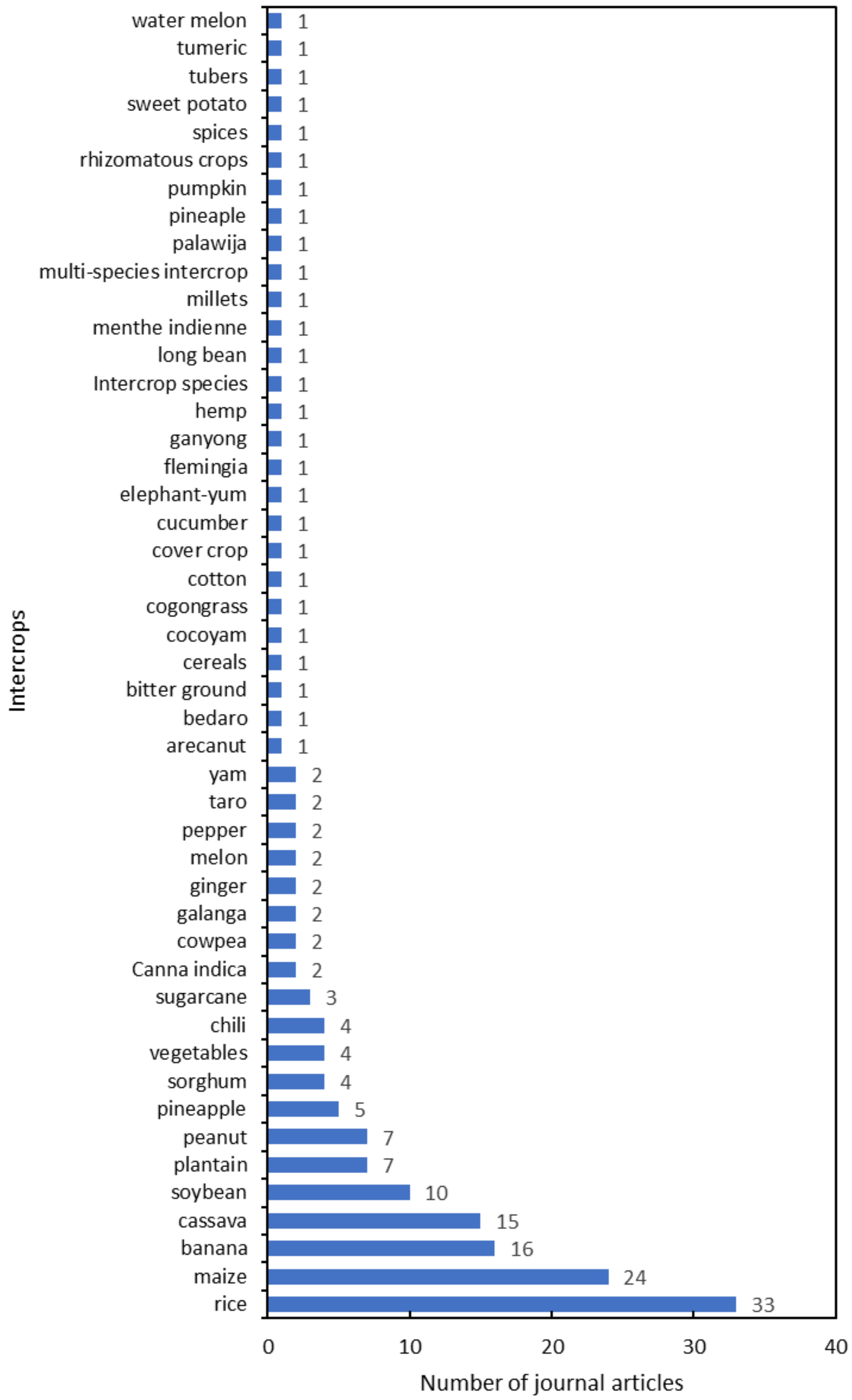

Figure 5. Food intercrop species associated with rubber.

3.5. Analysis of Intercrop Products and Level of Usage in Rubber-Based Agroforestry Systems

The usage of intercrop products is diverse, and was categorized as food for human beings, fodder for animals, industrial for transformation in factories, medicine for medical applications, and not determined when the papers did not clearly mention the usage of the products (Figure 6). Seventy-eight journal articles studied food crop for food production (41.3%), followed by 52 on industrial usage (28.8%), 18 journals on fodder (9.8%), 6 journals on medicine (3.3%), and 4 journal articles on fruit (2.2%). A similar proportion was also found for all references that studied food products then industrial products, except in books, which contain more studies on industrial crops (Supplemental Table S1).

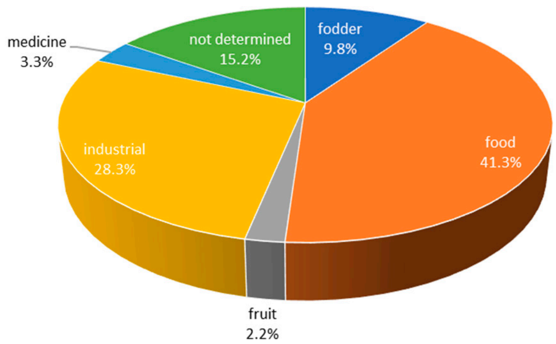

Figure 6. Proportion of intercrop products.

In order to understand if farmers use their products for self-consumption or for commercial activities, the library references were tagged with subsistence and commercial items, or both items. Intercrop products from agroforestry were firstly used for commercial activities (47.7% of journal articles) and then both commercial and subsistence (21.9%), and only 14.6% of the papers mentioned the usage of products for subsistence only (Figure 7).

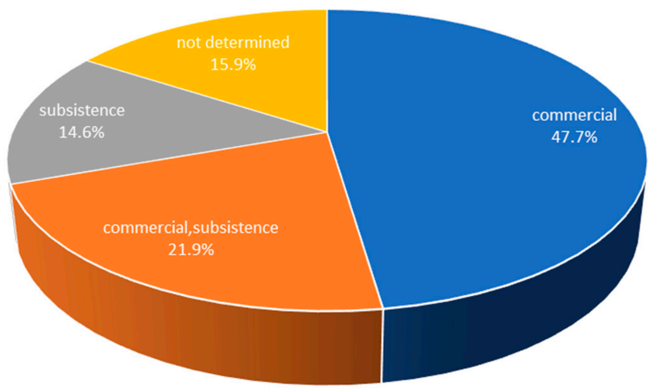

Figure 7. Proportion of level of usage of intercrop products.

3.6. Analysis of the Disciplines Studied in the Journal Articles

Disciplines were specified in tags for each reference of the library, namely agronomy, economy, sociology, ecology, plant physiology, breeding, and forestry. A total of 135 journal articles had a tag for one or several disciplines (Table 3). Agronomy is the most studied discipline in RASs, with 71 journal articles as unique disciplines (63 journal articles) or in combination with other disciplines (8). Ecology is also an important discipline, with 33 papers: 28 specifically on ecology and 4 on other disciplines. Economy and socio-economy were covered by 12 and 19 papers, respectively, plus 6 papers combining several disciplines, while sociology was studied in only 4 papers, plus 5 in combination with other disciplines.

The percentage of journal articles ranges from 40.7% to 58.5% for all disciplines, except for breeding, where all studies are published in scientific journal articles. Apart from plant physiology (three journal articles), forestry and breeding were mentioned in two papers in combination with economy and agronomy, respectively.

In an attempt to better describe the implemented studies, journal articles were tagged with 26 research topics (Figure 8). For some journal articles, it was difficult to detail the study, and some general topics have been mentioned, such as socio-economic, ecosystem services, etc. Farming systems, ecosystem services, and cropping practices represent the largest number of studies: 33, 33, and 35, respectively. Soil science and socio-economic studies were implemented in 11 and 20 journal articles, respectively. The other research topics were analyzed in only one to a maximum of six papers.

Table 3. Disciplines covered in journal articles.

Disciplines Covered by Articles	Journal Article (No)
Agronomy	63
Ecology	28
Economy	12
Plant physiology	3
sociology	4
Agronomy, breeding	1
Agronomy, ecology	2
Agronomy, economy	1
Forestry, economy	1
Sociology, economy	19
Agronomy, economy, sociology	3
Ecology, sociology, economy	1
Agronomy, ecology, sociology	1

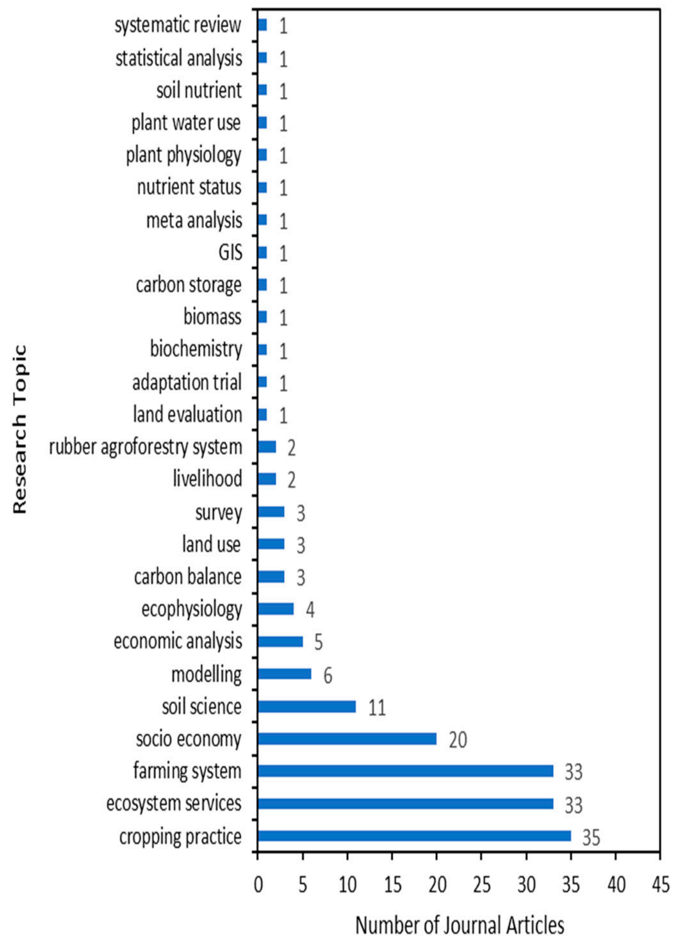

Figure 8. Number of journal articles per research topic.

4. Discussion

The growing demand for food production is driving agricultural intensification and deforestation, in particular, for palm oil, soy, cocoa, and cattle [17]). The development of industrial crop-based agroforestry systems may offer huge land spaces for the cultivation of food crops by farmers. For many years, rubber farmers have had a low income due to low rubber prices and low productivity, in particular, in Indonesia [18]. Low rubber prices affect plantation conversion and tapper movements in different countries. The conversion from rubber to oil palm plantations was estimated at 1.9% and 2.6% for Indonesia and Malaysia, respectively [19]. In southern Thailand, rubber plantation labor is being displaced by falling rubber prices [20].

The diversification of income by developing rubber-based agroforestry systems associated with food crops may be a solution to support both food, rubber, and wood production as well as the welfare of farmers and ecosystem services inherent to agroforestry. Rubber monoculture plantations are dominant and represented globally 14 million ha in 2021 [21]. Little is known about the proportion of RASs in the world, but Indonesia, Thailand, Sri Lanka, and China are known to have such producing systems and active research. Twenty-eight rubber-producing countries presently exist in South America, Africa, and Asia [21]. These plantations offer huge potential for food, when converted to agroforestry. Although RASs can improve the biodiversity in plantations, there is a lack of knowledge about the resilience of these systems to climate change.

The literature analysis performed in this paper helped to organize the Discussion Section in four parts related to the evolution of research on rubber agroforestry, the breeding of food crops for agroforestry systems, the development of adapted crop management, and providing some recommendations for RASs associated with food crops.

4.1. Evolution of Research on Rubber Agroforestry

Four-hundred-and-fifteen references reporting studies on agroforestry associated with food crops have been collected and analyzed. Of the 232 journal articles, 143 dealt with rubber as the main tree crop. One-hundred-and-twenty-four studies were conducted in Indonesia, Thailand, China, and Brazil since 1989. The large number of publications from the main rubber-producing countries, Indonesia and Thailand, is understandable. Interestingly, the number of studies in China, Brazil, and Sri Lanka, which account for less than 1 M ha in total, revealed a great interest in RASs by these countries. Rubber is associated with at least 12 perennial species, including industrial crops like oil palm, cocoa, and coffee, and forest tree species like teak [22], mahogany [22,23], acacia [24], coffee [25], cocoa [26,27], fruit trees [28], and oil palm [27]. The analysis of 12 economic papers revealed that shade-tolerant crops with small canopies, such as coffee, bamboo, and tea, are ideal intercrop for RASs [8]. Scientists from Brazil and China have published a lot of papers, although rubber agroforestry was poorly implemented by smallholders in these countries. Interestingly, 34 papers reviewed RASs in China and Indonesia. From the first review papers written from studies in China and Indonesia [29,30], reviews were also published from Brazil, Nigeria, Thailand, and Sri Lanka, as well as combining several countries in Africa and Asia. These review papers are often based on the gray literature (reports, thesis, etc.). Of the 48 references from the gray literature in the library set up in this study, 39 are from Indonesia and Thailand in the reference library (Supplemental Table S1). Most research articles reported studies on agronomy, economy, sociology, and ecology. For agronomy, the studies on farming systems and cropping practices may reflect the need to improve the productivity of systems. For ecology, many studies showed the interest of agroforestry to improve biodiversity in plantations. Ecosystem services are particularly important in the context of climate change.

The first rubber agroforestry system was likely jungle rubber in the wild Amazonian forest and then established as a plantation system using rubber seedlings. In Indonesia, jungle rubber was estimated at 3 Mha in 1990, representing 80% of rubber plantations [9]. In Nigeria, jungle rubber was planted on 300,000 ha 20 years ago. The current situation of jungle rubber plantations is not well known for these countries, but it still seems to be very significant. The development of efficient RASs requires the use of clonal material. Rubber was associated with 47 annual crops in these studies. Food crops are also often associated with rubber, for example rice [13], maize [13,31], banana [32], cassava [33], soybean [13,25,34], and many others, such as peanut, chili, corn, sesame, etc. [9]. These research studies may reflect the demand for food safety and industry with 42% and 28% of journal articles on food crops and industrial applications, respectively.

Breeding rubber clones for RASs is necessary to develop efficient RASs. Some vegetables can grow in conditions of low sunlight, such as beetroot, kale, radish, spinach, etc. But, most essential food crops (rice, maize, soybean, etc.) need light penetration. Although most rubber clones can be used for intercropping during the immature period, a few of them are adapted to grow food crops during the mature period. Several studies showed that the RRIM 600 clone is the most suitable clone for agroforestry [35]. In mature plantations, the canopy is not completely enclosed for this clone (60 to 80%), allowing light to penetrate the crops below. By contrast, clones with a dense canopy, such as clone PB 260, are less adapted to agroforestry. Some strategies using leaf disease-susceptible clones have also been developed [36,37]. In this case, leaf fall improves light penetration below the canopy, but severely affects growth and rubber yield. For conventional planting density, it contributes to a better situation for associated crops during the mature period. Consequently, developing new rubber clones for RASs in conventional planting density requires characterizing tree architecture. In the context of climate change, extreme conditions of temperature, wind, and water (drought and flooding) will increasingly affect plantations. Competition for resources between species of agroforestry systems is also a challenge for breeders, in particular, for water availability during the dry season. For these reasons, breeders have to consider a combination of traits in the breeding program.

Another approach is to develop new cropping systems to allow the long-term association of rubber with food crops. Cropping system adaptation is also an alternative to the conventional plantation density of RASs. A double-row system with wide spacing between the double rows (DRs) was set up with several intercrop species [25,38]. This technology consists of three main planting designs: 18 m × 2 m × 2.5 m, 19 m × 4 m × 2 m, and 20 m × 4 m × 2 m; the planting density is 400, 435, and 417 trees/ha, respectively. DRs have been implemented for banana, rice, soybean, and sugarcane [13]. The still-high light intensity allows the intercropping system to grow over a longer period of time. To keep the area exposed to light penetration for longer, it is best to plant rubber clones with pine branch types, such as clones IRR 112, IRR 118, IRR 220, and IRR 230. The average light penetration in the center of the single-row (SR) system is 22.35%, while it is 15.6% for the narrow space of the DR. This means that light penetration is no more than 30% at each point measured in the SR system. Meanwhile, the penetration of light in the DR system is >80% within 4 m of rubber rows. Thus, the DR system is more suitable for long-term food crop production than conventional RASs [39,40].

4.2. Breeding Food Crops for Agroforestry Systems

Competition within AFSs between primary tree crops and secondary food crops for the same limited growth resources is readily apparent and has become a focal point for crop breeding programs. Annual food crops are typically cultivated as monoculture crops to maximize yields in favorable environments. In contrast, agroforestry systems in tropical regions often exist in acidic and infertile soils, where primary crops consist of perennial, woody vegetation that has adapted to these challenging conditions. These systems not only contribute to environmental conservation, but also help prevent soil from erosion and runoff [41]. In an AFS, secondary food crops must adapt to compete with primary crops as well as unfavorable conditions, including acidic soil, low nutrient levels, and other limited resources. During the initial growth of primary crops, the alley remains spacious, allowing shared access to environmental resources; thus, the competition between tree crops and secondary food crops evanesces. However, several interconnected environmental factors, such as microclimate, soil characteristics, and pest and disease pressure, can elicit diverse responses to the growth and development of food crops.

Several environmental factors associated with AFSs potentially affected the growth and development of food crops, including temperature, light, water, metal toxicity, and pests and diseases (Table 4). Shading becomes a significant concern when larger tree crops are closely integrated or tree plants grow rapidly in a narrow-alley cropping system, outpacing the growth of food crops. The shade leads to lower temperatures and reduced light-interception quality. Lower temperatures also imply reduced evaporation and increased water retention by the roots of secondary food crops, enhancing water use efficiency. However, the extensive root systems of tree crops can pose a drought risk to food crops, which is contingent on the relative difference in soil water content.

Metal toxicity can be a challenge in agroforestry systems for food crops. Traditional agricultural practices, like liming and inorganic nutrient applications, have been suggested as solutions. Nevertheless, liming may not enhance root development in areas with high levels of aluminum saturation for certain tree species not adapted to acidic soil conditions [42]. The best alternative is to cultivate adapted food crop varieties capable of developing tolerance mechanisms to thrive in unfavorable environments and provide reliable crop yields.

Breeding food crops to develop varieties better suited to RASs focuses on enhancing several important traits. These include shade tolerance, drought resistance, aluminum toxicity resistance, and protection against pests and diseases. Additionally, the quality of the grains in these varieties should align with market preferences in the target region. The choice of breeding approaches hinges on the availability of genetic sources and underlying genetic mechanisms of these traits. In some cases, genetic variation in annual food crops under adverse conditions can be naturally found in the form of wild relatives, sub-species, or genus [43]. Transferring tolerance genes from available genetic resources to adapt to unfavorable environments is challenging due to the broad genetic distance. Crossbreeding domesticated food crops with their wild relatives often results in F1 abortion and incompatibility [44]. However, there have been successful instances of gene introgression using interspecific hybrids, alien introgression lines (AILs), and chromosome segment substitution lines (CSSLs), which broaden the gene pool and enhance abiotic tolerance, as seen in rice [45]. Genetic variation can also be induced through direct mutation using chemical mutagenesis and irradiation [46,47].

Table 4. Generic potential effects of implementing agroforestry for food crop production.

Factor	Growth and Development of Tropical Food Crops	Reference
Temperature	Optimum yield can be achieved at a temperature range of 22 and 32 °C; beyond this range, at temperatures exceeding 42 °C, yields begin to decline. Extreme temperatures, both high and low, have a significant impact on the formation of starch in tubers, while pod development does not exhibit any signs of endothelial formation.	[48–52]
Light	The threshold for the red/far red ratio is greater than 0.5. When this ratio is met, it leads to the elongation of stem-like structures, an upward orientation of leaves (hyponasty), reduced branching or tillering, and earlier flowering. However, it also diminishes the root anchorage capacity, making the crops more susceptible to lodging.	[53,54]
Water	Competition among plants for limited shallow-water resources increases their susceptibility to drought stress. The extent of this competition is influenced by the relative difference in soil water content due to soil water absorption.	[55,56]
Metal toxicity	Mostly in the form of soluble aluminum, such as $[Al(H_2O)_6]^{3+}$, which, at a millimolar concentration can stimulate the division of root cells in cereal and legume crops. Aluminum also triggers an increased accumulation of reactive oxygen species and higher fatty acid peroxidation, resulting in an alteration in plasma membrane integrity.	[42,57]
Pests and diseases	Certain insects and pathogens can be shared among related plant species. For instance, Bruchid, which are pantropical seed pests of grain legumes, commonly feed on the seeds of tree legumes as well. Additionally, various vertebrata pests, fungi, virus, nematodes, and phytoplasmas have been identified as having relationships with both crop and tree species.	[58–60]

Advancements in the understanding of genetic mechanisms of important traits related to resistance against biotic and abiotic factors have paved the way for the utilization of modern breeding techniques, including marker-assisted selection, genomic selection, and genome editing, to enhance the resistance of food crops' resistance to both biotic and abiotic stresses [61–63]. These techniques will help breeders in developing new crop varieties suitable for AFSs. Moreover, breeding food crops for AFSs is an important approach to enhance agricultural productivity, sustainability, and resilience. The combination of different plant types can provide numerous benefits, such as improved soil health, increase biodiversity, and better climate adaptation.

The breeding strategy for the genetic improvement of food crops under the agroforestry system might follow the breeding strategies for an unfavorable environment. The shuttle breeding scheme has been successfully adapted for selection breeding material, where the targeted sites are difficult to access and located in remote areas, and less researchers are involved compared to a favorable ecosystem [64]. Shuttle breeding is growing in two or more generations in contrasting environments to advance generations and shorten the breeding cycle. Two different environments, e.g., research stations and targeted locations of agroforestry, are very distinctive in terms of the environment factor, as shown in Table 3. When developing suitable food crop cultivars in unfavorable environments, such as agroforestry systems, the direct selection of grain yield in the target environment is apparently more effective compared to an indirect selection under no-stress conditions [65,66].

Participatory breeding process involving farmers is also imperative to establish a suitable farming system and employ farmers' strategies for intercropping in AFSs, which depends both on soil/climate scenarios, as well as existing markets for associated products. Implementing such a participatory breeding approach from the development of food crop varieties in unfavorable environments will boost the adoption of these cultivars in the target environment [67].

4.3. Crop Management for Food Crops in Agroforestry

Agroforestry is defined as a sustainable use of land that involves the intentional introduction or mixture of trees or other woody plants in crop/animal production fields to benefit from the result of ecological and economic interactions [68], whereas Lundgren and Raintree defined agroforestry as a general name for land-use systems and technologies, where woody plants are intentionally planted in the same land management area as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence [69]. Agroforestry is considered as a sustainable agriculture system because of its ability to provide multiple ecosystem functions, such as carbon sequestration, habitat for soil biological activity, and a wind erosion-resistance system [70]. Tree intercropping is the farming system that is practiced in agroforestry. Intercropping increases land-use efficiency by planting different crops either at different periods or by varying harvesting times, and the land is utilized in an efficient way with the same amount of irrigation or fertilizer application. There are different requirements for intercropping, such as the second crops must be younger and support the main crops, they must have a low effect on the main crops, and their nutrient needs must differ from the main crops. There are different crop types found in agroforestry systems, but food crops are the most common (Figure 5).

In Indonesia, different food crops that have been found in agroforestry systems [71]. In Java, different species and cultivars showed different life cycles, which determine the farming system (Table 5). Tuber species, such as arrowroot, canna root, taro, and yam, which are considered as shade-tolerant plants, are among the potential species to be developed in forest stands in agroforestry systems [72] and as commodities for the diversification of carbohydrate-rich foods other than rice [73]. Most tubers grow naturally, while some are deliberately planted by communities [74]. There is no irrigation in agroforestry systems. Crop life depends on daily rainfall. Cassava, pigeon pea, and tuber species will therefore be the only food crops covering the aboveground land in the whole year, except for special planting arrangements, such as for cassava, pigeon pea, and taro. These plants are normally cultivated close to tree rows.

Table 5. Food crops found in agroforestry systems in Java.

Food Crop	Life Cycle (Month)
Upland rice	3.5–7.0
Maize	3.0–5.0
Sorghum	3.0–5.0
Soybean	2.5–5.0
Mung bean	2.5–4.0
Cowpea	2.5–3.0
Pigeon pea	3.0–9.0
Cassava	6.0–12.0
Sweet potato	3.5–5.0
Arrowroot	8.0–12.0
Canna root	8.0–10.0
Yam	5.0–7.0
Coco yam	5.0–6.0
Taro	7.0–12.0
Elephant foot yam	7.0–9.0

When trees are grown regularly using wide spacing between tree rows, the area between the tree rows can be used to cultivate some annual crops, such as upland rice, corn, sorghum, soybean, mung bean, and cowpea. There are different cultivars for rice, corn, and sorghum, which can be harvested for a maximum of 4 months, whereas legumes can be harvested for 3 months. Cereal–legume crop rotation can therefore be introduced to the area within 6 months of the rainy season. Interestingly, legumes can improve soil fertility because they can fix free nitrogen. Growing annual food crops, especially with legume crop rotations under agroforestry, is recommended because of the ability of the system to support carbon sequestration, a habitat for soil biological activity, and wind erosion tolerance. Crop rotation was also recommended to control pests, especially diseases. It was found that cop rotation could enhance natural pest control [75,76]. Choice of crops and or cultivars will determine effectiveness due to genetic heterogeneity and the use of resistance cultivars for pests and also optimal weed control. Legume-based rotation enhances biological nitrogen fixation; improves soil pores through deep root systems; improves P-availability; improves soil fertility; enhances nutrient cycling; reduces the use of external inputs, thereby minimizing greenhouse gas emissions and groundwater pollution, improving water productivity; and minimizes disease and pest incidences [77]. Rice–pulse can reduce the pathogens population in aerobic rice cultivation [78].

4.4. Tentative Recommendation for RASs with Food Crops

The implementation of rubber plantations associated with food crops requires some specific recommendations to make RASs efficient. Access to sunlight for food crops, the sharing of resources between trees and annual crops, land and labor productivity, and the skills of farmers are all factors to be considered.

The canopy or planting density of rubber trees must be adapted to grow food crops during the immature and mature periods of rubber plantations. Rubber clones with a pine branching type, namely RRIM 600, IRR 112, IRR 118, IRR 220, and IRR 230, are particularly well-adapted to RASs. Their shading is estimated at 60% [39,79]. These clones have a potential latex yield of about 2.5–3 tons per ha per year. These clones can be used for single-row as well as double-row systems, with wide spacing between the double rows [39,40]. In the case of RASs with a DR system, more clones should be suitable.

Rubber smallholders often use high-intensity tapping, such as daily tapping (S/2 d1) or tapping every two days (S/2 d2). Clones with a high sucrose content and low susceptibility to TPD, such as IRR 112, IRR 118, GT1, or RRIC 100, are well-suited to this smallholder practice [80]. Nevertheless, frequent periods of low rubber prices encourage the low tapping frequency (LTF) and diversification of farmers' activities. LTF can be considered for tapping frequencies less than 10 times a month (every 3 days (S/2 d3) with 4 to 6 stimulations/year for PB 260). Such clones suitable for LTF are under development at the Indonesian Rubber Research Institute (see website: www.rubis-project.org, accessed on 12 May 2024). The implementation of LTF will dramatically increase labor productivity. The time thus saved can be used by farmers to diversify their activities by growing food products or taking on outside jobs.

The implementation of RASs associated with food crops requires farmers to have good skills for rubber (land clearing, planting, manuring, harvesting, ethephon stimulation, pruning, etc.) and food crop management. Food crop species must be adapted to SR or DR rubber agroforestry, particularly to shade. Rice, maize, soybean, banana, and cassava were intensively studied, and seem suitable to grow under rubber (Figure 5). Interestingly, new varieties adapted to shade have been developed by the Indonesian Center for Food Crops and could be endorsed for RASs with conventional density and a DR system. However, cassava was shown to encourage the development of white root disease in rubber tree plantations [40]. Consequently, growing cassava under rubber trees is not recommended to control white root disease outbreaks.

Nowadays, most rubber plantation areas are in environmentally marginal zones reducing the yield [81]. In The context of climate change, breeding efforts must be maintained for both rubber and food crops. Many studies on drought tolerance [82]; resistance to new diseases, such as Pestalotiopsis [83]; tolerance to tapping panel dryness [80,84]; and wind damage [85], should foster the development of new, adapted rubber clones. For annual crops, a number of varieties have been developed, specifically for intercropping. In fact, thousands of food crop varieties have been marketed for their specific characteristics, such as soil acidity, and drought, pest, and disease resistance under monoculture environments, and on the basis of an adaptation study, these food crop varieties have been adapted under AFSs [86]. However, in the last two decades, there have been concerns regarding the release of food crops specific for AFSs. Based on the regulations for released varieties, in Indonesia, food crops released for AFSs must be shade-tolerant. There are some crop varieties that were released commercially, having shade resistance and being suitable for AFSs, including rice varieties Rindang 1 and Rindang 2 [87]; soybean varieties Dena 1 and Dena 2 [88]; the maize variety Jhana [89]; and cassava varieties Malang 6 and Adira 1 [90].

5. Conclusions

The analysis of the literature in this paper reveals that the development of efficient RASs associated with food crops is possible to address socio-economic, environmental, and climate issues. The main research directions to achieve this are breeding for RASs and adaptation to climate change, developing new cropping systems for long-term intercropping, such as DR systems, and sustainable intensive agriculture with low chemical inputs.

Rubber is intensively studied in agroforestry systems associated with food crops. Converting rubber monoculture plantations in rubber-based agroforestry systems instead of converting these plantations for other more profitable crops could be a sustainable way to overcome the low rubber price and low labor productivity of rubber plantations. More than 10 papers have been published every year on RASs since 2010. Scientific advances are mainly driven by four countries: Indonesia, Thailand, China, and Brazil. Rubber is often associated with annual crops during the immature period (intercropping system) and fruit trees during the entire rubber production cycle (RAS). Although little is known about the areas planted in RASs among smallholders, intercropping is common in most countries during the immature period, and RASs developed during the mature period in Indonesia, India, Thailand, and Sri Lanka. For instance, a new policy in Thailand may foster the extension of RASs in the short term. Such a policy could be an example for other rubber-producing countries.

Annual crops adapted to shade and drought, as well as new cropping systems, such as a double-row system with wide spacing between the double rows, should facilitate the implementation of long-term food production in rubber plantations. A better understanding of the interaction between rubber and annual crops, as well as annual crop rotation, is necessary to improve long-term productivity in the context of low-chemical-input agro-ecology. This literature survey may be biased, since many studies have dealt with commercial activities of intercrop products likely supported by the food industry, while smallholders may grow food crops more for subsistence. Institutional and academic reports cover a wider range of cropping systems. Access to these sources of information is more difficult and creates a bias in their analysis. Only coordinated socio-economic surveys will be able to better describe the real situation of RAS areas. Indeed, the analysis of the gray literature provides another viewpoint of RASs, in particular, in Indonesia, where conservation areas and ecological studies are well represented.

However, the current results allow a number of recommendations to be made and call for strengthening certain areas of research. The development and adoption of new rubber clones should take into account biotic and abiotic constraints, and not just yield, especially in the context of climate change. The use of rubber trees in agroforestry systems also requires a consideration of the low frequency of tapping, to leave farmers more time for other activities. Lastly, cropping systems with wide spaces between rows should be favored for food production throughout the rubber production cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture14071038/s1, Table S1: All 415 references extracted from the zotero library.

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