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Co-Designing Sustainable and Resilient Rubber Cultivation Systems Through Participatory Research with Stakeholders in Indonesia

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Abstract

The rubber industry is facing major socio-economic and environmental constraints. Rubber-based agroforestry systems represent a more sustainable solution through the diversification of income and the provision of greater ecosystem services than monoculture plantations. Participative approaches are known for their ability to co-construct solutions with stakeholders and to promote a positive impact on smallholders. This study therefore implemented a participatory research process with stakeholders in the natural rubber sector for the purpose of improving inclusion, relevance and impact. Facilitation training sessions were first organised with academic actors to prepare participatory workshops. A working group of stakeholder representatives was set up and participated in these workshops to share a common representation of the value chain and to identify problems and solutions for the sector in Indonesia. By fostering collective intelligence and systems thinking, the process is aimed at enabling the development of adaptive technical solutions and building capacity across the sector for future government replanting programmes. The resulting adaptive technical packages were then detailed and objectified by the academic consortium and are part of a participatory plant breeding approach adapted to the natural rubber industry. On-station and on-farm experimental plans have been set up to facilitate the drafting of projects for setting up field trials based on these outcomes. Research played a dual role as both knowledge provider and facilitator, guiding a co-learning process rooted in social inclusion, equity and ecological resilience. The initiative highlighted the potential of rubber cultivation to contribute to climate change mitigation and food sovereignty, provided that it can adapt through sustainable practices like agroforestry. Continued political and financial support is essential to sustain and scale these innovations.

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1. Introduction

The natural rubber sector is facing unprecedented socio-economic and environmental issues and must urgently adapt to the impact of climate change. One of the key threats to the sustainability of this industry has been persistently low rubber prices over the past decade. Rubber products are subject to price volatility, with cycles being significant features of commodity price trends. After peaking at USD 5.58 per kg in February 2011, the price of natural rubber steadily declined, reaching a low of USD 1.37 per kg in 2023. Although there was a slight increase to USD 1.74 per kg in 2024, there are still no clear signs of a substantial recovery in the industry (Sicom, 2011–2024) (https://www.sgx.com, accessed on 26 February 2025). Labour availability and cost are also essential issues, particularly in traditional rubber-producing countries where the younger generation is increasingly reluctant to pursue agricultural occupations. As a result, these countries often depend on foreign labour, while new producers such as Vietnam, Cambodia, and Côte d'Ivoire are emerging as competitive players in the global market. In addition, several countries are grappling with low productivity that contributes to farmer poverty or, when feasible, the conversion of rubber plantations into more profitable crops. In Indonesia, low productivity is often attributed to the poor quality of planting material, poor soil fertility management, ageing plantations with declining yields and, more recently, the emergence of circular leaf fall disease caused by the *Pestalotiopsis* species [1]. This decline in productivity has led to a significant reduction in domestic rubber output, severely impacting rubber processing industries that are now operating at less than 50% of their installed capacity (https://gapkindo.org/, accessed on 3 March 2024). Over the past five years (2019–2023), Indonesia's rubber production has declined at an average of −5.3% per year, falling from 3.3 million tons in 2019 to 2.7 million tons in 2023 [2].

Rubber cultivation serves as a renewable source of both natural rubber and timber. While rubber plantations provide important ecosystem services such as water cycle regulation and carbon sequestration [3,4], the widespread use of monoculture systems and chemical inputs has contributed to biodiversity loss and the degradation of soil fertility. The long-term sustainability of such a cropping system is increasingly being questioned, particularly in the face of climate change, which is expected to intensify drought, heatwaves and typhoons. A more sustainable model for natural rubber production systems must address several key challenges: improving smallholders' incomes, ensuring consistent production to support the industry, and adopting agroecological practices that contribute to both climate change mitigation and adaptation. In the context of low and fluctuating natural rubber prices, income diversification appears to be a reassuring solution for smallholders that cushions the effects of the market, but the increase in rubber productivity must also be taken into account. In this way, rubber-based agroforestry systems could serve as effective and efficient alternatives to monoculture for smallholder rubber farmers, allowing them to engage in responsible production without compromising the needs of future generations. By adopting a sustainable approach, it is possible to enhance the quality of life and well-being of small-scale rubber farmers [5].

Agroforestry significantly contributes to the achievement of several Sustainable Development Goals (SDGs) and serves as a viable strategy for climate change adaptation [6]. Agroforestry is gaining importance as an approach to sustainable agricultural land management [7], biodiversity and ecosystem services [8]. In rubber cultivation, the implementation of efficient agroforestry systems enhances ecosystem services and helps alleviate poverty [9]. Income diversification is a key factor in farm resilience [10], and the productivity of rubber-based agroforestry systems was shown to compete with oil palm plantations in North Sumatra. Rubber can be intercropped with a wide range of species, including forest trees, fruit trees, resin trees, rattan palm and food crops [11]. Among the various agroforestry models, two main approaches stand out: short-term intercropping during the immature phase of rubber plantations and long-term intercropping with shade-adapted crops under standard planting densities. For systems with lower tree density, the two-row system with wide spacing is emerging for long-term intercropping of light-requiring intercrops [12]. Furthermore, breeding programmes are ongoing to develop shade-tolerant varieties of major food crops to enhance the viability of long-term intercropping under rubber canopies [13]. Whether subsistence or market-oriented, these intercrops play a vital role in strengthening the food sovereignty of producing countries.

The adoption of climate-smart practices encompasses a range of practices designed to strengthen the resilience of agricultural systems, improve productivity and reduce greenhouse gas emissions [14]. This requires interdisciplinary approaches and the integration of advanced technologies to address the challenges posed by climate change. Such an approach becomes urgent because an intersection of environmental, economic, and social factors exists and cannot be solved by just one scientific discipline [15]. As described in Indonesia's Nationally Determined Contribution (NDC), Indonesia moves forward to transition to a low-carbon and climate-resilient future, as well as the enhanced actions and the necessary enabling environment [16]. By fostering collaborative efforts among local communities, the private sector, and international organisations, Indonesia hopes to create a sustainable future that addresses the dual threat of climate change and economic development, ultimately paving the way for adaptive measures and innovative solutions [16–18]. The Indonesian government prepared a National Action Plan for Climate Change Adaptation (FAN-API) or National Adaptation Plan (NAPs) in order to maintain food production by improving infrastructure, technology, capacity building, and governance [19]. In the implementation strategy aimed at improving the effectiveness and efficiency of water and nutrition used to increase crop productivity, profitability and the reduction of greenhouse gas emissions, the indicative intervention mentions the integration of several types of plants in an agricultural land consisting of agroforestry systems. The Indonesian government also considers rubber wood production as one of the factors to reduce greenhouse gas emissions and achieve the goals of low-emission and climate-resilient development [16]. Three types of adaptation measures to climate change can be hybridised for rubber cultivation [20,21]. The first solution is the planning of plantation renewal and expansion in areas better suited to the future climate. However, this could lead to socio-economic problems and competition with more profitable crops, and could be hampered by the long production cycle, the transfer of know-how of planters and the cost of replanting. The second solution is to adapt practices in both nurseries and plantations to favour shading, conservation of soil moisture, water infiltration, appropriate soil nutrient management, etc. The third solution is to adapt rubber clones. However, breeding is often considered a long-term solution, taking 35 to 40 years to recommend a new clone [22]. Furthermore, rubber breeding has focused on creating high-yielding rubber clones, which are often poorly adapted to farmers' practices, and has shown a yield gap between clone evaluation and farmers' growing conditions [23]. In addition, little data are yet available on how monoclonal plantations and agroforestry systems function under high temperature, drought and high carbon dioxide concentrations. Hence, adaptation of rubber clones to climate change will require more studies in ecophysiology and modelling, as well as the implementation of marker-assisted selection to accelerate this process.

Transfer of technology has lost its usefulness in understanding the sources and, therefore, the solutions to extremely complex contemporary problems [24]. Participatory approaches to agricultural extension have revolutionised knowledge dissemination by fostering collaborative learning, farmer empowerment, and the co-creation of context-appropriate innovations [25]. The rubber industry has shown weakness in the adoption and appropriation of innovations, which calls into question its ability to make the necessary changes to develop a sustainable rubber production model. In 1990, Indonesian rubber production came mainly from jungle rubber systems. In order to extend the clonal plantations, which covered 350,000 ha, the government supported several development programmes that ended in 2002 [26]. As of this time, no strong support has been obtained on key issues, such as the absence of a tapping school to improve the quality of tapping and to teach the use of the reduction of tapping frequency and ethephon stimulation, or access to good quality clonal planting material and to technical information on agroforestry practices. The difficulties in transferring innovations, observed, in particular, in the case of non-organised smallholder plantations, are due to the lack of extension agents with the necessary knowledge and experience in rubber cultivation [27]. In general, village extension workers are food crop and horticulture extension workers. As a forum for all Indonesian stakeholders, the Sustainable Natural Rubber Platform of Indonesia (SNARPI) has unsuccessfully attempted to mobilise unity and joint actions to create a better management system and sustainable development for the Indonesian rubber sector. Consequently, the lack of active farmers' groups or institutions that serve as forums to provide a source of technological knowledge and information for farmers also stands in the way of the transfer and adoption of rubber crop innovations [26].

In addition to all these structural barriers, the failure of dedicated programmes and of the adoption of technical innovations can be attributed to the lack of dialogue between stakeholders and the fact that the natural rubber sector is not one of the government's priorities. Analysis of these two factors leads us to formulate two hypotheses for the successful development of sustainable rubber production. The first hypothesis is the existence of barriers that prevent the adoption of innovation, awareness-raising and education, as well as the lack of a global vision, supportive policies and dialogue between stakeholders. The second hypothesis is that the sector needs "enablers" to encourage participatory action research, awareness-raising, co-learning and capacity-building in order to develop systems thinking and a vision of the value chain. Participatory action research is a more integrative and horizontal approach that draws on the principles of agroecology, such as stakeholder participation and the co-production of knowledge. Applied to participatory plant breeding, especially plant variety selection [28–30], it involves research into the diversity of promising lines and varieties. The paradigm shift towards agroecological transition advocates the co-construction of knowledge and options for resilient farming systems as an entry point for transforming practices and behaviours and engaging stakeholders. This goes hand-in-hand with participatory approaches conducive to dialogue and co-construction. It should be noted that agroforestry is part of the paradigm of agroecology and, as such, is part of the principles that define it [31] and on which the design and implementation of agroforestry systems must be based. Among these principles, the participation, sharing and co-production of knowledge are considered to be the most transformative principles of the agroecological transition [32]. In addition, they constitute entry points into the search for an integrative transition towards sustainable food systems since they are drivers that enable research to adopt a systemic, inter- and transdisciplinary approach, and to include social, cultural, political and economic issues [33]. Over and above the scientific considerations linked to the design and testing of rubber-based agroforestry systems and their socio-economic impacts, this implies a paradigm shift in research practices towards participatory action research (PAR). As Méndez and collaborators point out [34], PAR is particularly well-suited to agroecological transitions because it enables iterative, context-specific learning between researchers and non-academic stakeholders. It hybridises complexity, integrates relational knowledge and supports co-learning processes that strengthen adaptive capacity and shared action. Empirical examples across multiple contexts confirm that the integration of the knowledge of non-researchers—farmers, practitioners, and value chain actors- leads to the production of new and actionable knowledge [35].

The aim of this study is to initiate a participatory approach involving Indonesian stakeholders in the natural rubber sector, with a view to developing sustainable rubber production systems with regard to socio-economic and environmental issues, as well as adaptation to climate change. This is reflected in the project's methodological aspects, which are better aligned with the inclusiveness and hybridisation of academic and empirical knowledge, and which aim to ensure that producers' preferences, needs and constraints are fully integrated. The participatory approach was designed and implemented to facilitate the design of innovative rubber-based agroforestry systems and to ensure the ownership of scenarios resulting from the project results and its co-construction process. The facilitation of collective intelligence was systemic within this research protocol, aiming to create an environment favourable to the co-design of integrative scenarios and, therefore, their appropriation by stakeholders, including smallholders. This included establishing the construction of a global and shared vision of the situation and issues as a starting point, promoting the convergence of the objectives of multiple stakeholders, and bringing about consensual solutions.

This study was conducted following the establishment of a multi-stakeholder working group (MSWG) with representatives of the main stakeholders of the natural rubber sector, their training in facilitation methods to ensure a dialogue and collective intelligence, and the organisation of participatory co-building workshops following an incremental protocol. The results presented in this study are structured around a co-designed value chain and actors involved from upstream to downstream, the identification of problems and solutions for the sector as envisioned by the participants, and the design of adaptive technical packages for smallholders. The working group used data collected from a farm survey in three provinces, an international workshop on the "Resilience of Rubber-based Agroforestry Systems in the Context of Global Change" [36], and a national workshop on "Challenges and Opportunities for Sustainable Natural Rubber Production in Fast-Changing Socio-Economic and Climate Conditions in Indonesia". The MSWG first co-designed the natural rubber value chain and identified actors, and then identified the problems and solutions they envision to solve these problems. Finally, the group drafted specifications for adaptive technical packages for replanting programmes. The academic consortium completed this information by designing experiments for further on-farm adaptation trials.

2. Materials and Methods

2.1. Presentation of the RUBIS Project

The Rubber agroforestry Breeding Initiative for Smallholders (RUBIS) was conducted by a consortium consisting of the CIRAD (Centre de Coopération Internationale en Recherche Agronomique pour le Développement), the Indonesian Rubber Research Institute (IRRI) and the University of Gadjah Mada (UGM). This project aimed to develop agroforestry systems based on high-performance rubber trees combined with food crops (https://www.rubis-project.org/). This solution was designed to meet the challenges of low incomes for smallholders, food sovereignty for producing countries such as Indonesia, environmental degradation and adaptation to climate change.

2.2. Implementation of a Participatory Approach

A participatory approach was set up as the starting point of the project to be inclusive and integrate the constraints and needs of the stakeholders (farmers, civil society, industry, etc.), as well as their experience and knowledge. With a transformative ambition, the RUBIS project has implemented an educational approach designed both to raise awareness of the research process among stakeholders and to enhance their capacity in terms of understanding the mechanisms at play and the levers for action, as well as in terms of the systemic approach and the co-construction process.

The project used a collective intelligence methodology to conduct a multi-stakeholder co-design process in order to ensure that it was inclusive and drew upon all the knowledge and experience of the various stakeholders, as well as the possible solutions envisaged by them. A tailor-made collective intelligence protocol has been put in place to perform the following:

- Break down the vertical way of working by catalysing interdisciplinarity and transdisciplinarity, as well as sharing a common vocabulary between researchers.
- Enable shared modelling of the rubber value chain by producing a common vision among the stakeholders.
- Lead to the co-construction of research priorities, in the form of adaptive technical packages.
- Bridge the gap between farmers, researchers, policy-makers, the private sector and civil society, and create an environment conducive to trust.

A liaison officer, a collective intelligence facilitator, was tasked with designing a comprehensive and precise protocol for catalysing dialogue between the stakeholders, including the research, by proceeding step-by-step through workshops and progressive sessions towards the ultimate objective of co-defining the terms of reference for profitable and sustainable rubber-based agroforestry systems (RAS). A number of young volunteer researchers were trained in the concept and tools of collective intelligence, as well as in 'systems thinking', the value chain approach and the interactive and participative innovation model as opposed to the linear model. These secondary facilitators were trained in the methodology and also in the use of some facilitation tools (ice-breaking, group discussion, World Café, Bono hats). The starting point was for the participants to know each other and be able to introduce each other to the group. This helped to create an atmosphere of trust conducive to the exchange of information and experience.

Group discussion and the World Café as facilitation tools have been used to support participative co-design and collective intelligence, as these tools are also well suited to complex, multi-stakeholder environments. The World Café is a rotating table format that reinforces social cohesion and helps participants to take ownership of the co-design results. This shared ownership makes subsequent implementation more likely, as solutions are jointly developed rather than imposed. This aspect has been decisive in the work to build multi-stakeholder value chains. The World Café also enables us to imagine collectively desirable futures (for example, climate-resistant rubber tree systems).

Both methods promote inclusion and equality of expression and help to break down hierarchies. They stimulate collective intelligence by enabling the cross-fertilisation of ideas between disciplines and types of stakeholders, and by triggering the emergence of new knowledge, particularly when ideas evolve collectively. They also encourage divergent thinking followed by convergence, which is essential for complex innovation (e.g., co-selection of breeding traits and intercropping models). This applies to the co-definition of varietal preferences, climate risks or trade-offs in the design of agroforestry.

The Six Thinking Hats method was used as a powerful facilitation tool in a game-like atmosphere [37], as we found it well-suited to complex contexts such as agroecology, agroforestry and participatory plant breeding; it helped to structure thinking by guiding participants to adopt different perspectives, one at a time.

We used caps instead of hats, but we followed the same colour code, with each colour supposed to embody a certain mood:

- When wearing the white hats (facts and data), they should simply be neutral and share information: What do you know about current rubber varieties, farmers' practices, and rainfall data? What are the documented constraints and yields?
- When wearing red hats (emotions), participants are invited to express their feelings: What are the producers' concerns? How do they feel about risk, debt or dependence on the market? Are researchers frustrated by political blockages
- When wearing black hats (critical mood), participants are encouraged to talk about the risks and challenges they face: for example, what are the potential problems associated with intercropping rubber and other annual crops? What are the potential pest risks or institutional bottlenecks?
- When wearing the yellow hats (positive mood), they are invited to be optimistic, for example: what are the potential benefits of the new agroforestry model for nutrition, biodiversity or income diversification?
- When they wear the green hat (innovation), they are invited to try to feel innovative by thinking of new ways, for example: What if we integrated local fruit trees? Could we develop farmer-led extension groups?
- When they wear the blue hat (process control), they are invited to comment on the process: Are we balancing the points of view? Should we pause and reframe the issue? How do we summarise and move forward?

The game helped to give equal importance to emotional, intuitive and creative contributions, to support collective innovation and to reduce the fear of wrong answers.

2.3. Setting Up a Multi-Stakeholder Working Group

The First RUBIS Multi-Stakeholders Workshop (MSHW1) was organised by the Indonesian Rubber Research Institute (IRRI) on 16 September 2022. This workshop was entitled "Challenges and Opportunities for Sustainable Natural Rubber Production in Fast-Changing Socio-Economic and Climate Conditions in Indonesia, as well as Resolution Tracks for a Better Future of the Natural Rubber Industry", and was attended by 180 participants representing governmental organisations, national associations, plantation companies and academic institutions (Table 1). The participants shared their visions for sustainable rubber cultivation and the rubber industry sector in Indonesia. A representative was assigned by each organisation in order to set up a Multi-Stakeholder Working Group (MSWG). This group was then in charge of co-constructing solutions.

Table 1. List of organisations attending the first RUBIS Multi-Stakeholders Workshop (MSHW1).

Organisation	City, District
Directorate General of Estate Crops (Ditjenbun)	Jakarta
GAPKINDO (Rubber Association of Indonesia)	Jakarta
APKARINDO (Rubber Smallholder Association of Indonesia)	Tanggerang
UPPB (Raw Rubber Processing and Marketing Unit, Musi Banyuasin)	Musi Banyuasin

Table 1. *Cont.*

Organisation	City, District
UPPB (Raw Rubber Processing and Marketing Unit, South Sumatra)	Sembawa
Estate Crop Agency (South Sumatra)	Palembang, Muara Enim, Musi Rawas
Estate Crop Agency (Jambi)	Jambi, Tebo, Merangin
Candidate farmers from South Sumatera Province	Muara Enim, Musi Rawas
Candidate farmers from Jambi Province	Jambi, Tebo, Merangin
Plantation company (Royal Lestari Utama)	Jakarta
RUBIS Academic Consortium (CIRAD, IRRI, UGM)	Montpellier (France), Sembawa, Yogyakarta
Invited universities (UNSRI, UNJA, USU) and research organisation (BRIN)	Palembang, Jambi, Medan, Cibinong

3. Results

3.1. Participative Process for the Integration of Results from Farm Surveys, On-Station Evaluations and Each of the Multi-Stakeholder Workshops

The MSWG was in charge of describing the value chain, identifying all the actors involved, helping to identify a list of the problems occurring at the different steps of the value chain and also the corresponding solutions of the rubber industry. It ended up with a process of co-designing adaptive technical packages by an academic group to be recommended for further replanting programmes. This group co-designed the process during two complementary workshops held successively in November 2023 to ensure continuity in the co-construction process, even though they were held separately (Figure 1). These workshops used the information generated by the MSHW1 workshop, the farm survey and the on-station evaluation. The principle is based on incremental sessions that gradually lead to terms of reference and end with adaptive technical packages for smallholder rubber growers. The facilitation process was designed to support participants step-by-step, starting with the sharing of visions of the state of the sector and the value chain, constraints and opportunities, problems and envisioned existing and innovative solutions, and ending with the co-construction of what could be translated into terms of reference for the design of technical packages.

The Second Multi-Stakeholder Workshop (MSHW2) was organised by the IRRI in Sembawa on 7–8 November 2023. MSHW2 was entitled "Designing solutions for resilient rubber cultivation systems for smallholders in a context of climate change. Identification of issues and solutions in the natural rubber value chain and development of terms of reference for sustainable adaptive technical packages for rubber smallholders". The aim of MSHW2 was to identify problems and solutions in the natural rubber value chain and to develop terms of reference for sustainable adaptive technical packages for smallholder plantations. This workshop brought together 23 participants representing all of the stakeholders, including the Directorate General of Estate Crops and Seeds, rubber associations (GAPKINDO, APKARINDO, and UPPB), farmers, rubber experts, private companies (RLU), academics (UGM, UNJA, USU, and UNSRI), and 10 researchers from the IRRI as facilitators.

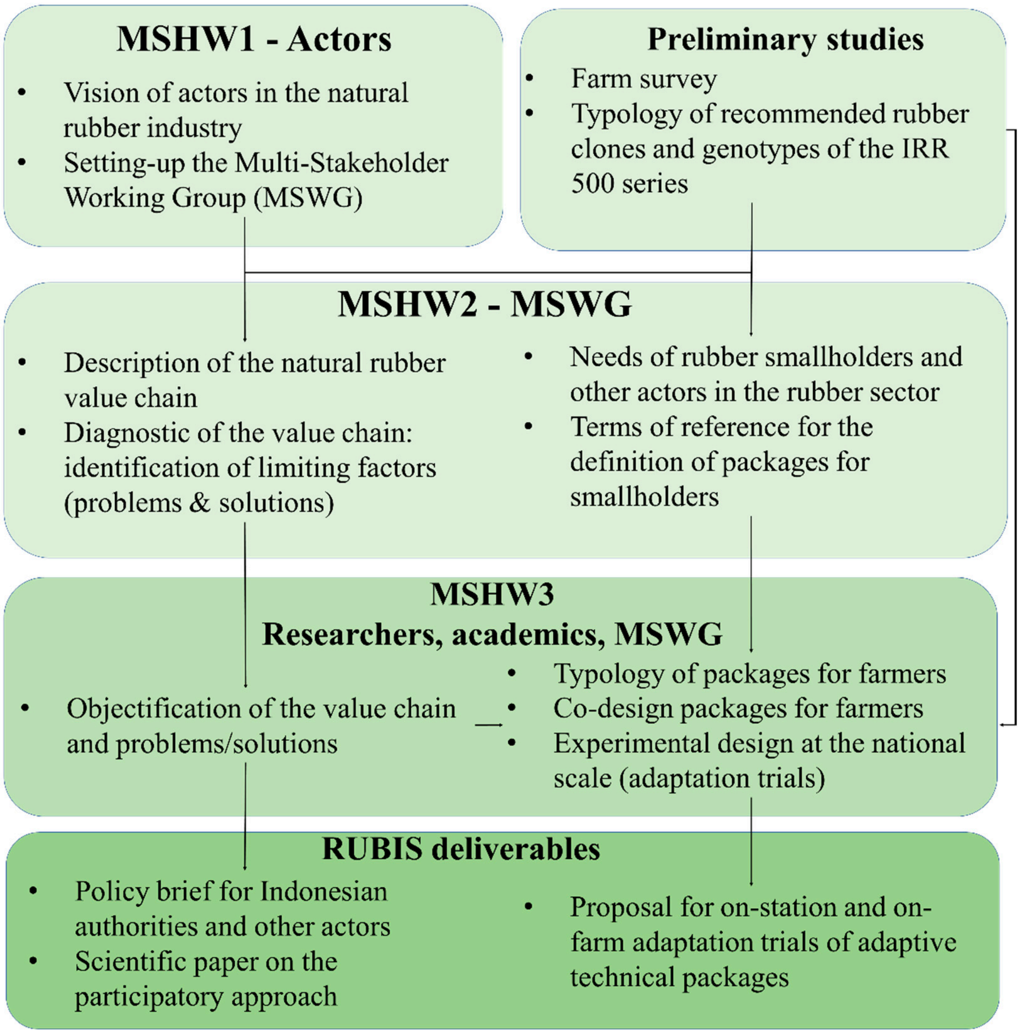

Figure 1. Participative process for the integration of results from farm surveys, on-station evaluations and each of the multi-stakeholder workshops to support the expected deliverables of the RUBIS project. MSHW and MSWG refer to multi-stakeholder workshop and multi-stakeholder working group, respectively.

The Third Multi-Stakeholder Workshop (MSHW3) was organised by the UGM in Yogyakarta on 7–8 November 2023. MSHW3 was entitled "Designing adaptive technical packages for sustainable rubber and food production by smallholders in a context of climate change". MSHW3 gathered 24 participants from scientific organisations (BRIN, CIRAD, IRRI, UGM, UNJA, UNSR, USU) and representatives of stakeholders. The results of MSHW2 were to be supplemented, enriched and objectified by the academic vision during MSHW3. Problems and solutions as expressed by the stakeholders in MSHW2 were scientifically objectified, leading to the design of relevant technical packages to be tested in on-farm and on-station multi-location trials in a further project.

3.2. Co-Designed Rubber Value Chain and Actors

The second participatory multi-stakeholder workshop resulted, among other things, in the co-design of the rubber value chain and a common vision of it. This was a good basis on which to build, as it enabled weaknesses to be identified and leveraged actions to be defined. The value chain in the rubber sector consists of ten main steps and numerous actors (Figure 2). In this scheme, the IRRI appears as an actor in charge of the plant breeding programme, the development of seed gardens for the production of rootstock, and the multiplication of planting material by grafting. Breeders register superior *Hevea* clones with the Ministry of Agriculture for the distribution of this planting material. The BPSTP (Balai Pengawasan dan Sertifikasi Perbenihan Tanaman/Seed Supervision and Certification Agency) and the Directorate General of Estate Crops are responsible for certifying seed and budwood gardens. Farmers and large plantations use this certified planting material for cultivation and rubber harvesting. Farmers and tappers are also involved in the post-harvest process as well as the marketing of rubber raw material through the preparation of latex into slumps or cup lumps. This activity is coordinated by the UPPB (Raw Rubber Processing and Marketing Unit), farmers' groups, cooperatives or agents.

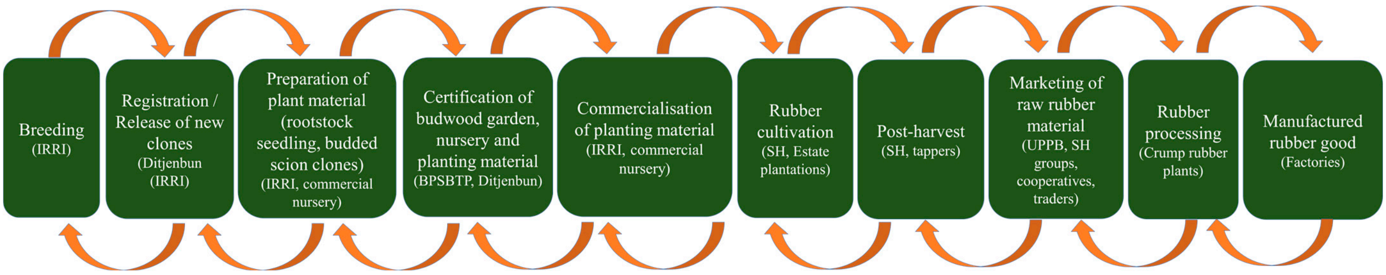

Figure 2. Value chain co-designed by the participants of the multi-stakeholder workshops.

The supply chain, which is commonly operated by farmers in several rubber centre areas in Indonesia, showed that the rubber marketing system can be distinguished from an organised marketing system through the UPPB, which has a short supply chain and a conventional (unorganised) marketing system through intermediary traders. The more marketing institutions that are involved (the longer the marketing chain is), the higher the marketing margin generated and the lower the share received by farmers will be; thus, the rubber supply chain becomes inefficient [38,39]. Previous studies reported that the organised supply chain system through the auction market by the UPPB provides higher marketing efficiency than the unorganised supply chain system through intermediary traders [40].

To become a member of the UPPB, farmers must meet the following requirements: (1) raw rubber material must be dry and not wet; (2) raw rubber material must be free of contaminants; (3) raw rubber material should be coagulated using recommended rubber coagulants; (4) raw rubber material should be in solid form [39]. To strengthen the institutional role of the UPPB, government and stakeholder support is needed to strengthen the organisational function in the form of cooperatives in order to improve the performance of the smallholders' rubber marketing system, whose function is to coordinate between all of the institutions and to provide transparent information regarding matters related to rubber marketing [41].

Rubber processing in Indonesia consists of the transformation of field latex into primary rubber products, i.e., Ribbed Smoked Sheet (RSS), latex concentrate, Standard Indonesian Rubber (SIR) 3, and the transformation of coagulated rubber into SIR 10 and SIR 20. Crumb rubber factories manage the exportation of SIR 3, SIR 10 and SIR 20 as well for domestic consumption. In Indonesia, some factories also manufacture rubber goods such as tyres and related products, latex goods, industrial rubber goods and general rubber goods [42].

3.3. A Problem/Solution Framework Identified by Stakeholders

Based on the value chain as conceived by the stakeholders, a session was organised to help express the problems and the solutions envisaged or attempted in order to deal with these problems in a specific way. The problems and solutions were identified during

MSHW2 (Supplemental Data S1) and then objectified during the academically-focused MSHW3 (Supplemental Data S2). These problems and solutions were summarised and translated into research questions to be addressed (Table 2). Among the problems that emerged, the fluctuation and low level of rubber prices were identified as a major issue. It depends on the international context and the governments, which have a low domestic consumption and cannot adjust the price. This low price affects the farmers' incomes and investments. The lack of investments, notably to renew old plantations and to train farmers, worsens the low productivity per hectare.

Table 2. Summary of problems and solutions as objectified in the multi-stakeholder workshop MSHW2.

Topic	Problem	Solution
Breeding	Funding Human resources Low genetic variability Non-clonal rootstock Combination of stresses (abiotic, biotic) Long-term breeding process	Government funding and policy directives New genetic materials (IRRDB exchange clones, germplasm, jungle rubber) In-vitro culture Physiology and ecophysiology modelling under stress Molecular-assisted selection
Production of superior planting material	Funding Rootstock (seeds and recommended clones) Fake scion clones Certification by qualified inspectors Infrastructure Low demand for new material	Government and CSR support In-vitro culture Seed garden Maintenance of budwood garden by government Control of commercial nursery Training Socialisation of planting material
Rubber cultivation	Lack of knowledge of tapping systems, intercropping practices Poor soil fertility Leaf diseases	Training of farmers Co-designing solutions with actors Double row system Low tapping frequency Integrated Pest Management
Marketing and downstream sector	Low rubber prices Limited government involvement Selling regulations Low rubber quality for farmers not members of the UPPB Low domestic consumption EUDR policy	Price regulation: SPM (Sustainable Price Mechanism), RPM (Remunerative Price Mechanism), Livelihood Rubber Price Mechanism (LRPM) Demand Promotion Scheme (DPS) Funding from CESS Farmers' groups and training, UPPB, collaboration between companies to enhance rubber-based downstream industries Geo-mapping, traceability method and technology

Many farmers have old and damaged plantations due to both a poor replanting programme and the poor application of good agricultural practices. Most farmers are not members of associations such as the UPPB and do not pay attention to rubber quality. Farmers who can afford replanting convert their plantations to more profitable crops such as oil palm. Others use poor quality planting material that leads to non-optimised plantations. Climate change and disease pandemics have already had a real impact on domestic natural rubber production, which affects processing plants that suffer from a lack of supply of raw material.

The solutions expressed by the stakeholders during the workshop involved the revitalisation of the sector, in particular, by proposing adaptive technical packages enabling greater resilience among smallholders. This implies finding the necessary funding to train planters and to set up new plantations with these packages, including high-quality planting material. The development of technologies remains an essential means of tackling the problems of low productivity, pandemics and climate change. Low productivity is often associated with the low quality of planting material, disease attacks and the ageing of plantations due to ineffective replanting programmes. Farmers often buy cheap clonal or non-clonal planting material. Stakeholders believe that in vitro propagation, integrated pest management and modern breeding programmes can improve the quality of planting material and plantations. The involvement of research institutions and universities is needed to support the development of these innovations, including genetic resource management, the introduction of in vitro techniques, the development of physiological and ecophysiological models under both biotic and abiotic stresses, and molecular-assisted selection.

3.4. Setting Up Adaptive Technical Packages

3.4.1. Terms of Reference

The second participatory multi-stakeholder workshop was facilitated to build on the set of problems and solutions for the co-writing of the terms of reference, which would be used to set up innovative and adaptive packages (Supplemental Data S3). The packages should consist of components linked to production, technology transfer and funding. The production component should be a package composed of superior clones, fertiliser, pest control, harvesting equipment and land clearing methodology. In terms of technology transfer, training courses should be organised for cultivation and marketing. In order to support all these aspects, several sources of funding were identified: the BPDP (Badan Pengelola Dana Perkebunan/Plantation Fund Management Agency), the KUR (Kredit Usaha Rakyat/People's Business Credit), government assistance, the recycling of rubber wood from former plantations, foreign aid, partnership assistance, etc.

3.4.2. Typology and Co-Design of Packages

Given that several cropping systems are used for rubber cultivation, the typology of packages was defined during a plenary session and then analysed during World Café sessions. Four types of packages were defined as follows:

- P1 for monoculture as a control.
- P2 for RAS with standard tree spacing associated with annual crops such as corn, rice, or vegetables such as chilli cayenne, which could be grown during the immature phase (4 years), and pineapple, ginger, turmeric or coffee after 4 years.
- P3 for RAS with double rows with wide spacing associated with annual crops such as corn, rice or vegetables, including chilli cayenne.
- P4 for RAS with double rows with wide spacing associated with annual crops and perennial crops. Corn, rice or vegetables such as chilli cayenne could be grown during the immature phase (4 years), while pineapple, ginger, turmeric or coffee could be planted after 4 years. For perennial tree crops, durian, *Lansium domesticum*, rambutan, longan and other fruit trees, as well as coffee, abaca for textiles and some timber species, except *Acacia mangium*, may be used in the central part of the interrow.

For P2 and P3, annual crops could be used in rotation according to their production cycle: chilli (6 months), corn (4 months), yard-long bean (4 months), eggplant (4 months), rice (4 months) and grasses for livestock feeding when integrating RAS with livestock (king and napier grasses).

SWOT analyses (short for strengths, weaknesses, opportunities, threats) were performed for the main rubber cropping systems in order to help to assess factors that may affect the different packages: monoculture (Supplemental Data S4), RAS with food crops (Supplemental Data S5), RAS with fruit trees (Supplemental Data S6), and RAS with food crops and fruit trees (Supplemental Data S7). Given the focus on the RAS solution, SWOT information was combined for the three RAS systems (Table 3). The strengths of RAS are to provide regular and stable income, ensure food security and provide ecosystem services. It is also an opportunity for the family to participate in the activities and to access new markets via diversification. However, RAS requires a higher cost of investment and maintenance, time to manage the plantation, and additional agricultural and market knowledge. RAS with fruit trees provides the highest income but also requires the highest level of investment. There is also competition of crops for water and nutrient resources, and frequent land preparation can affect soil fertility. Among the threats, market fluctuations, pests, diseases, and climate change bring more uncertainty.

Table 3. SWOT analysis of RAS packages as aggregated from SWOT analyses of MSHW3 (see Supplementary Data).

Strengths • Short-term income, faster return investment, short cycle, faster time to turnover return • Optimum use of resources over time • Diverse and stable income during immature and mature periods • Better economic resilience since the price of fruits is relatively stable or even higher • Dynamic and flexible system • Potential for innovative processed products (added value) • Market incentive for natural rubber produced in agroforestry systems • Farmers have the basic knowledge • Food security (nutrient security) during immature period • System flexibility for crop choice • Diverse C source • Improved biodiversity (soil, birds and insects)	**Opportunities** • Mitigation of the risk of rubber price fluctuation with income diversification • Utilisation of available family labour when several crops are cultivated • Market incentive for natural rubber produced in agroforestry systems • High demand for fruits • Miscellaneous food and fruit products • New increasing timber market • More carbon stocks • Livestock integration with pasture grasses • Environmentally friendly
Weaknesses • More cost investment due to more crops • More time and labour necessary to manage the plantation • Potential competition for water, nutrients and light, not optimal growth, in particular, if climate change • High nutrient demand requiring fertilisation • More time necessary for harvest and maintenance • More attention to different commodities and marketing challenges • High cost of maintenance • Lack of knowledge about technology package • Higher labour cost if use of external labour • Potential labour availability • Limited knowledge of crop management • Limited technology • Low income for rice and some annual rainfed crops • Neglected rubber maintenance if lack of labour • Potential soil degradation if the system is too intensive • Disturbance of soil fertility due to frequent land preparation	**Threats** • Complex marketing • Price uncertainty • Fluctuating market demand for food crops • Less productivity of each crop • Soil nutrient and water competition • Climate change, long dry season, rainfall dependence • Quality control export • Sharing the same diseases between rubber and associated crops • Competition for water, nutrients and light between plant species • Exacerbated competition for water in the context of climate change

3.4.3. Scheme for the Implementation of Trials and Experimental Design

A simplification process was implemented during the workshop sessions in order to make two simple packages that could be evaluated for several clones (Figure 3). Adaptation trials could then be conducted with at least two motives: monoculture rubber tree planting, and RAS in double rows of rubber trees with a wide spacing system (DR). DR is the most promising system for long-term food crop intercropping since light penetration is good for up to 9 years. Standard spacing is 6 × 3 m (550 trees/ha), while DR spacing can be either 6 × 2 × 14 (450 trees/ha) or 5 × 2.5 × 18 (400 trees/ha). When the DR spacing is less than 2.5 m between rows, it can affect girth. Consequently, the lower density is not recommended for these trials. In that case, DR is comparable in terms of growth and production to standard spacing. However, when using DR, it is necessary to maintain or use interrows all the time.

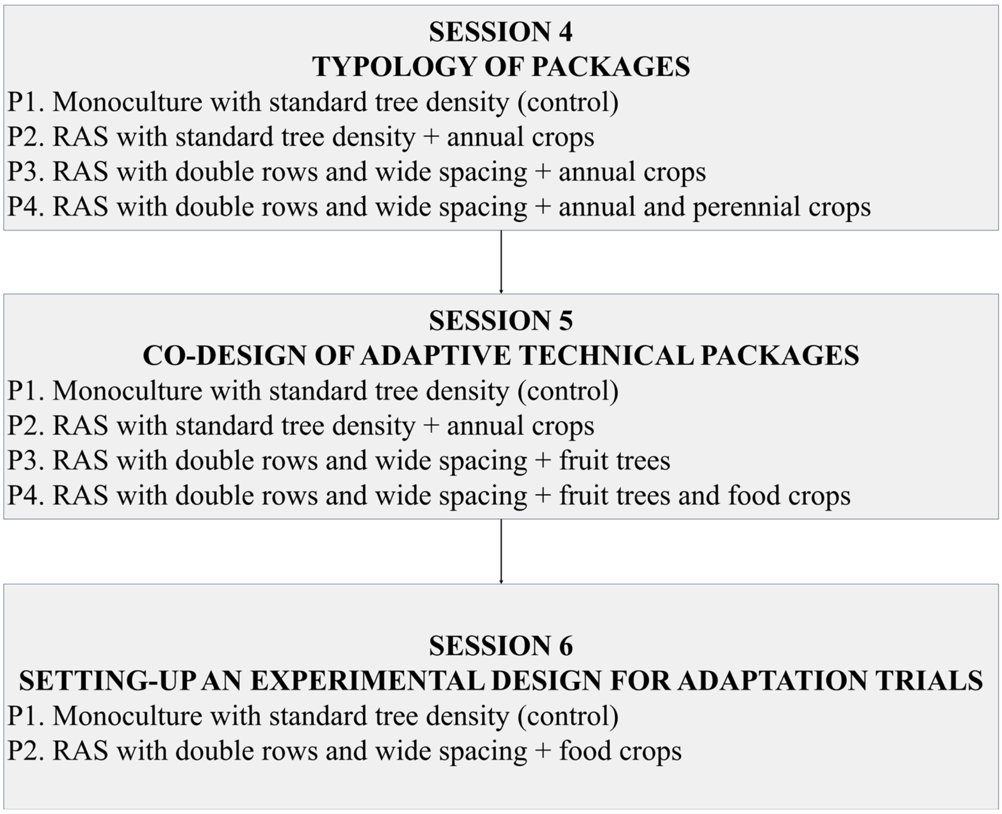

Figure 3. Simplification process from typology to co-construction of adaptive technical packages.

The package with food crops was selected to evaluate intercrops in the short term and provide income during the immature period. Food crop seeds and plants could be prepared by UGM and BRIN. These organisations offer shade-tolerant candidate varieties for rice (Rindang 1 Agritan, Rindang 2 Agritan, Inpago 12 Agritan, Inpago 13 FORTIZ, Situ Patenggang) and soybean (Denasa, Grobogan, Dega1, Dena1 and Anjasmoro). A crop rotation scheme was proposed for the immature (1–4 years) and mature (5–10 years) rubber periods.

Adaptation trials could be set up at IRRI stations and on the farms of 90 candidates of the 150 farmers interviewed during the first RUBIS farm survey. The IRRI could manage 15 ha of trials in three locations in Sungei Putih, North Sumatra, Sei Kijang, Riau and Sembawa, South Sumatra. A scheme for the implementation and monitoring of on-station and on-farm adaptation trials shows two main steps: (1) multiplication of rubber planting material and seeds for 3 years; (2) planting and monitoring of adaptation trials for 10 years (Figure 4). The multiplication of rubber planting material will necessitate the establishment of a juvenile budwood garden and a commercial budwood garden at the Sembawa Research Centre. It will take about 3 years to obtain sufficient planting material for the establishment of the on-farm and on-station adaptation trials. The new rubber clones from the IRR 500 series will be chosen within the framework of the RUBIS project, as well as the best promising clone, IRR 112, as the control for all plots. The selected new clones should combine several traits: good yield potential without stimulation; resistance to leaf diseases (*Pestalotiopsis*, *Corynespora*, *Colletotrichum* and *Oidium*); tolerance to Tapping Panel Dryness, short immature period (4 to 5 years max); low tapping frequency (d3); a canopy typology adapted to agroforestry. For on-station trials, some new clones adapted to ethephon stimulation, including very low tapping frequency (d7), could be tested (non-published data).

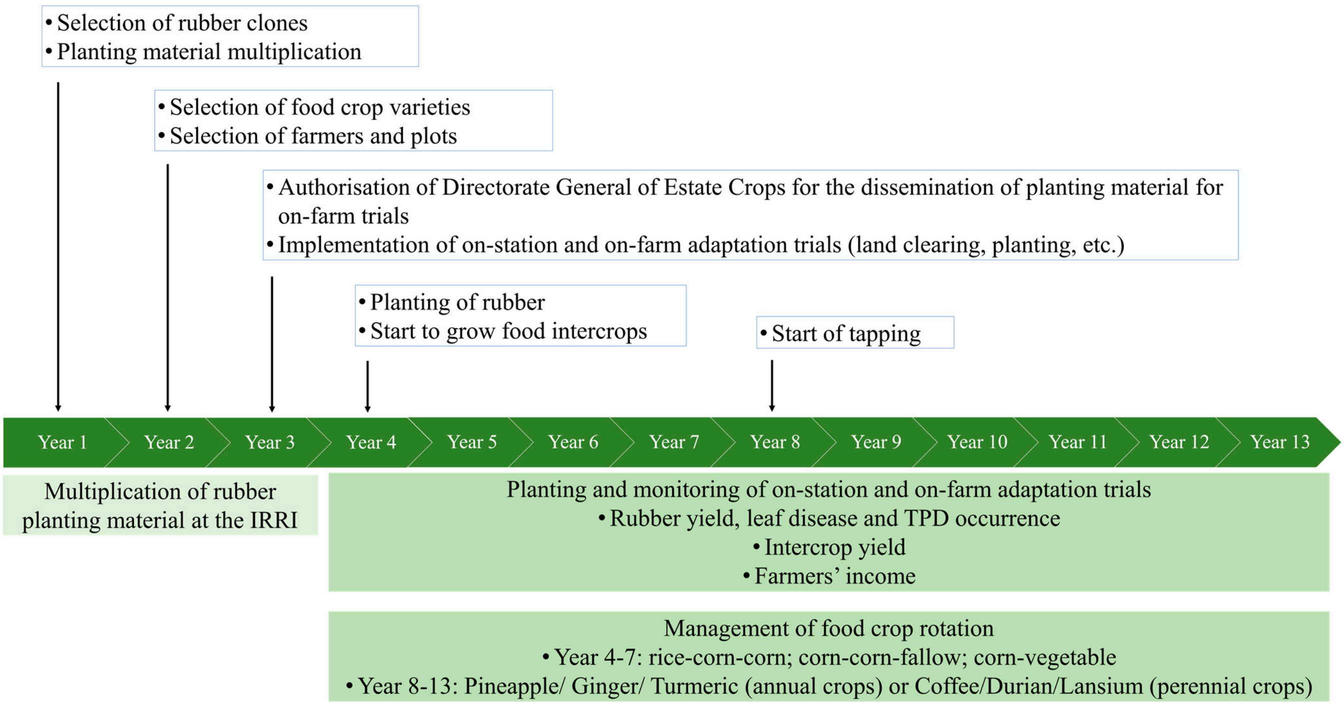

Figure 4. Scheme for the implementation and monitoring of on-station and on-farm trials.

Indonesian regulations governing the release of new recommended rubber clones require new clones to be compared with at least one previously recommended clone on one hectare per site for 10 years, in at least two sites with contrasting agroclimatic conditions [43]. During the MSHW2, the Directorate of Seeds agreed to provide a special authorisation to RUBIS for the implementation of on-farm trials with new clones within the framework of a participatory breeding programme, respecting the same regulations.

Research stations can compare all defined packages on the same site comprising 11 clones, including the control clone, IRR 112, and all cropping systems (Supplementary Table S8). The experimental design can consist of four replicates of 0.25 ha per clone. The statistical design for on-station trials will be a randomised complete block design using a statistical mixed model such as $y_{ijkl} = \mu + G_i + L_k + (GL)_{ik} + B_{j(k)} + \varepsilon_{ijkl}$, where μ = overall mean, G_i = effect of clone, L_k = effect of site k, $(GL)_{ik}$ = interaction of genotype and site, $B_j(k)$ = block j within site k, and ε_{ijkl} = residual error.

IRRI researchers consider it difficult to design several plots as replicates at the farm level. For that reason, it is suggested to consider each farmer's plot as a replicate for the implementation of an on-farm adaptation trial. For that reason, three farmers with one hectare per clone will conduct trials with one control clone, IRR 112, and one or two newly selected clones from the IRR 500 series (Supplementary Table S8). Given on-farm trials will be conducted in several provinces with varying numbers of farmers, and an unbalanced incomplete block design will be carried out with a statistical mixed model such as $y_{ijkl} = \mu + G_i + L_j + (GL)_{ij} + F_{k(j)} + \varepsilon_{ijk}$, where G_i = fixed or random effect of clone, L_j = effect of province, $(GL)_{ij}$ = interaction of genotype and site, $F_{k(j)}$ = random effect of farmer nested within province, and ε_{ijkl} = residual.

Monitoring of rubber production by farmers is a limiting factor. Farmers collect their production and sell it once a week to traders or UPPB units. Quality control of rubber and food crop production should involve the local university at a regular frequency.

With regard to harvesting systems, the application of tapping frequencies d2, d3 and d7 is difficult in Indonesia. Further discussion with farmers about the acceptability of one of these low tapping frequencies is necessary. Otherwise, a specific clone from the IRR 500 series adapted to high tapping frequency (d1) should be chosen for the on-farm trials [44].

3.4.4. Tentative Roadmap for Applications

A roadmap can now be drawn up (Figure 5). A great deal of work on the physiology and genetics of natural rubber production and rubber-based agroforestry has been carried out from the 1990s to 2021. The RUBIS project integrated the results of these projects. As part of the RUBIS project, this work has led to the development of a participatory approach that has resulted in the co-construction of adaptive technical packages. A production phase for the clonal planting material selected by IRRI will make it possible to initiate evaluation trials of these packages from 2027, which will be monitored by a consortium extended to several local universities and research centres. Corporate social responsibility funds are supposed to help set up these trials with the local populations who will benefit from these technical packages. Evaluation data could be used as the basis for a government replanting programme to revitalise the sector and make it more sustainable.

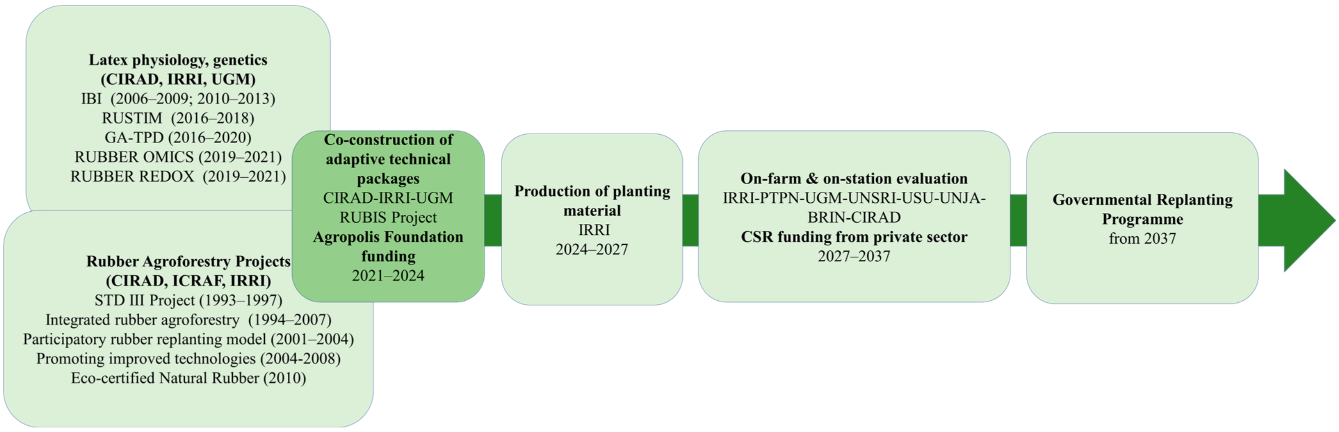

Figure 5. Road map for the application of adaptive technical packages.

4. Discussion

The RUBIS project has sought to create a favourable and inclusive environment for the co-construction of solutions by stakeholders in the natural rubber sector. The researchers involved have been trained and have undergone a paradigm shift in the way they work and communicate with stakeholders. This innovative approach was conducted with a multi-stakeholder working group that co-constructed the value chain and identified the actors in the natural rubber sector. This stakeholders' group identified the problems related to this sector and then listed potential solutions. Finally, these group members defined adaptive technical packages to propose a more efficient and sustainable production system. This participatory approach raised several questions, which are developed below. The first concerns the difficulties of implementing the approach itself. The second aims to put the main problems and solutions into context and assess their relevance. Finally, the sustainability of these solutions is discussed.

4.1. Effectiveness and Limitations of the Participatory Approach and Associated Challenges

The participatory approach implemented in this project required significant human and financial support, both in the preparation and holding of workshops, as well as in the formalisation and dissemination of results. This work has generated great enthusiasm and hope for this struggling natural rubber sector. However, methodological limitations, potential data biases and challenges were encountered.

Methodological limitations were identified in the choice of stakeholder representatives, the difficulty of having the same interlocutors over a long period and limited discussion time. Stakeholder representatives were selected by their own organisations, and it was difficult to keep the same contacts over a long period of time, particularly due to the turnover of posts at the Ministry of Agriculture or in the private sector. Upstream, academic and research stakeholders worked hard to organise the workshops, and some of them participated in workshop facilitator training, creating a strong involvement. During the workshops, participants realised that the term 'participatory' is often misused and felt that they were making a real contribution thanks to the facilitation methods that allowed each participant, in particular local farmers and less confident participants, to express themselves and take their ideas into account. This power asymmetry, revealing how dominant institutions impose unbiased narratives, is a well-known epistemic exclusion and co-optation that we tried to reduce in the workshop [45]. It was noticed that stakeholders often focus on their own problems in their own professional language. The scientists' objectification stage attempted to fill in the gaps and act as translators to arrive at a common vision and a shared vocabulary. The challenge of the facilitation process was not to give priority to scientific knowledge over experiential or tacit knowledge, and at the same time to avoid producing results that would not be rejected as non-reproducible, which would limit their use beyond the RUBIS project.

The co-construction of the value chain and the positioning of the players in the natural rubber sector on this chain has allowed everyone to better understand the role of the various players and their interdependence in order to have a dynamic and beneficial sector for everyone involved. The presentation of the various problems and solutions allowed everyone to express themselves and develop their arguments to finally see the robustness of the proposed solutions. This also made it possible to integrate these solutions into a broader dimension, including socio-economic, environmental and climatic constraints. After each workshop, the academics formatted the information collected into a document. Circulating this document was also a necessary step in providing this overall vision and ensuring the validation of the results obtained. The results of participation are often qualitative, relational and difficult to measure using conventional indicators. The risk is that our process, even if successful, remains invisible or unrecognised, which limits its adoption or replication on a larger scale. Processes are difficult to learn, teach or reproduce. The challenge is to systematise the documentation of results and processes and to develop meta-learning platforms (e.g., communities of practice, living laboratories, etc.) to share how participation worked, not just what it produced.

The question of wider dissemination at the sector level is also an issue. The policy brief tool is a widely used solution to ensure broad dissemination at the level of authorities and not just among workshop participants. Dissemination to smallholders, particularly those who are not part of groups (associations, cooperatives, etc.), remains an open question. This participatory approach is also a guarantee for donors that the proposed solutions are robust and will be more easily adopted by stakeholders in the sector.

In Section 4.3, we will see that adaptive technical packages need to be validated through a participatory plant breeding programme that will take place over a period of around ten years. This also calls into question the maintenance of the momentum initiated over the long term. This may involve coordination between authorities, various academic actors and stakeholders in the sector. Moreover, the multi-stakeholder working group must continue to play a leading role in the future. This coordination remains a challenge, but models exist, including living labs that make it possible to maintain the dynamics between stakeholders at a low cost. The development of rubber-based agroforestry systems with food crops and fruit trees also raises questions about how to make the agricultural sectors interact to develop shared production systems. Projects generally have a short cycle, whereas the participatory process is iterative and takes a long time. Participatory Action Research approaches support agroecological scaling-up. The challenge is to establish a climate of trust, commitment and long-term dialogue that will last beyond the project, thanks to the facilitation process [46].

The results of this participatory approach confirm some existing knowledge and challenge others. It should be noted that this study, like most socioeconomic or agronomic studies, did not take into account the vast majority of unorganised smallholder farmers in Indonesia, who live in remote areas and have low levels of education. By providing context-based explanations, we were able to demonstrate the multitude of factors underlying development barriers. For example, it will not be easy to improve the quality of planting material without considering the problems of commercial nurseries, which are themselves driven by the demand for planting material at a fair price that is profitable for all parties. Another example concerns the adoption of good practices, particularly harvesting systems, which also requires a set of actions from the government and research institutes, which must find a relay to enable the practices to be widely disseminated. Interestingly, although stakeholders have opinions on solutions, researchers remain a driving force in identifying and clearly describing these solutions.

4.2. Action Levers Revealed by the Participative Approach for the Rubber Sector

Understanding the factors that affect the income of farmers is crucial for developing strategies to enhance key aspects of rubber sustainability. Given the context of low rubber prices, competition with more productive crops, chronic underinvestment and the growing risks associated with climate change, developing a resilient natural rubber production system is not negligible. Four main issues must be addressed.

The first is the guarantee of a decent income for smallholders. In addition to international agreements between producing and consuming countries, this can be achieved by diversifying activities within the farm, either by growing associated crops throughout the rubber growing cycle, by other fruit-based cropping systems, or even via off-farm activities in the tertiary sector, for example. Policies to promote the development of RAS are beginning to be applied, particularly in Thailand, through guidelines published by the Earthworm Foundation [47]. In this way, rubber-based agroforestry systems could be an efficient alternative to monoculture for rubber smallholders. Smallholders usually tap rubber trees with a high tapping frequency (every day or every two days). The best system would be to combine agroforestry practices to diversify income and to adopt better agricultural practices, such as good-quality tapping to ensure good yields, and low-frequency tapping systems using stimulation to improve the family's labour productivity. This, therefore, requires dedicated training in the use of low-frequency tapping systems or even the use of more efficient clones adapted to very low-frequency tapping (every four days or more). Such rubber clones are under development at the IRRI. Traditional training systems are not very effective in Indonesia and do not reach enough farmers since most of them abandon farming. Therefore, new processes such as rubber wiki-type applications [48] may be implemented to facilitate easy learning by each farmer at any time and for all stages of cultivation.

The second involves growing new crops to diversify income, particularly when rubber prices are low. Annual crops are particularly well-suited to intercropping during the immature phase of rubber cultivation, but also potentially during the mature phase, with varieties adapted to shade (curcuma, ginger, pineapple, taro and yam) or by using double-spaced systems with large spaces to allow light to penetrate. Interestingly, several shade-tolerant varieties have been bred in Indonesia for soybean, maize [49] and rice [50]. Rubber-fruit tree systems are also very profitable [26]. However, they require a greater investment to set up the plantation, and the return on investment is long. A balance between the various associated crops is therefore necessary to guarantee an income from the outset of the plantation. Regardless of the case, farmers must acquire additional knowledge to manage these intercrops, and local markets should exist to sell their output.

The third area of research relates to adaptation to climate change. It involves adapting cultivation practices and improving rubber clones, or even redeploying rubber cultivation to areas better suited to the future climate. Rubber research must take future climate data into account and, in particular, work to develop cultivation systems and clones adapted to high temperatures, longer dry seasons and strong winds, as well as to new diseases that may emerge. This also raises questions about the resilience of monoculture and agroforestry systems, particularly with regard to competition between species for water and soil nutrient resources. More in-depth knowledge in the field of ecophysiology is therefore needed to gain a better understanding of these interactions. Agroforestry makes it possible to better manage risks by diversifying agricultural products. Crops grown under trees benefit from a microclimate that is more favourable to their development. Increased biodiversity can also help reduce vulnerability to pests, disease and climatic shocks. Better fertility and soil management can also help to improve productivity compared with monoculture without chemical inputs.

The fourth axis aims to seize the opportunity of developing new adaptive technical packages to implement more environmentally sustainable agriculture with a transition to more agroecological practices. The rubber tree is an essential tree species that absorbs carbon dioxide from the atmosphere and stores it in its biomass, litter and in the soil [51]. In this way, rubber cultivation contributes to climate change mitigation [4]. Chemical inputs are increasingly expensive, and their use has led to the depletion of soils in terms of both organic compounds and biodiversity. Gradually improving soil fertility through more agroecological practices would therefore have an economic impact by reducing the cost of inputs, and an environmental impact by encouraging carbon storage, which plays a role in mitigating climate change.

4.3. Obstacles to Implementing Solutions for More Sustainable Rubber Cultivation

There are a number of obstacles to the implementation of these priorities in terms of financing replanting, guaranteeing the performance of adaptive technical packages, training farmers and extension service staff, the duration of the process, and, finally, forecasting the effects of climate change.

Funding for replanting new rubber plots is very low in Indonesia, which has not yet implemented an export cess system to support the sector. The support is generally local and very limited to extension services or similar administrative entities. Research funding depends on government plantation companies (PTPN), which are themselves under significant financial pressure due to the low price of natural rubber. However, authorities in the second-largest producing country are questioning the relevance of establishing an Indonesian Rubber Board and including rubber among commodities already benefiting from export taxes, such as palm oil. A new policy could thus revitalise this agricultural and industrial sector.

The adaptive technical packages co-constructed during the participatory process aim to develop more sustainable plantations from a socio-economic and environmental perspective, but their performance remains to be demonstrated in different agroclimatic contexts. Although the long-term economic viability of the proposed agroforestry systems has been demonstrated, it remains uncertain and dependent on the magnitude of climate change. A wider consortium of local players is needed to evaluate these trials on the scale of several provinces. Common performance indicators for the trials will have to be defined by this consortium. They will have to be simple and robust in terms of the many potential observers who will be carrying out the evaluation, and avoid any drift over the duration of the trials. For instance, the long-term viability could be recorded through the gross margin per hectare of various cropping systems and impact on net farm income per year, which could be made through regular farm surveys. Income stability through diversification is considered a very good indicator of resilience [26]. A participatory plant breeding process is under construction with the co-design of adaptive technical packages and the establishment of on-farm and on-station evaluation trials. These trials require significant funding, which could be contributed by the private sector via corporate social responsibility (CSR) funds. The Medco Company has implemented a CSR programme for the development of rubber smallholders' plantations in partnership with the Indonesian Rubber Research Institute. The company provides assistance funds to rubber farmers by establishing smallholders' rubber plantations using superior clone planting materials and implementing Good Agricultural Practices (GAP) provided by the Indonesian Rubber Research Institute.

In addition, this evaluation process is a long-term process (10 years) and must involve numerous local actors, both academics and non-governmental organisations, as well as extension services, to support farmers. These packages must also benefit from improvements in adaptation to climate change. This requires, in addition to the participatory plant breeding approach, the implementation of research both in physiological and ecophysiological modelling and in genomic selection tools to predict the best ideotypes and accelerate selection. Efforts have begun to be made in this direction. Work on the physiological modelling of latex yield [52] and susceptibility to Tapping Panel Dryness [44], the use of ecophysiological proxies for drought tolerance [53], and the combination of bioassays with field data on disease susceptibility [1], should make it possible to carry out early selection and, consequently, to dramatically shorten the selection period. Combined with existing genomic selection tools [54], this remains a credible challenge for *Hevea* breeding.

If the adaptive technical packages prove even more efficient and resilient than the rubber-based agroforestry systems planted to date, this should bring lasting social and economic benefits to the communities. The RUBIS project and the evaluation trials that will follow, particularly in on-farm trials, will increase farmer engagement and skill improvement, and establish a network for disseminating these participatory practices and packages that can be gradually adapted locally through a participatory plant breeding approach. The diversification of farmers' activities should also facilitate participation in stakeholder groups by giving more available time, in particular by reducing rubber tapping frequencies and improving labour productivity, and increasing interactions with those involved in different agricultural activities. Although the study considers local solutions, networking across various Indonesian provinces offers potential for scaling up the initiative nationally. Regionally, several countries, such as Thailand [47], are promoting rubber-based agroforestry. There are, therefore, challenges and scalability strategies to be implemented to promote participatory research for local agroecological solutions through agroforestry. To this end, interaction with the International Rubber Research and Development Board, which brings together all the rubber research institutes and the major agricultural universities in rubber-producing countries, must be strengthened in these challenges.

5. Conclusions

This study constitutes the essential component of the participatory approach implemented as part of the RUBIS project. This process was marked by the involvement and training of young researchers in facilitation tools, the establishment of a multi-stakeholder working group, and the development and facilitation of a co-design process during the workshops. This made it possible to develop a shared vision of the value chain and the sector's challenges, and to co-construct solutions that led to the creation of adaptive technical packages.

The preparation and facilitation of these workshops enabled stakeholders to implement a shared understanding of systems thinking. Among the results of the participatory action research conducted by the RUBIS project is a shared vision of the sector and its challenges, as well as a shared vision of ways to address them, thus shedding light on the roles of the stakeholders. Research is one of the stakeholders, but here it acts not only as a provider of knowledge and techniques, but also as a facilitator of the entire process of co-constructing innovations, ensuring their relevance and adoption. It was also a co-learning process aimed at building capacity at different levels of the value chain. Over and above these tangible results, the process has also strengthened the capacities of all the players involved by promoting awareness of the systemic nature of agroforestry and the crucial importance of integrating the value chain logic into climate adaptation strategies. More importantly, it has created a space for dialogue between producers, researchers and policy-makers, thereby contributing to the participatory governance of innovation.

The RUBIS project's participatory research process relied on facilitating collective intelligence adapted to the agroecology paradigm and some of the challenges facing research in supporting change. From this perspective, collective intelligence is not an accessory, but a cornerstone of adaptive, inclusive and resilient agroecological transitions. Indeed, the research protocol used here combined agroecology principles focused on improving resource efficiency and strengthening the resilience of ecosystems and societies with principles based on social equity and inclusion. With a transformative ambition, the RUBIS project implemented an educational approach aimed both at raising stakeholders' awareness of the research process and building their capacity to understand the mechanisms at work.

Rubber cultivation, particularly in the context of an agroecological transition, can further contribute to climate change mitigation, but to do so, it must also adapt. The participatory approach undertaken in this study is a means of implementing sustainable solutions for the natural rubber sector. This participatory approach allowed us to identify several factors conducive to the development of a more sustainable sector, both socio-economically and environmentally, while taking the growing effects of climate change into account. The development of adaptive technical devices based on agroforestry systems partially addresses this challenge, as well as that of food sovereignty in producing countries. It raises research questions that the participatory plant breeding approach can address. Political support, particularly through financial incentives, research funding and extension services, will further promote adoption and transferability.

In practical terms, this study has led to the definition of adaptive technical packages that will form the basis of a proposal for on-station and on-farm evaluation trials. The involvement of plantation companies and factories affiliated with GAPKINDO will facilitate discussions to finance these trials with corporate social and environmental responsibility funds. The recommendations resulting from this study and the research publications on socio-economics, agronomy and breeding will provide the material for drafting a policy brief for the Indonesian authorities. Finally, this study could serve as a reference for other natural rubber-producing countries and be discussed in international bodies such as the IRRDB (International Rubber Research and Development Board), the ANRPC (Association of Natural Rubber Producing Countries), and the GPS-NR (Global Platform for Sustainable Natural Rubber).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17156884/s1, Table S1: Problems and solutions for smallholder and industrial plantations identified in the Multi-Stakeholder Workshop 2; Table S2: Objectivation of problems and solutions identified in the Multi-Stakeholder Workshop 2 during the third workshop; Table S3: Terms of reference defined by stakeholders for the design of packages for farmers; Table S4: SWOT analysis of package 1 for monoculture; Table S5: SWOT analysis of package 2 for rubber associated with food crops; Table S6: SWOT analysis of package 3 for rubber associated with fruit trees; Table S7: SWOT analysis of package 4 for rubber associated with food crops and fruit trees; Table S8: Experimental design for on-station and on-farm adaptation trials.

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